Advances in Constructed Wetlands for Wastewater and Stormwater Treatment

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Abstract

This paper reviews research and built projects to highlight the advances in environmental engineering and resulting effectiveness of wetlands for treatment of sewage and non-point pollution. Free water surface (FWS), horizontal subsurface flow (HSF) and vertical subsurface flow (VSF) wetlands can each effectively meet secondary treatment standards. Wetlands for wastewater treatment can be confidently applied to institutions like schools, residential subdivisions and towns, in diverse climates.

Nearly complete removal of both ammonium and nitrates by any of the three constructed wetland types alone is not possible. However, hybrid wetlands that combine the three types of wetlands in various configurations are effective in the removal of nitrogen species, total nitrogen and pathogenic bacteria. HSF and VSF wetlands are effective and safe for wastewater treatment when placed in the green infrastructure where treated effluent could be reused for a variety of non-potable needs. Wastewater and stormwater constructed wetlands are potential contributors to green infrastructure and an important example of ecological services provided by green infrastructure.

The concepts and technology gained from biological wastewater treatment can be adapted to the treatment of stormwater to avoid incomplete removal of nutrients and contaminants. The use of alternating stages of HSF and VSF for initial treatment followed by a FWS wetland are likely to produce the highest quality effluent while providing significant secondary benefits to the community open space system. While 99% reductions of pathogenic bacteria in waste and stormwater are possible, achieving primary recreation contact standards may require supplemental treatment.

INTRODUCTION

Experience with Water Quality Improvement

Because grading and drainage is an important facet of the profession, landscape architects have long been involved in stormwater management through the creation of swales, piping systems, artificial ponds and lakes. Initially, the central concerns of stormwater plans were the prevention of flooding and sedimentation or channel erosion of receiving streams. This typically involved a neighborhood sedimentation basin followed by a detention basin with a controlled outflow matching a predevelopment rate. Attempts to generate secondary benefits from these stormwater structures resulted in retention ponds with a margin of wetland plants. Stormwater detention was sometimes accommodated above the normal water level. These retention basins act as batch treatment constructed wetlands with some water quality improvement benefit.

Mounting evidence (Peters, 2009 and Kadlec, 2009) that non-point source pollution, conveyed in stormwater, is the primary threat to aquatic systems has increased our awareness and involvement in the improvement of the water quality of storm runoff. Correctly, this problem has been attacked at the site, neighborhood, municipal and watershed scales. Permeable pavement and rain gardens are examples of site scale efforts to reduce the amount of polluted stormwater runoff. At the neighborhood scale landscape architects are most familiar with wet ponds or constructed wetlands that mimic marshes and that are designed to ameliorate both flooding and water pollution. This marsh-like wetland, termed a free water surface wetland (FWS), has also been used extensively in the United States for finishing or polishing secondary effluent from wastewater treatment plants. For example, a 130 acre (52.6 ha) wetland in Columbia, Missouri provides some advanced treatment but primarily improves the performance of the activated sludge sewage treatment plant to meet US Environmental Protection Agency (EPA) secondary treatment requirements. The amenity value of these treatment wetlands is high and they serve as the primary water source for the Eagle Bluffs conservation area, which provides opportunities for hunting, bird watching and other public recreation. The treatment wetlands also host a waterfowl population in winter when the open water in the constructed wetland is preferred to the frozen wetlands in the conservation district. The Columbia wetlands are adjacent to a city trail and a state park, contributing to recreation and nature study (Kadlec, 2010). Given the pollution levels and the primary and secondary benefits of biological treatment systems, landscape architects can incorporate the design of these managed natural systems into the public landscape. The sections below draw on recent research presented in the environmental engineering literature with an emphasis on built examples rather than lab experiments.

Types of Constructed Wetlands

Free water surface and other types of constructed wetlands have been designed explicitly to treat sewage and other types of wastewater. The initial focus for all constructed wetland types was on the treatment of domestic and municipal wastewater for the single residence or small community. In the process a great deal is being learned about treatment for several contaminants also present in stormwater, and the complex biological and chemical processes involved. Figure 1 illustrates the several kinds of wetlands developed. This paper focuses on the horizontal and vertical subsurface flow wetlands.

