

Design Manual: Constructed Wetlands for the Treatment of Black Water

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General Information

What is a constructed wetland?

Wetlands, or areas where vegetation is adapted to periodic inundation, can be constructed in locations where they do not naturally exist for use in environmental management of impure waters. Subsurface flow (SSF) wetlands are recommended for wastewater treatment due to increased efficiency over typical surface flow wetlands, as well as isolation from human contact, decreased odors, lesser freezing potential and decreased mosquito breeding (Hammer 1989). These systems consist of a gravel bed planted with vegetation, where water flowing below the gravel surfaces provides water and nutrients to the emergent plants (Figure 1).

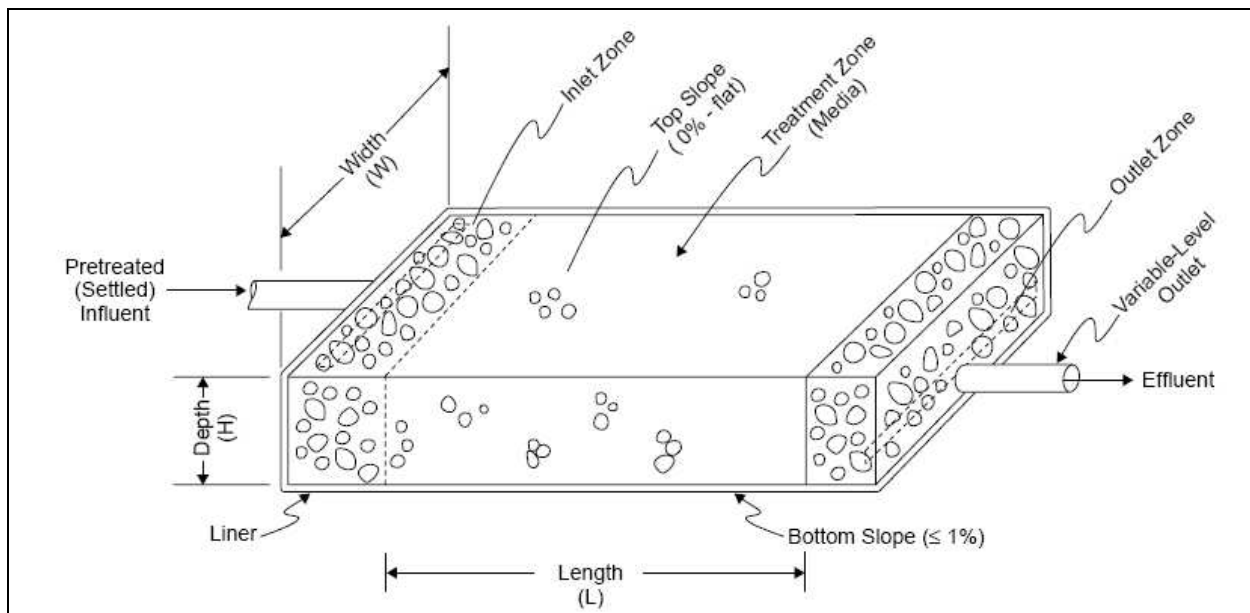


Figure 1. Generic design for an SSF wetland cell (US EPA 1999)

Normally, a constructed wetland is preceded by a primary treatment unit. Primary treatment for wastewater may be accomplished by a variety of technologies, although the simplest and easiest to maintain is a stabilization pond (Figure 2) (Crites et al. 2006; Hammer 1989). The effluent from the pond can then be treated to higher water quality by the constructed wetland, which removes pollutants and bacteria. Smaller garden-sized constructed wetlands may be used for individual homes, while larger systems with several wetland channels may be used for municipal water treatment (US EPA 1999).

Benefits of this technology include: a simple process design, low operation and maintenance expense, and in some cases wildlife enhancement (Hammer 1989). SSF constructed wetlands are considered an “appropriate” technology when total annual costs are within the user’s ability to pay, operation of the system can be performed with locally available labor, and the treatment is reliable in meeting the desired effluent quality standards (US EPA 1999).

