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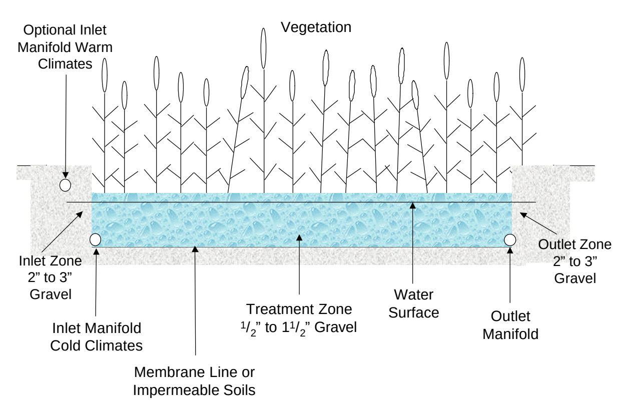
Wastewater Technology Fact Sheet
Wetlands: Subsurface Flow

DESCRIPTION

Wetland systems are typically described in terms of the position of the water surface and/or the type of vegetation grown. Most natural wetlands are free water surface systems where the water surface is exposed to the atmosphere; these include bogs (primary vegetation mosses), swamps (primary vegetation trees), and marshes (primary vegetation grasses and emergent macrophytes). A subsurface flow (SF) wetland is specifically designed for the treatment or polishing of some type of wastewater and are typically constructed as a bed or channel containing appropriate media. An example of a SF wetland is shown in Figure 1. Coarse rock, gravel, sand and other soils have all been used, but a gravel medium is most common in the U.S. and Europe. The medium is typically planted with the same types of emergent vegetation present in marshes, and the water surface is designed to remain below the top surface of the medium. The main advantages of this subsurface water level are prevention of mosquitoes and odors, and elimination of the risk of public contact with the partially treated wastewater. In contrast, the water surface in natural marshes and free water surface (FWS) constructed wetlands is exposed to the atmosphere with the attendant risk of mosquitoes and public access.



Source: Adapted from drawing by S.C. Reed, 2000.

FIGURE 1 SUBSURFACE FLOW WETLAND

The water quality improvements in natural wetlands had been observed by scientists and engineers for many years and this led to the development of constructed wetlands as an attempt to replicate the water quality and the habitat benefits of the natural wetland in a constructed ecosystem. Physical, chemical, and biochemical reactions all contribute to water quality improvement in these wetland systems. The biological reactions are believed due to the activity of microorganisms attached to the available submerged substrate surfaces. In the case of FWS wetlands these substrates are the submerged portion of the living plants, the plant litter, and the benthic soil layer. In SF wetlands the available submerged substrate includes the plant roots growing in the media, and the surfaces of the media themselves. Since the media surface area in a SF wetland can far exceed the available substrate in a FWS wetland, the microbial reaction rates in a SF wetland can be higher than a FWS wetland for most contaminants. As a result, a SF wetland can be smaller than the FWS type for the same flow rate and most effluent water quality goals.

The design goals for SF constructed wetlands are typically an exclusive commitment to treatment functions because wildlife habitat and public recreational opportunities are more limited than FWS wetlands. The size of these systems ranges from small on-site units designed to treat septic tank effluents to a $1.5x10^7$ liters per day (4 MGD) system in Louisiana treating municipal wastewater. There are approximately 100 systems in the U.S. treating municipal wastewater, with the majority of these treating less than $3.8x10^3$ m^3/day (1 MGD). Most of the municipal systems are preceded by facultative or aerated treatment ponds. There are approximately 1,000 small scale on-site type systems in the U.S. treating waste waters from individual homes, schools, apartment complexes, commercial establishments, parks, and other recreational facilities. The flow from these smaller systems ranges from a few hundred gallons per day to 151,400 liters per day (40,000 gallons per day), with septic tanks being the dominant preliminary treatment provided. SF wetlands are not now typically selected for larger flow municipal systems. The higher cost of the rock or gravel media makes a large SF wetland uneconomical compared to a FWS wetland in spite of the smaller SF wetland area required. Cost comparisons have shown that at flow rates above 227,100 liters per day (60,000 gallons per day) it will usually be cheaper to construct a FWS wetland system. However, there are exceptions where public access, mosquito, or wildlife issues justify selection of a SF wetland. One recent example is a SF wetland designed to treat the runoff from the Edmonton Airport in Alberta, Canada. The snow melt runoff is contaminated with glycol de-icing fluid and a SF wetland treating 1,264,190 liters per day (334,000 gallons per day) was selected to minimize habitat values and bird problems adjacent to the airport runways.