<table>
<tr><td rowspan="3">Emergent Plants</td><td>Surface Flow (FWS)</td><td></td><td rowspan="3">Hybrid</td></tr>
<tr><td rowspan="2">Subsurface Flow</td><td>Horizontal Flow (HSF)</td></tr>
<tr><td>Vertical Flow (VSF)</td></tr>
<tr><td>Free Floating Plants</td><td></td><td></td><td></td></tr>
<tr><td>Submerged Plants</td><td></td><td></td><td></td></tr>
<tr><td>Floating Leaf Plants</td><td></td><td></td><td></td></tr>
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Figure 1 Constructed Wetland Types. Source: adapted from Vymazal, 2007

Free water surface (FWS), horizontal subsurface flow (HSF) and vertical subsurface flow (VSF) wetlands are all effective in treating domestic and municipal sewage (after pretreatment in a septic tank) to meet US EPA standards although the required sizes of the wetlands will differ (Cooper, 2009).

Wastewater Characteristics

Domestic sewage contains high levels of organic carbon, nitrogen, phosphorus and microorganisms including those that can cause disease in humans. Americans, living in dwellings built after 1994, generate 40 to 60 gallons of domestic sewage per person per day. Raw sewage is composed of organic carbon, biological oxygen demand, total suspended solids, ammonia, nitrite and nitrate, organic nitrogen, phosphorus and fecal coliform bacteria (Kadlec, 2009; Wallace, 2006). The concentrations of these contaminants are reduced substantially by pretreatment in a septic tank to about 180 mg/L of biological oxygen demand and 80 mg/L of total suspended solids. The EPA standard for fecal coliform is 100 cfu/100L for primary recreational contact and 200 cfu/100L for secondary contact, while the standard for E. coli is 126 cfu/100L for primary recreational contact (EPA, 2009).

The US EPA regulates the concentration of biological oxygen demand (BOD) and total suspended solids (TSS) permitted in the effluent from sewage treatment plants. The standard for each is 30 milligrams per liter (mg/L). BOD measures the amount of oxygen required by microorganisms to consume organic material in a sample of water. TSS is a measure of the organic and inorganic particles suspended in a water sample. Both parameters are indirect measures of water pollution. A survey, of the performance of horizontal subsurface flow wetlands in the US, New Zealand, Mexico, India and several European countries, revealed that the average inflow of water from a septic tank was 108 mg/L of BOD and 107 mg/L of TSS

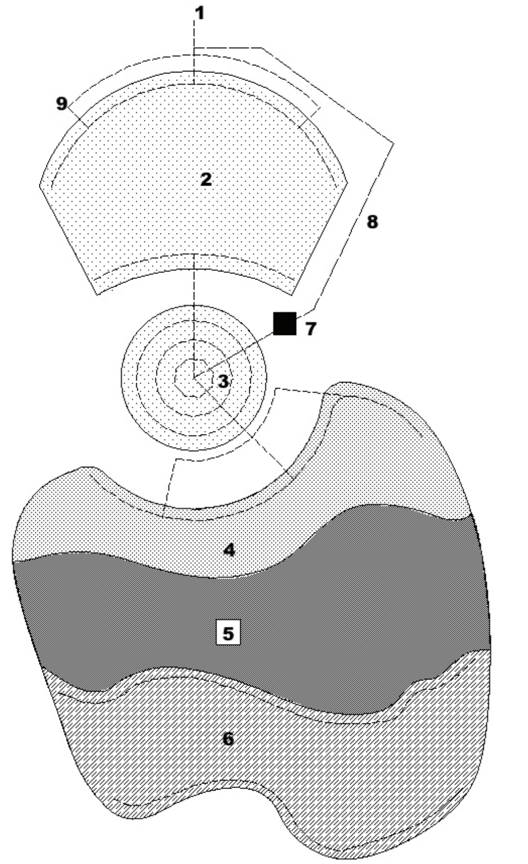

Figure 2 - Wetland System Plan 1 – Inlet from septic tank or lagoon; 2 – Horizontal subsurface flow wetland; 3 – Vertical subsurface flow wetland; 4 – Deep marsh (18" deep); 5 – Open water (4' deep); 6 – Shallow marsh (12" deep); 7 – Optional pump; 8 – Pipe to return 50% of water from VSF to HSF wetland for de-nitrification; 9 – Distribution, inlet and outlet pipes. All zones are densely planted except for the open water zone. Austin, 2009.

with outflow concentrations of 16 and 18.1 mg/L, respectively (Vymazal, 2005). Kadlec compared the performance of nearly 400 FWS wetlands to about 200 HSF wetlands and found very similar effectiveness for BOD and TSS compliance (Kadlec, 2009a).