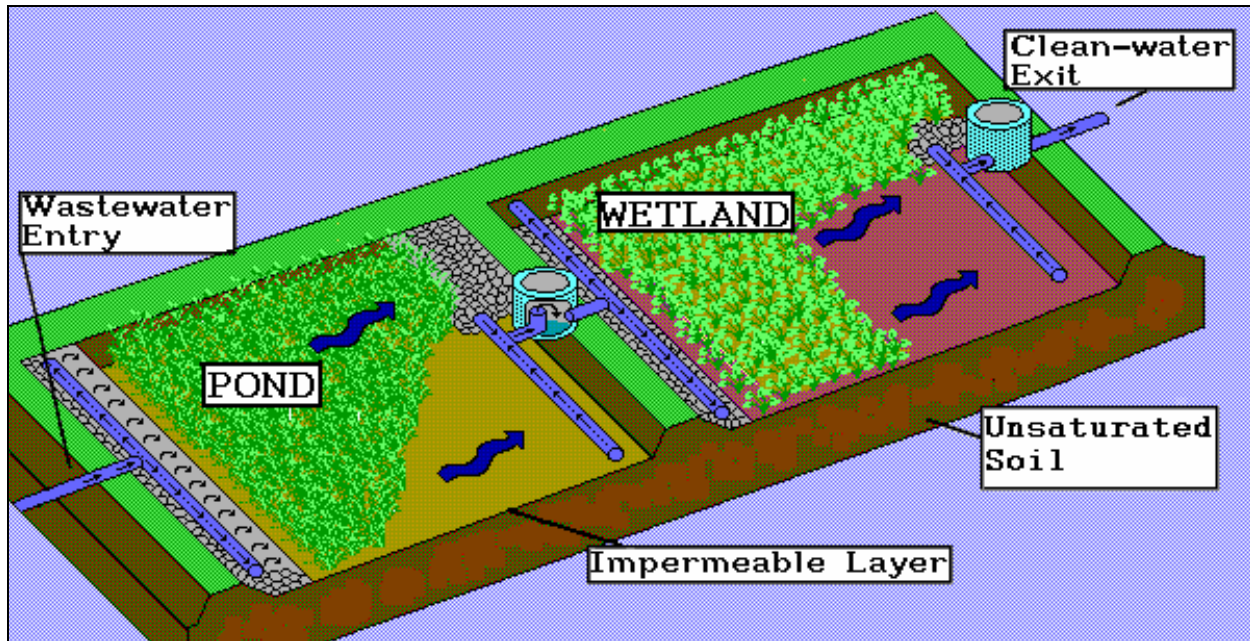


Figure 2. Schematic showing a stabilization pond coupled with a constructed wetland

How does it work?

In the stabilization pond, solids are removed by mechanical settling. Once separated out, the organic matter is then processed by microbes and plants, which prevents the accumulation of materials at the bottom of the pond. Next, as water flows through the gravel substrate in the wetland, pollutant removal occurs by physical processes (sedimentation and filtration), chemical processes (precipitation and adsorption), and biological processes (bacterial metabolism) (US EPA 1999).

Where can it be used?

Wetland treatment may be applicable wherever homes or other buildings are not connected to a centralized wastewater treatment plant and sufficient space is available. A larger land area is needed for wetland treatment than for some other technologies. SSF wetlands may be adapted to many different climates. For some constituents, treatment performance tends to decrease with colder temperatures, but Biochemical Oxygen Demand (BOD) and Total Suspended Solids (TSS) removal are not greatly affected, since they are accomplished primarily by physical mechanisms (US EPA 1999).

Construction

Siting/Location:

An ideal location has a level or very slight natural slope, partial shade, and is near the source of wastewater (US EPA 1999). For uniformity of flow, a firm underlying substrate is necessary when grading a wetland. Constructed wetlands for treating wastewater should not be built in areas with a very high water table, where the soil is inundated or mushy. This precaution prevents short-circuiting of the desired flow path as well as ground- and surface-water contamination.

For raw wastewater, a pretreatment system must be in place upstream of the wetland. Using a septic tank as pretreatment has the advantage of keeping much of the untreated waste out of sight, containing odors, and preventing unsanitary conditions (Figure 3) (Hammer 1989).

However, they do require additional construction materials, maintenance and troubleshooting. A more simple approach is to use an open stabilization pond, which is excavated and lined exactly like a constructed wetland cell (Figure 4). Open ponds typically do not produce bad odors unless they are overloaded or clogged, but they do create a hazard for children and should be surrounded by a fence to prevent public access. Minimal additional maintenance is required for either technology. Although they are not the focus of this design manual, more information on these two primary treatment options can be found under the “Construction” section below.