SF wetlands typically include one or more shallow basins or channels with a barrier to prevent seepage to sensitive groundwaters. The type of barrier will depend on local conditions. In some cases compaction of the local soils will serve adequately, in other cases clay has been imported or plastic membrane (PVC or HDPE) liners used. Appropriate inlet and outlet structures are employed to insure uniform distribution and collection of the applied wastewater. A perforated manifold pipe is most commonly used in the smaller systems. The depth of the media in these SF wetlands has ranged from 0.3 to 0.9 meters (1 to 3 feet) with 0.6 meters (2 feet) being most common. The size of the media in use in the U.S. ranges from fine gravel (≥0.6 centimeters or ≥ 0.25 in.) to large crushed rock (≥15.2 centimeters or ≥6 in.); A combination of sizes from 1.3 centimeters to 3.8 centimeters (0.5 to 1.5 inches) are most typically used. This gravel medium should be clean, hard, durable stone capable of retaining it's shape and the permeability of the wetland bed over the long term.

The most commonly used emergent vegetation in SF wetlands include cattail (*Typha* spp.), bulrush (*Scirpus* spp.), and reeds (*Phragmites* spp.). In Europe, *Phragmites* are the preferred plants for these systems. *Phragmites* have several advantages since it is a fast growing hardy plant and is not a food source for animals or birds. However, in some parts of the U.S. the use of *Phragmites* is not permitted because it is an aggressive plant and there are concerns that it might infest natural wetlands. In these cases cattails or bulrush can be used. In areas where muskrat or nutria are found, experience has shown that these animals, using the plants for food and nesting material, can completely destroy a stand of cattails or bulrush planted in a constructed wetland. Many of the smaller on-site systems serving individual homes use water tolerant decorative plants. The vegetation on a SF wetland bed is not a major factor in nutrient removal by the system and does not require harvesting. In cold climates, the accumulating plant litter on top of the gravel bed provides useful thermal insulation during the winter months. The submerged plant roots do provide substrate for microbial processes and since most emergent macrophytes can transmit oxygen from the leaves to their roots there are aerobic microsites on the rhizome and root surfaces. The remainder of the submerged environment in the SF wetland tends to be devoid of oxygen. This general lack of available oxygen limits the biological removal of ammonia nitrogen (NH_3/NH_4 - N) via nitrification in these SF wetlands, but the system is still very effective for removal of BOD, TSS, metals, and some priority pollutant organics since their treatment can occur under either aerobic or anoxic conditions. Nitrate removal via biological denitrification can also be very effective since the necessary anoxic conditions are always present and sufficient carbon sources are usually available.

The limited availability of oxygen in these SF systems reduces the capability for ammonia removal via biological nitrification. As a result, a long detention time in a very large wetland area is required to produce low levels of effluent nitrogen with typical municipal wastewater influents unless some system modification is adopted. These modifications have included installation of aeration tubing at the bottom of the bed for mechanical aeration, the use of an integrated gravel trickling filter for nitrification of the wastewater ammonia, and vertical flow wetland beds. These vertical flow beds usually contain gravel or coarse sand and are loaded intermittently at the top surface. The intermittent application and vertical drainage restores aerobic conditions in the bed permitting aerobic reactions to proceed rapidly. Cyclic filling and draining of a horizontal flow system has been successfully demonstrated at the 130,000 gallons per day SF wetland system in Minoa, NY. The reaction rates for BOD_5 and ammonia removal during these cyclic operations were double the rates observed during normal continuously saturated flow.