FREE WATER SURFACE WETLANDS

2.1 Introduction

The FWS wetland is a series of heavily planted marsh beds, 12”-30” deep. Sometimes open water cells 3’– 6’ deep are incorporated. As water flows through the vegetation, solids settle and bacteria growing on the plant stems and the soil surface consume organic material and reduce nutrient concentrations. One of the most important factors leading to high wetland performance is good pretreatment to remove some of the suspended solids and evenly distributed flow through the wetland. The tendency for water to establish preferred flow paths through the wetland is thwarted by redistribution of water in several cells arranged in a series. The design in Figure 2 calls for distribution pipes (#9), a deep marsh cell (#4) a deep water section (#5), a shallow marsh (#6) and collection pipes to ensure uniform flow. The Columbia wetland was comprised of 23 separate cells (Kadlec, 2010).

During secondary treatment, if the FWS wetland is the first or only stage in the treatment sequence, then public access, and perhaps animal access, to the water in the FWS wetland must be prohibited due to the elevated levels of pathogens present. There is also the problem of muskrat and mosquito control and some problems in locations that experience severe winters. In severe winter areas of northern US and southern Canada the size of the wetland may need to double to achieve the required BOD and TSS standards during winter. Monitoring of existing wetlands has established a sizing rule of 54 to 48 square feet (5-4.5 m^2) per person for FWS or HSF wetlands to accomplish secondary treatment standards (Cooper, 2009). This equals about one acre for every 850 people the system serves. For accurate wetland sizing, matched to target contaminants or nutrient reduction, communities should consult an environmental engineer.

Performance of Built Free Water Surface Wetlands

The following two examples of built free water surface wetlands demonstrate their effectiveness and typical use in the U. S. An example of a FWS constructed wetland as the third stage of a biological wastewater treatment system is the wetland in Cle Elum, Washington constructed to serve 2,300 people. The system included two facultative sewage lagoons, instead of septic tanks, followed by a 5 acre FWS constructed wetland divided into three sections by two 3’ deep, open water trenches. The marsh sections were planted with Bulrush (Scripus acutus) and represented 68% of the wetland area. The deep-water strips discouraged short circuit flows by redistributing water evenly across the width of the wetland. Performance of the system for BOD and TSS was outstanding. Influent BOD (182 mg/L at the lagoon inlet) was reduced 96% to 6.4 mg/L. Influent TSS (169 mg/L at the lagoon inlet) were reduced 98% to 3 mg/L at the wetland outflow. The level of dissolved oxygen at the constructed wetland outfall averaged 6.9 mg/L compared to minimum levels of .2-.6 mg/L required for conversion of organic matter to ammonium and the conversion of ammonium to nitrate (Zhang, 2010).

A large FWS constructed wetland in Minot, Norway (Lat 48 degrees N) included a four cell 126 acre (51.2 ha) marsh > pond > marsh system. Like at Cle Elum, water pretreatment occurred in facultative lagoons. The wetland was created to meet an effluent level of 1 mg/L for nitrate. Wetland influent was 12.7 mg/L, 39.7 mg/L, and 2 mg/L for BOD, TSS and nitrate, respectively. Effluent concentrations and removal percentages were: BOD - 7.3 mg/L, 42.6%; TSS - 19 mg/L, 52.2% and nitrate - .06 mg/L, 69.4% (Hammer, 2002). The US EPA drinking water standard for nitrate is 10 mg/L (EPA, 2009). This example illustrates the effectiveness of FWS constructed wetlands for both secondary treatment but also advanced treatment for the removal of ammonium and nitrates. Performance in the coldest weather was less effective, especially for nitrate removal.

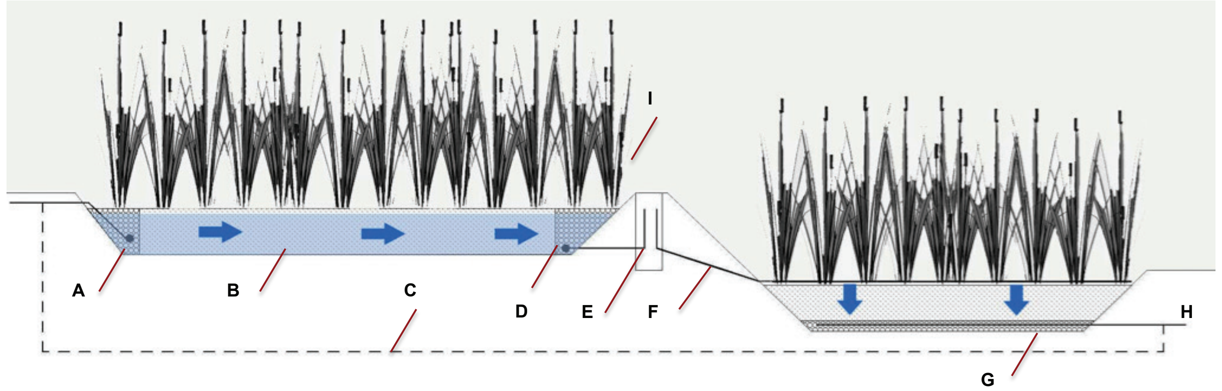

Figure 3 - Horizontal Subsurface Flow Wetland (left), Vertical Flow Subsurface Wetland (right)
A – Inlet from septic tank; B – Horizontal flow through medium to fine gravel; C – Recirculation of 50% of the flow from VSF to HSF wetland for de-nitrification; D – Collection zone, coarse gravel; E – Water level control; F – Intermittent dosing of VSF; G – Water drains vertically through gravel to bottom drain; H – Outflow to free water wetland; I – Dense planting. For the plan view of the HSF and the VSF wetland see Figure 2. Austin, 2009