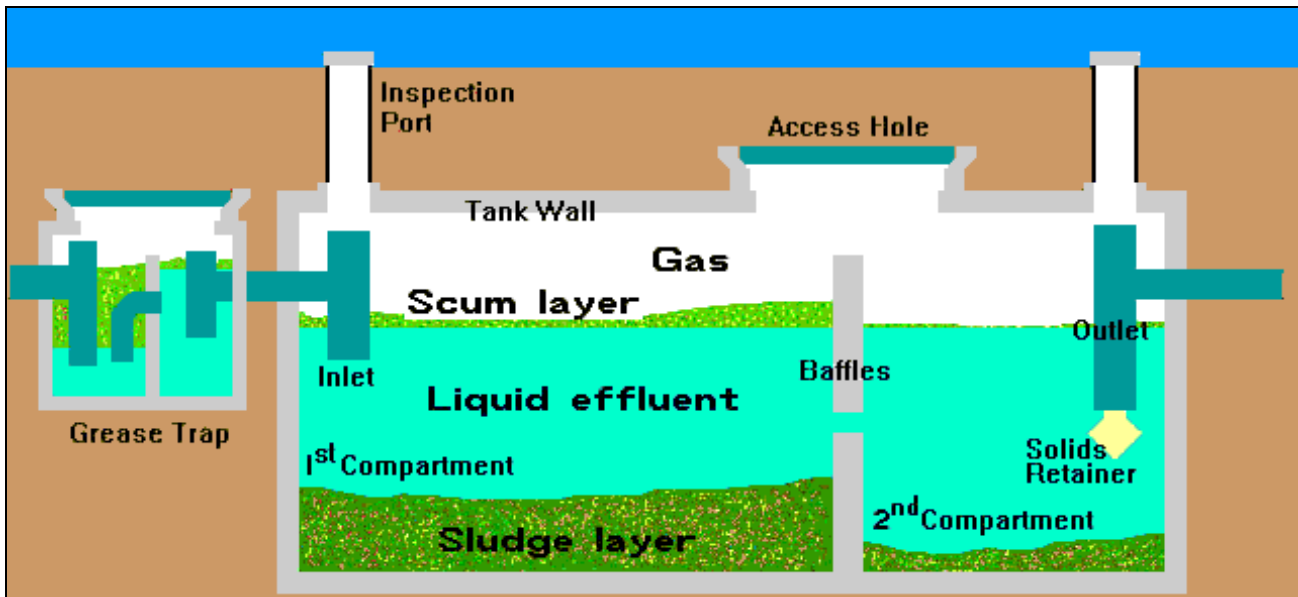


Figure 3. Basic layout of a septic system installed below ground: influent wastewater enters on the left side, and flows out to the constructed wetland via the pipe on the right side of the diagram (Purdue 1999).



Figure 4. Photograph of a settling lagoon used for wastewater processing in a small municipality (Purdue 1999)

Materials:

Vegetation - Bulrushes, reeds and cattails are the most typical types of vegetation, although other native sedges and local wetland species may be used as well (Crites and Tchobanoglous 1998; Hammer 1989). Plants that grow rapidly, spread quickly and have extensive root systems are most desirable. Using multiple types of native plants rather than a single species will help to avoid a major plant die-off, since different genetic varieties are resistant to different types of stressors (US EPA 1999). Aesthetics is another consideration, since pollutant removal is similar among these different plant types. Plants ought to be transplanted from a natural wetland near the site if at all possible. In the absence of surrounding wetlands, plants can also be purchased from nurseries, collected in the wild, or grown onsite for a specific project.

Liner – A liner should be used in wastewater treatment wetlands to prevent the seepage of contaminated water into the groundwater table (Hammer 1989). Liner materials range from soil or clay with a very low permeability ($<10^{-6}$ cm/sec) to bentonite, asphalt, or synthetic plastics. The liner should be strong, thick, and smooth, and must be protected from puncture by sharp rocks or gravel (US EPA 1999). Most systems utilize specially manufactured polyvinyl chloride (PVC) or high-density polyethylene (HDP). Laying down a thin layer of sand or geotextile fabric above or below the liner can protect it from puncture by sharp rocks. Some liners need to be shielded from UV light, and can be covered with stones or soil for this purpose. Loading on the liner will be approximately $2,200 \text{ kg/m}^2$, including the plant mass.

Inlet – Inlet and outlet configurations should promote uniformity of flow across the channel. Several designs are possible. A “T” formation (Figure 5) is recommended, as it allows rapid adjustment of flow distribution and easy flushing of settled solids (Hammer 1989). Holes in the pipe should be evenly spaced at a distance approximately 10% of the cell width, of the same size and shape, and large enough to prevent clogging (US EPA 1999).

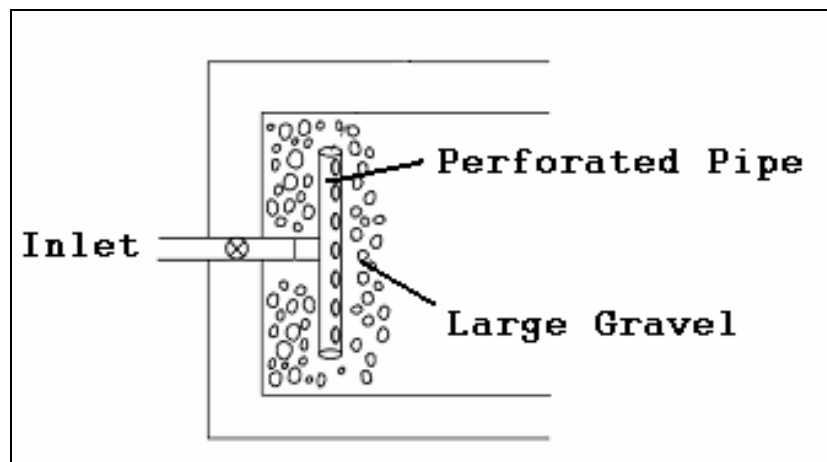


Figure 5. Diagram of an inlet structure using perforated PVC pipe underlying a gravel bed (US EPA 1999)

Outlet - In smaller wetland systems for homes, discharge is often released into the underlying soil, while in larger municipal wetlands, discharge usually flows into surface water. A perforated leach field tubing system can be used if a point discharge is not desired. Other types of outlets include an open-ended pipe, channel, or spillway. To collect water from the

channel at the wetland's outlet, a slotted or perforated collector pipe can be laid across the channel bottom, below the gravel (US EPA 1999). This structure will be similar to that shown in Figure 5, except that holes can be made smaller, since solid materials will have settled out by the time the water exits the system, and clogging is not a concern. If this setup is connected to a riser pipe, the height of the outlet can then be used to control water depth in the wetland. (See side view in Figure 12.)