The phosphorus removal mechanisms available in all types of constructed wetlands also require long detention times to produce low effluent levels of phosphorus with typical municipal wastewater. If significant phosphorus removal is a project requirement then a FWS wetland will probably be the most cost effective type of constructed wetland. Phosphorus removal is also possible with final chemical addition and mixing prior to a final deep settling pond.

The minimal acceptable level of preliminary treatment prior to a SF wetland system is the equivalent of primary treatment. This can be accomplished with septic tanks or Imhoff tanks for smaller systems or deep ponds with a short detention time for larger systems. The majority of existing SF wetland systems treating municipal waste waters are preceded by either facultative or aerated ponds. Such ponds are not necessarily the preferred type of preliminary treatment. At most of these existing systems the SF wetland was selected to improve the water quality of the pond effluent. Since the SF wetland can provide very effective removal for both BOD_5 and TSS, there is no need to provide for high levels of removal of these constituents in preliminary treatments.

The SF wetland does not provide the same level of habitat value as the FWS wetland because the water in the system is not exposed and accessible to birds and animals. However, wildlife will still be present, primarily in the form of nesting animals, birds, and reptiles. If provision of more significant habitat values is a project goal it can be accomplished with deep ponds interspersed between the SF wetland cells. The first pond in such a system would be located after the point where water quality is approaching at least the secondary level

APPLICABILITY

SF wetland systems are best suited for small to moderate sized applications (≤ 227,100 liters/day or ≤60,000 gallons per day) and at larger systems where the risk of public contact, mosquitoes, or potential odors are major concerns. Their use for on-site systems provides a high quality effluent for in-ground disposal, and in some States a significant reduction in the final disposal field area is allowed. SF wetlands will reliably remove BOD, COD, and TSS, and with sufficiently long detention times can also produce low levels of nitrogen and phosphorus. Metals are removed effectively and about a one log reduction in fecal coliforms can be expected in systems designed to produce secondary or advanced secondary effluents.

ADVANTAGES AND DISADVANTAGES

Some advantages and disadvantages of subsurface flow wetlands are listed below.

Advantages

- SF wetlands provide effective treatment in a passive manner and minimize mechanical equipment, energy, and skilled operator attention.

- SF wetlands can be less expensive to construct and are usually less expensive to operate and maintain as compared to mechanical treatment processes designed to produce the same effluent quality.

- Year-round operation for secondary treatment is possible in all but the coldest climates.

- Year-round operation for advanced or tertiary treatment is possible in warm to moderately temperate climates. The SF wetland configuration provides more thermal protection than the FWS wetland type.

- SF wetland systems produce no residual biosolids or sludges requiring subsequent treatment and disposal.

- The SF wetland is very effective and reliable for removal of BOD, COD, TSS, metals, and some persistant organics in municipal wastewaters. The removal of nitrogen and phosphorus to low levels is also possible but requires a much longer detention time.

- Mosquitoes and similar insect vectors are not a problem with SF wetlands as long as the system is properly operated and a subsurface water level maintained. The risk of contact by children and pets with partially treated wastewater is also eliminated.

Disadvantages

- A SF wetland will require a large land area compared to conventional mechanical treatment processes.

- The removal of BOD, COD, and nitrogen in SF wetlands are continuously renewable processes. The phosphorus, metals, and some persistent organics removed in the system are bound in the wetland sediments and accumulate over time.

- In cold climates the low winter water temperatures reduce the rate of removal for BOD, NH_3, and NO_3. An increased detention time can compensate for these reduced rates but the increased wetland size in extremely cold climates may not be cost effective or technically possible.