Other basic materials include gravel and construction equipment. Costs will vary significantly depending on the site and the type of materials used. In the US, total cost of SSF constructed wetlands was on average \$601,716 per hectare (1998 US dollars) (Crites et al. 2006). The major items included in startup costs for constructed wetlands are listed below:

- Land costs
- Site investigation
- Clearing and grubbing the site
- Excavation and earthwork
- Liner
- Gravel
- Plants
- Inlet structures
- Outlet structures
- Other piping, pumps, etc.
- Fencing (if needed)
- Cost of engineering/legal advice
- Contractor's overhead and profit

Simplified Construction Steps:

Primary Treatment – Septic Tank (Optional):

- 1.) Sizing – An engineering assessment should be done to determine the proper size of septic tank(s) to use for a given flow volume of wastewater (US EPA 1999; Crites and Tchobanoglous 1998). As a rough estimate, flow will be approximately 50-100 gallons (0.189-0.378 m³) per capita per day. Multiplying this number by the number of people utilizing the system will provide a volume estimate. The volumetric capacity for the tank should be five times the average flow, to accommodate room for sludge, airspace, and, most importantly, unusually high flow events. For larger systems, several septic tanks can be used in conjunction (Figure 6).

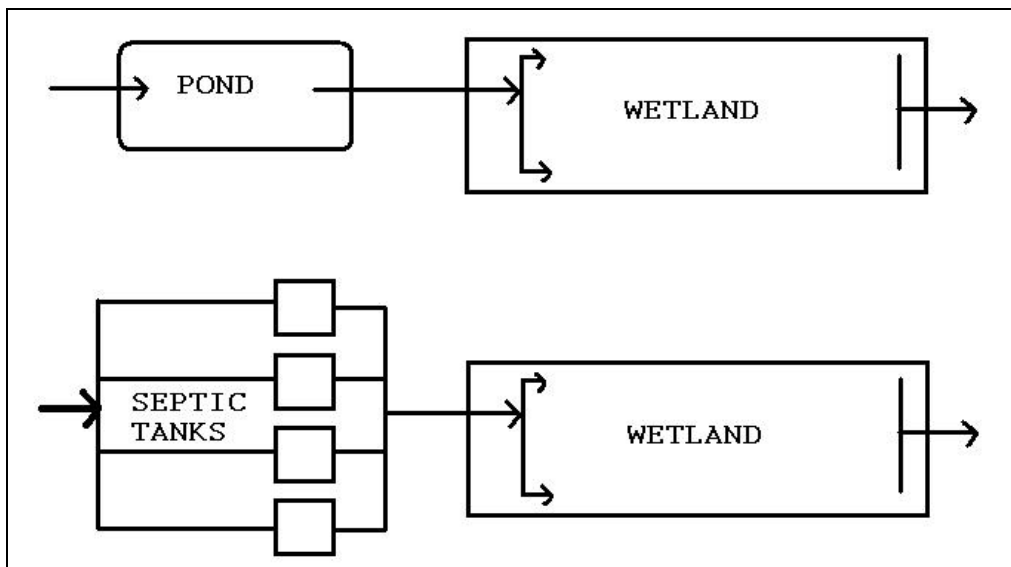


Figure 6. Schematic of primary and secondary treatment options

- 2.) Excavation and Concrete Work – After an area of the proper size is excavated, the bottom and walls of the tank should be poured monolithically. A solid concrete roof with a watertight seal along the edges should be placed just below ground level with the access hatch above ground. A divider (as depicted in Figure 3) should separate the first two-thirds of the tank from the last one-third. Prefabricated tanks may also be available for purchase.
- 3.) Install Piping – PVC pipe or another type of channel may be used to collect the wastewater from a sewerage conveyance and funnel it into the tank.
- 4.) Maintenance – Inspect annually for water-tightness, breaks in the piping, and accumulation of scum and sludge. Scum, sludge, and grease will accumulate at a rate of about 2-3 cm/year, and will need to be physically removed about once every 3-6 years (Hammer 1989). For the best performance, trash should be kept out of the sewer system, drains in homes should have lint traps installed, and only biodegradable toilet tissue should be used.

Primary Treatment – Stabilization Pond (Optional):

- 1.) Clearing, Excavation, Grading, Construction, and Maintenance – Steps 4 and 5 below should be used in the creation of a stabilization pond. An optional component is a mechanical aerator, which can be placed underwater in the pond to circulate oxygen and speed microbial decomposition of solids (Purdue 1999). Floating plants may also be added for treatment or aesthetic purposes. Maintenance of the stabilization pond is the same as for the constructed wetland.

Subsurface Flow Constructed Wetland:

- 1.) Siting - The location of treatment should be near the source, so that little energy input is required to guide the wastewater into the system. Also see siting guidelines above.
- 2.) Calculation of Design Parameters - General guidelines for design parameters are adaptable to a specific site, given the known wastewater loads and a series of mathematical calculations related to hydrology and reaction time (Hammer 1989). An example of these calculations can be found in the accompanying case study, “BMP Technology: Constructed Wetlands for Treatment of Black Water – Case Study in Chiapas, Mexico.”
- 3.) Clearing, Excavation, Grading - Cells should be graded levelly from side to side with a slight uniform slope in the direction of flow (Figure 7) (US EPA 1999). If possible, it is desirable to balance the cut and fill onsite, in order to avoid using remote borrow pits or offsite soil disposal. Uniform compaction of the soil is necessary to protect the integrity of the liner. External and internal berms can be simply constructed of compacted earth or reinforced with cement. More information about berms is located in the “Detailed Construction Information” section.



Figure 7. Excavated and graded site showing a slight slope (~1%) in the lengthwise direction of flow (Purdue 2007)

- 4.) Construction - The liner should be set into place once the earth at the site is prepared (Figure 8). Next, inlet and outlet structures can be built, followed by the addition of gravel media to the system (see Figure 10). More information about each of these components can be found in the detailed construction information section below.



Figure 8. Construction site showing a synthetic plastic wetland liner (Purdue 2007)

- 5.) Vegetation Establishment - Whole plants or dormant rhizomes and tubers work well for transplanting, while seeds do not (Figure 9) (Hammer 1989). Tubers with a 20-25 cm stem are most desirable because the stem can obtain oxygen while the roots are flooded in water. Vegetation should be planted securely below the top layer of gravel to prevent plants from floating or washing away. In temperate climates, the best planting period starts after dormancy has begun in the fall, and ends after the first one-third of the summer growing season (US EPA 1999). In most cases, wetlands are planted during the spring.



Figure 9. Wetland plants purchased from a nursery with rhizomes attached (Abulk 2007)

As far as hydrologic regime, wet conditions should be maintained after planting to inspire initial growth (US EPA 1999; Hammer 1989). The water level can be increased slowly as new shoots develop and grow. If the water level exceeds the tips of the green shoots, though, then the plants will die. Planting density between 0.3 and 1 meter apart is appropriate. Higher density planting will result in faster establishment of a mature and functional wetland system, but construction costs do increase with higher plant densities. After a few weeks of plant growth, wastewater can be introduced. If high temperatures or strong sunlight conditions exist, a layer of straw or hay mulch 15-20 cm thick can be placed above the gravel surface to protect the new plants.



Figure 10. A constructed wetland complete with gravel and vegetation (Purdue 2007)

Detailed Construction Information

Specific Design Parameters:

Since size is often calculated according to the BOD and hydraulic loading of the influent wastewater, a matrix is offered to give a rough idea of wetland size (Hammer 1989). Though the standard design equations are not noted for their widespread accuracy, more detailed step-by-step calculations can be found in the accompanying case study, “BMP Technology: Constructed Wetlands for Treatment of Black Water – Case Study in Chiapas, Mexico” (Crites et al. 2006; US EPA 1999).

For large systems, the wetland should be subdivided into several smaller cells, either in series, parallel, or another combination such that maintenance can be performed on one section without impairing the entire wetland’s functioning (Hammer 1989). Important design parameters for a wetland are indicated in Table 2, while discussion of some of the characteristics not previously considered in this manual follows the table.

Table 1. Commonly used design parameters for a SSF constructed wetland (Crites et al. 2006; US EPA 1999; Crites and Tchobanoglous 1998; Hammer 1989)

Parameter	Range	Typical Value
Hydraulic Loading	0.02 - 0.24 m ³ /m ² /day 0.8 - 62 cm/day 100 - 1,000 m/day	4.7 cm/day
Detention Time	4 - 20 days	6-8 days
Inflow	--	0.34 L/sec
Flow Velocity	< 8.6 m/day	--
Depth of Gravel	0.3 - 0.6 m (deeper at outlet)	0.5-0.6 m
Depth of Water	0.15 - 1 m (from bottom)	0.4-0.6 m
Depth of Root Zone	0.3 - 1 m (below surface)	0.6 m
Gravel Size (Diameter): <i>Inlet</i> <i>Outlet</i> <i>Surface (top 25% or <0.1m from surface)</i> <i>Other (lower 75%)</i>	40-100 mm 40-100 mm 5-20 mm 10-60 mm	40-80 mm 40-80 mm 5-20 mm 20-30 mm
Porosity of Gravel	0.18 - 0.35	--
Slope of Bed	0.5 - 2%	0.5 - 1%
Slope of Gravel Surface	0%	0%
Slope of Berms	2:1 - 3:1 (exterior) ≥ 3:1 (interior)	3:1
Width	< 61 m	--
Length	> 15 m	--
Length : Width Ratio	< 4:1	1:1 – 1:2
Length of Inlet Zone	--	2 m
Length of Outlet Zone	--	1 m

Depth – Using plants with deeper roots will require a deeper bed (US EPA 1999). In general, bulrushes and reeds have longer roots than cattails.