- Most of the water contained in the SF wetland is anoxic and this limits the potential for nitrification of wastewater ammonia. Increasing the wetland size and detention time will compensate, but this may not be cost effective. Alternative methods for nitrification in combination with a SF wetland have been successful. SF wetlands cannot be designed for complete removal of organic compounds, TSS, nitrogen, and coliforms. The natural ecological cycles in these wetlands produce “background” concentrations of these substances in the system effluent.

- SF wetland systems can typically remove fecal coliforms by at least one log. This is not always sufficient to meet discharge limits in all locations and post disinfection may be required. UV disinfection has been successfully used in a number of applications.

- Although SF wetlands can be smaller than FWS wetlands for the removal of most constituents, the high cost of the gravel media in the SF wetland can result in higher construction costs for SF systems larger than about 227,100 liters per day (60,000 gallons per day).

DESIGN CRITERIA

Published models for the design of SF wetland systems have been available since the late 1980’s. More recent efforts in the mid to late 1990’s have produced three text books containing design models for SF wetlands (Reed, et al 1995, Kadlec & Knight 1996, Crites & Tchobanoglous, 1998). In all three cases, the models are based on first order plug flow kinetics, but results do not always agree due to the author’s developmental choices and because the same databases were not used for derivation of the models. The Water Environment Federation (WEF) presents a comparison of the three approaches in their Manual of Practice on Natural Systems (WEF, 2000) as does the US EPA design manual on wetland systems (EPA, 2000). The designer of a SF wetland system should consult these references and select the method best suited for the project under consideration. A preliminary estimate of the land area required for a SF wetland can be obtained from Table 1 of typical areal loading rates. These values can also be used to check the results from the previously cited references.

The SF wetland size is determined by the pollutant which requires the largest land area for it's removal. This is the bottom surface area of the wetland cells and, for that area to be 100 percent effective, the wastewater flow must be uniformly distributed over the entire surface. This is possible with constructed wetlands by careful grading of the bottom surface and use of appropriate inlet and outlet structures. The total treatment area should be divided into at least two cells for all but the smallest systems. Larger systems should have at least two parallel trains of cells to provide flexibility for management and maintenance.

These wetland systems are living ecosystems and the life and death cycles of the biota produce residuals which can be measured as BOD, TSS, nitrogen, phosphorus and fecal coliforms. As a result, regardless of the size of the wetland or the characteristics of the influent, in these systems there will always be a residual background concentration of these materials. Table 2 summarizes these background concentrations.

It is necessary for the designer to determine the water temperature in the wetland because the removal of BOD, and the various nitrogen forms are temperature dependent. The water temperature in large systems with a long HRT (>10 days) will approach the average air temperature except during subfreezing weather in the winter. Methods for estimating the water temperature for wetlands with a shorter HRT (<10 days) can be found in the published references mentioned previously.

It is also necessary to consider the hydraulic aspects of system design because there is significant frictional resistance to flow through the wetland caused by the presence of the gravel media and the plant roots and other detritus. The major impact of this flow resistance is on the configuration selected for the wetland cell. The longer the flow path the higher the resistance will be. To avoid these hydraulic problems an aspect ratio (L:W) of 4:1 or less is recommended. Darcy's law is generally accepted as the model for the flow of water through SF wetlands and descriptive information can again be found in the published references mentioned previously. The flow of water through the wetland cell depends on the hydraulic gradient in the cell and on the hydraulic conductivity (k_s), size, and porosity (n) of the media used. Table 3 presents typical characteristics for potential SF wetland media. These values can be used for a preliminary estimate and for design of very small systems. For large scale systems the proposed media should be tested to determine these values.

TABLE 1 TYPICAL AREAL LOADING RATES FOR SF CONSTRUCTED WETLANDS

Constituent	Typical Influent Concentration mg/L	Target Effluent Concentration mg/L	Mass Loading Rate lb/ac/d*
Hydraulic Load (in./d)	3 to 12**		
BOD	30 to175	10 to 30	60 to 140
TSS	30 to150	10 to 30	40 to 150
NH_3/NH_4 as N	2 to 35	1 to 10	1 to 10
NO_3 as N	2 to 10	1 to 10	3 to 12
TN	2 to 40	1 to 10	3 to 11
TP	1 to 10	0.5 to 3	1 to 4

Note: Wetland water temperature » 20°C.