Slope - The bottom of the wetland should be uniformly sloped toward the outlet to allow for easy draining during maintenance work (US EPA 1999). Care should be taken during the grading

process to eliminate low spots, channels, and side-to-side sloping. Gravity can be taken advantage of in naturally sloping sites, in order to reduce pumping costs.

Berms – Berms can be made of bricks and cement or earth. Earthen berms are typically less expensive to construct and provide a more natural aesthetic appearance. Slope of the berms should be as steep as possible to prevent outside water sources from entering the wetland (US EPA 1999). The amount of “freeboard” (the distance between normal water level and the top of the structure that impounds or restrains water) should be enough to contain a typical heavy rainfall event in the area (Figure 11). External berms should provide approximately 0.6 to 1 m of freeboard, to a distance great enough to allow flooding to a depth of about 5 cm higher than the gravel surface. This design consideration will become useful for weed control through forced flooding, as well as drawing down or draining the cell for maintenance. The top of the berm can provide space for an access path or road to afford maintenance. The liner and surrounding berm must be structurally sound and watertight, as these qualities are critical to the wetland’s proper functioning. Placing a soil layer over the berm’s side slope helps to establish vegetation, but also leaves the slope susceptible to erosion. Liners or erosion control blankets can be used to promote durability.

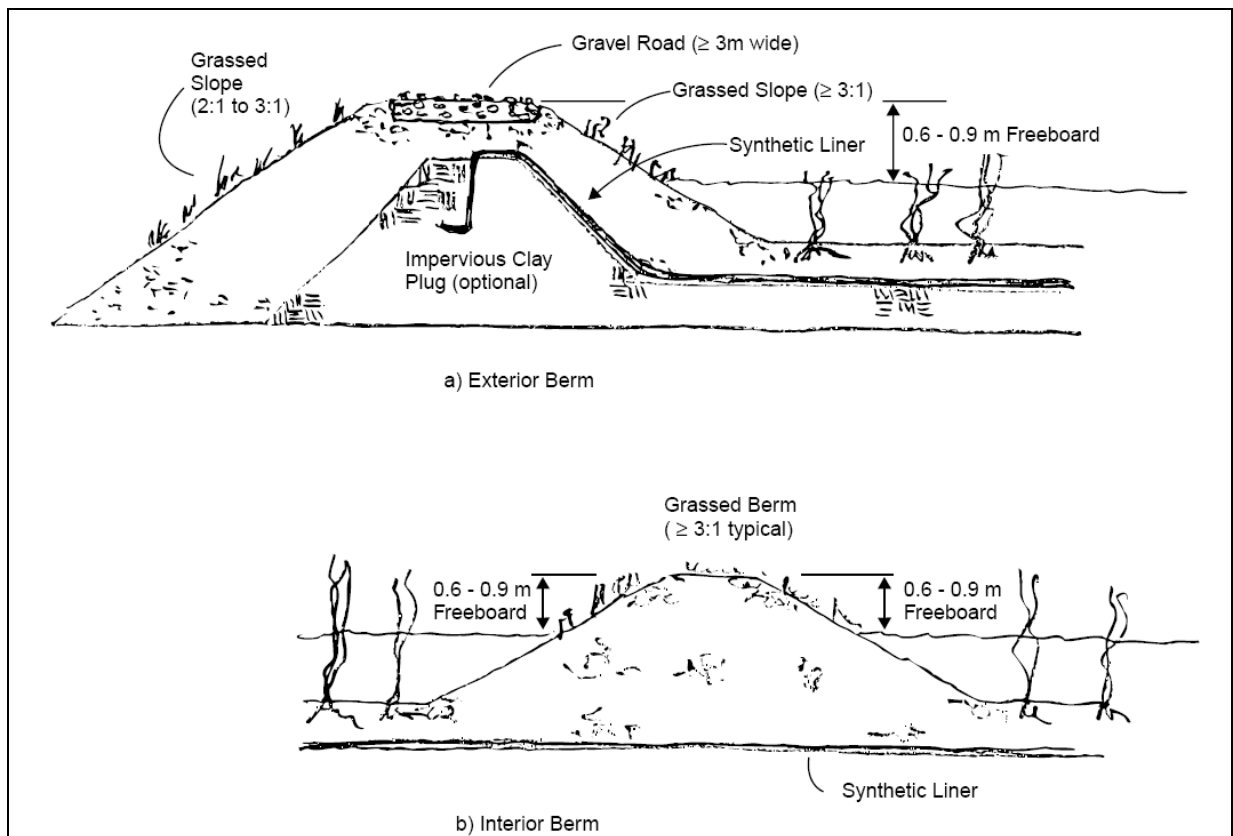


Figure 11. Example of earthen berms used to contain the wetland cell, for both the periphery (top) and internal divisions (bottom) (US EPA 1999).

Gravel – Smooth, rounded, hard and durable river gravel is recommended over sharp-edged crushed rock, since it packs more loosely, allowing water to flow through (US EPA 1999; Hammer 1989). Crushed limestone, which is soft and easily disintegrates, should be avoided. A cheap local supply is best. The gravel should be washed to eliminate fine material that can contribute to clogging. Different sizes of gravel, as long as they are within the ranges specified,

are relatively unimportant to the pollutant removal efficiency; however, very small gravel is more susceptible to clogging, while very large gravel becomes more difficult to handle during construction or maintenance. Figure 12 displays one example of gravel size and spacing within the wetland cell.

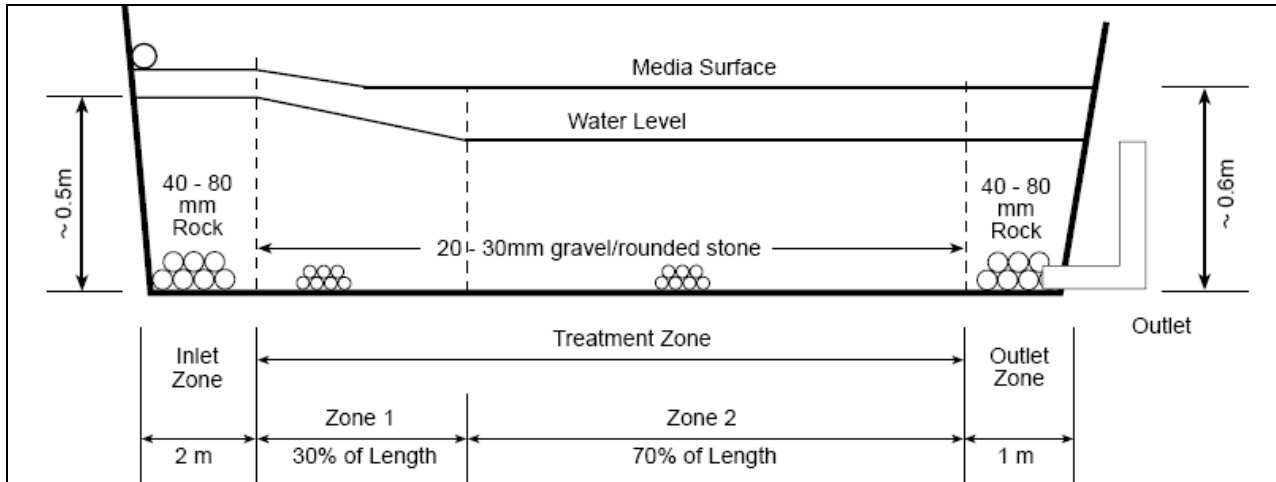


Figure 12. Distribution of gravel within the SSF wetland (US EPA 1999)

Length:Width Ratio - There is no significant difference in treatment capabilities for varying aspect ratios, so this is not considered an important design criteria (US EPA 1999; Hammer 1989).

Maintenance:

Maintenance of a stabilization pond and constructed wetland should involve only one day per week or less (US EPA 1999):

- Harvesting of plants is generally not required for SSF wetlands, but annual removal, burning, thinning, or replanting of vegetation may be beneficial if flow patterns are impaired (Hammer 1998). Although the wetland plant communities are self-maintaining and will grow, die, and re-grow each year, plants will naturally spread to un-vegetated areas and be displaced from areas that are environmentally stressful. A uniform dispersal should be maintained to ensure effective treatment.
- Berms may require trimming unwanted vegetation and erosion control. Periodic removal of tree seedlings from within the wetland bed may also be necessary.
- The wetland should be checked on a regular basis for flow uniformity, undesirable odors, and integrity of berms and dikes. Invasion of unwanted aquatic plants, pest insects, and burrowing animals should be observed as well.
- If desired, water quality monitoring may be done to ensure desired functioning and track wetland performance. This will increase the cost and time required for maintenance, but is a useful indicator of successful wastewater treatment. Parameters important for monitoring include pH dissolved oxygen (DO), suspended solids (SS), Biological Oxygen Demand (BOD), and Coliform (Purdue 1999; Hammer 1989).



Figure 13. Water quality monitoring should be done to ensure that the wetland is functioning properly.

- The primary treatment system may also need maintenance. Septic tanks require sludge removal to a drying bed, from which residuals are eventually disposed of as solid waste or re-used for soil amendment (Hammer 1989). Stabilization ponds should be monitored for unwanted vegetation growth and clogging.

Frequently Asked Questions

What are the potential problem areas?

Odors – Odors are seldom a nuisance problem in properly loaded wetlands. However, odors arise more easily when the water pools or the flow clogs. This situation can be avoided by preserving uniform channel conditions and conducting proper maintenance (US EPA 1999). Odorous compounds emitted from open water areas typically result from anaerobic conditions, which can be created by excessive influent BOD and ammonia loadings (Hammer 1989). A very effective way to eliminate odors is to sequentially drain and refill the wetland cell over a period of several days, allowing about 24 hours for each change.

Homogeneous flow conditions - Short-circuiting of the desired pathway, creation of “dead zones,” and accumulation of solids should all be prevented, so that contact time between the water and the substrate is maximized, allowing treatment to occur (Hammer 1989).