TABLE 2 “BACKGROUND” SF WETLAND CONCENTRATIONS

Constituent	Units	Concentration Range
BOD_5	mg/L	1 to 10
TSS	mg/L	1 to 6
TN	mg/L	1 to 3
NH_3/NH_4 as N	mg/L	less than 0.1
NO_3 as N	mg/L	less than 0.1
TP	mg/L	less than 0.2
Fecal Coliforms	MPN/100ml	50 to 500

Source: Reed et al., 1995 and U.S. EPA, 1993.

PERFORMANCE

A lightly loaded SF wetland can achieve the “background” effluent levels given in Table 2. In the general case, the SF constructed wetland is typically designed to produce a specified effluent quality and Table 1 can be used for a preliminary estimate of the size of the wetland necessary to produce the desired effluent quality. The design models in the referenced publications will provide a more precise estimate of treatment area required. Table 4 summarizes actual performance data for 14 SF wetland systems included in a US EPA Technology Assessment (EPA, 1993).

In theory, the performance of a SF wetland system can be influenced by hydrological factors. High evapotranspiration (ET) rates may increase effluent concentrations, but this also increases the HRT in the wetland. High precipitation rates dilute the pollutant concentrations but also shorten the HRT in the wetland. In most temperate areas with a moderate climate these influences are not critical for performance. These hydrological aspects need only be considered for extreme values of ET and precipitation.

OPERATION AND MAINTENANCE

The routine operation and maintenance (O&M) requirements for SF wetlands are similar to those for facultative lagoons, and include hydraulic and water depth control, inlet/outlet structure cleaning, grass mowing on berms, inspection of berm integrity, wetland vegetation management, and routine monitoring.

The water depth in the wetland may need periodic adjustment on a seasonal basis or in response to increased resistance over a very long term from the accumulating detritus in the media pore spaces. Mosquito control should not be required for a SF wetland system as long as the water level is maintained below the top of the media surface. Vegetation management in these SF wetlands does not include a routine harvest and removal of the

TABLE 3 TYPICAL MEDIA CHARACTERISTICS FOR SF WETLANDS

Media Type	Effective Size D_{10} (mm)*	Porosity, n (%)	Hydraulic Conductivity k_s ($ft^3/ft^2/d$)*
Coarse Sand	2	28 to 32	300 to 3,000
Gravelly Sand	8	30 to 35	1,600 to 16,000
Fine Gravel	16	35 to 38	3,000 to 32,000
Medium Gravel	32	36 to 40	32,000 to 160,000
Coarse Rock	128	38 to 45	16×10^4 to 82×10^4

* mm x 0.03937 = inches
** $ft^3/ft^2/d \times 0.3047 = m^3/m^2/d$, or x 7.48 = $gal/ft^2/d$

Source: Reed et al., 1995.

TABLE 4 SUMMARY OF PERFORMANCE FOR 14 SF WETLAND SYSTEMS*

Constituent	Mean Influent mg/L	Mean Effluent mg/L
BOD_5	28** (5-51)***	8** (1-15)***
TSS	60 (23-118)	10 (3-23)
TKN as N	15 (5-22)	9 (2-18)
NH_3/NH_4 as N	5 (1-10)	5 (2-10)
NO_3 as N	9 (1-18)	3 (0.1-13)
TN	20 (9-48)	9 (7-12)
TP	4 (2-6)	2 (0.2-3)
Fecal Coliforms (#/100ml)	270,000 (1,200-1,380,000)	57,000 (10-330,000)

* Mean detention time 3 d (range 1 to 5 d).
** Mean value.
*** Range of values.