Mosquitoes - Mosquito control is much less difficult with SSF wetlands for which the water flow is kept beneath the gravel surface, reducing the area for mosquitoes to breed.

Flooding - Although the vegetation used in wetlands is generally water-tolerant, flooding can hamper the growth of the plant or kill it off entirely. To prevent flooding, care should be taken that berms are high enough to direct outside rainfall away from the wetland. The water level

should never exceed the holding capacity of the gravel substrate, even with heavy wastewater and precipitation inputs. Otherwise, wastewater would be able to flow untreated into the surrounding area.

Political Issues - In areas where environmental protection laws to prevent the dumping of raw wastewater are absent, the motivation for homes or communities to implement these systems may be lacking.

How long will the system last?

Start-up period varies depending on the design, characteristics of the influent wastewater, and the season of year (US EPA 1999). A typical startup time lasts 12-22 months after construction, although the startup period is not as critical for subsurface flow wetlands, since much of the filtration is by physical means (Hammer 1989). Performance of the system should improve during the first few years as root penetration brings oxygen further into the gravel bed. With proper maintenance, lifetime of the system depends only on the integrity of the structure. The materials cited in this manual will typically last more than 20 years (Purdue 1999).

What performance can be expected?

SSF wetlands can diminish a number of the harmful characteristics of wastewater. Field studies have shown adequate treatment performance for most wastewater constituents, including BOD, TSS, and fecal Coliform (Table 2) (US EPA 1999). Removal of nitrogen and phosphorus varies throughout the year with plant growth and senescence, but is usually poor. Most excreta-related diseases worldwide are a result of bacteria and viruses, both of which are effectively removed by this type of wastewater treatment (Hammer 1989). Proper treatment of these types of waste contributes to both improved environmental health and integrity of aquatic systems.

Table 2. Typical percentage reduction and expected effluent concentrations for common contaminants in SSF wetlands (Crites et al. 2006; US EPA 1999; Crites and Tchobanoglous 1998; Hammer 1989)

Parameter	Expected Reduction	Expected Effluent Concentration (mg/L)
Total Suspended Solids (TSS)	51-98%	3.7-64 (typically <10)
Coliform	82-100%	(MPN) 50-577,000/100ml
Biological Oxygen Demand (BOD)	49-96%	5.3-90
Nitrogen	12-86%	6.3-29.6
Phosphorus	-12-91%	0.5-9.6
Metals: <i>Al, Cu, Zn, Cd</i> <i>Fe, Mn</i>	84-99% -10%	<0.01-0.05 0.288-1.234

Removal of these parameters is influenced by many factors. An example of how residence time affects total suspended solids levels is shown in Figure 14 (US EPA 1999). As an estimate, the removal of bacteria and viruses in wetlands, normally elements of the greatest concern to human health, is usually correlated well with removal of suspended solids and the residence time.

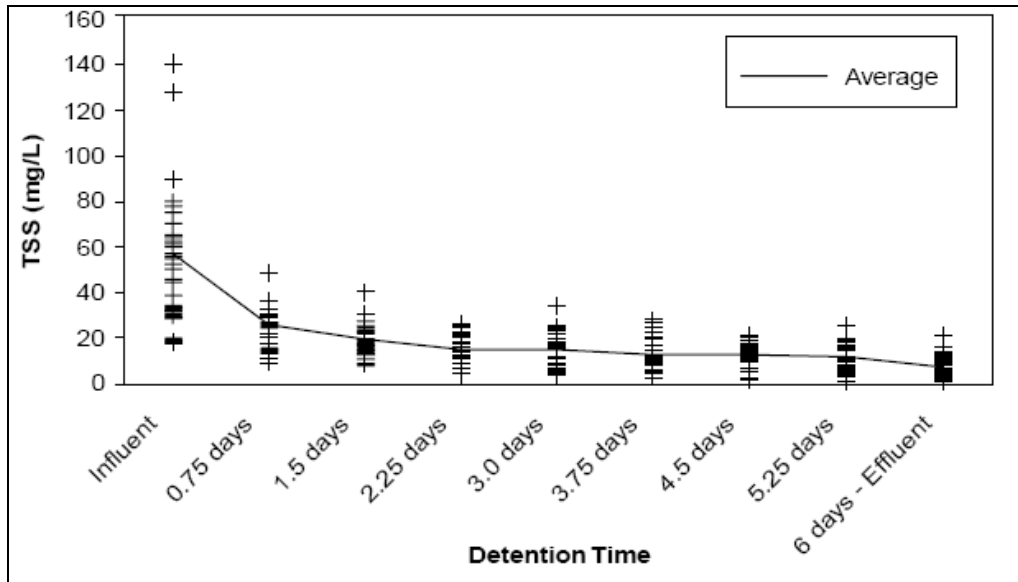


Figure 14. Graph showing average reduction in total suspended solids as water flows through a constructed wetland (US EPA 1999)

Thank you for your interest in BMP Technologies. Please contact the author with any questions or concerns (ksetty@bren.ucsb.edu).

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