Source: U.S. EPA, 1993.

harvested material. Plant uptake of pollutants represents a relatively minor pathway so harvest and removal on a routine basis does not provide a significant treatment benefit. Removal of accumulated litter is unnecessary, and in cold climates it serves as thermal insulation to prevent freezing in the wetland bed. Vegetation management may also require wildlife management, depending on the type of vegetation selected for the system, and the position of the water. Animals such as nutria and muskrats have been known to consume all of the emergent vegetation in constructed wetlands. These animals should not be attracted to a SF wetland as long as the water level is properly maintained. Routine water quality monitoring will be required for all SF systems with an NPDES permit, and the permit will specify the pollutants and frequency. Sampling for NPDES monitoring is usually limited to the untreated wastewater and the final system effluent. Since the wetland component is usually preceded by some form of preliminary treatment, the NPDES monitoring program does not document wetland influent characteristics. It is recommended, in all but the smallest systems that periodic samples of the wetland influent be obtained and tested for operational purposes in addition to the NPDES requirements. This will allow the operator a better understanding of wetland performance and provide a basis for adjustments if necessary.

COSTS

The major items included in the capital costs for SF wetlands are similar to many of those required for lagoon systems. These include land costs, site investigation, site clearing, earthwork, liner, gravel media, plants, inlet and outlet structures, fencing, miscellaneous piping, etc., engineering, legal, contingencies , and contractor’s overhead and profit. The gravel media and the liner can be the most expensive items from this list. In the Gulf States where clay soils often eliminate the need for a liner the cost of imported gravel can often represent 50 percent of the construction costs. In other locations where local gravel is available but a membrane liner is required the liner costs can approach 40 percent of the construction costs. In many cases compaction of the in-situ native soils provides a sufficient barrier for groundwater contamination. Table 5 provides a summary of capital and O & M costs for a hypothetical 378,500 liters/day (100,000 gallons per day) SF constructed wetland, required to achieve a 2 mg/L ammonia concentration in the effluent. Other calculation assumptions are as follows: influent NH_3= 25 mg/L, water temperature 20°C (68°F), media depth = 0.6 meters (2 ft), porosity = 0.4, treatment area = 1.3 hectares (3.2 ac), land cost =$12,355/hectare ($5,000/ac).

TABLE 5 CAPITAL AND O&M COSTS FOR 100,000 GALLONS PER DAY SF WETLAND

Item	Cost $*	
	Native Soil Liner	Plastic Membrane Liner
Land Cost	$16,000	16,000
Site Investigation	3,600	3,600
Site Clearing	6,600	6,600
Earthwork	33,000	33,000
Liner	0	66,000
Gravel Media**	142,100	142,100
Plants	5,000	5,000
Planting	6,600	6,600
Inlets/Outlets	16,600	16,600
Subtotal	$229,500	$295,500
Engineering, legal, etc.	$133,000	$171,200
Total Capital Cost	**$362,500**	**$466,700**
O & M Costs, $/yr	$6,000/yr	$6,000/yr

* June 1999 costs, ENR CCI = 6039
**12,000 cy of 0.75 in. gravel

TABLE 6 COST COMPARISON SF WETLAND AND CONVENTIONAL WASTEWATER TREATMENT

Cost Item	Process	
	Wetland	SBR
Capital Cost	$466,700	$1,104,500
O &M Cost	$6,000/yr	$106,600/yr
Total Present Worth Costs*	$530,300	$2,233,400
Cost per 1000 gallons treated**	$0.73	$3.06

*Present worth factor 10.594 based on 20 years at 7 percent interest (June 1999 costs, ENR CCI = 6039).
**Daily flow rate for 365 d/yr, for 20 yr, divided by 1000 gallons

Source: WEF, 2000.

Table 6 compares the life cycle costs for this wetland to the cost for a conventional treatment system designed for the same flow and effluent water quality. The conventional process is a sequencing batch reactor (SBR).

REFERENCES

Other Related Fact Sheets

Free Water Surface Wetlands
EPA 832-F-00-024
September, 2000

Other EPA Fact Sheets can be found at the following web address:
http://www.epa.gov/owmitnet/mtbfact.htm

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