HORIZONTAL SUBSURFACE FLOW WETLANDS

Introduction

Subsurface flow wetlands are common in Europe where tens of thousands exist (Cooper, 2009; Vymazal, 2005). About 50 ft2 (4.5 m2) of wetland area per person served is required to meet EPA secondary treatment standards in summer and winter (Vymazal, 2005). The HSF wetland is less sensitive to cold weather than the FWS wetland and is easier to insulate. A Minnesota HSF wetland is insulated with 6” (15 cm) of mulch to protect it from freezing at temperatures as low as -45°F (Kadlec, 2009). In Norway, HSF systems preceded by a buried bio-filter have proven to be very effective (Jenssen, 2005). In the HSF wetland (Figure 3, left) there is no standing water on the surface, so there is no odor or contact hazard, but, like the FWS wetland, the bed is densely planted making it an open space feature. Several factors are critical to the effectiveness of HSF wetlands, including gravel size, uniform flow, and dense plant coverage. Pre-treated wastewater must be evenly distributed through a coarse gravel inlet trench by a perforated pipe (Figure 3 A). In early designs, the distribution pipe was above ground but this caused algae clogging problems. Placing the distribution pipe a below grade, but above the elevation of the outlet collection pipe, reduced clogging and maintained a hydraulic gradient through the bed. Water flows slowly through the gravel that is 24”-30” (.6 - .8 m) deep. Most HSF wetlands consist of a 6’ wide inlet and outlet zone (Figure 3 A and D) composed of 1 ½” –

3” diameter (40 - 80 mm) gravel and a main bed (Figure 3 B) composed of gravel .8 – 1.2” (20 - 30 mm) in size. The gravel size limits clogging but provides a high surface area for biofilm growth. The size of the gravel in the main bed varies according to the shape of the wetland and the organic loading rate. There is no longitudinal slope on the bottom or the top of the bed (Wallace, 2006).

Beneficial bacteria growing on the gravel and roots consume many contaminants in the water. The plant roots must reach all the way to the bottom of the bed. If they do, then the amount of ammonia removed will be increased (Vymazal, 2005). Secondary treatment can be accomplished if the water moves through a gravel bed for two days. Three days of residency time is generally required to achieve the maximum removal of pathogens. The HSF wetland is very effective at reducing BOD and TSS to achieve secondary treatment water quality. HSF wetlands are moderately able to convert nitrates to nitrogen gas but are ineffective at converting ammonia to nitrate and removing phosphorus unless a special media is used.

Performance of Horizontal Flow Constructed Wetlands

An example of a subsurface flow constructed wetland is a system to treat wastewater in the town of Ondrejov, Czech Republic. Built in 1991 to serve 362 people, the HSF constructed wetland covers 8675.7 ft^2 (806 m^2), representing 59 ft^2 (5.5 m^2) per person, and treats 14,873 gallons (56.3 m^3) per day. It is densely planted with *Phragmites australis.* Monitored from 1991 through 2004, this wetland achieved an average BOD of 18.3 mg/L and TSS of 8.3 mg/L. The removal of phosphorus was low but continuous over the study period. Removal of ammonium was only 14.8% but nitrate removal was better at 41% (Vymazal, 2009), suggesting low oxygen in the wastewater. However, phosphorus, ammonia and nitrate are not regulated for secondary treatment in the Czech Republic or in the US, except when receiving waters are sensitive or severely degraded.

A second HSF constructed wetland serving 1,400 people in another Czech town, for a similar duration, demonstrates similar performance (BOD = 4.6, TSS = 9.5, ammonia removal = 19%, nitrate removal = 40%, phosphorus removal = 7%) with very little reduction in effectiveness over time (Vymazal, 2011).

The wetlands in the Czech Republic featured a single horizontal subsurface flow wetland cell, while in Little Stretton, United Kingdom a treatment system was built to serve 40 people and featured eight horizontal flow beds situated on a sloping site. Although BOD and TSS concentrations (7.3 mg/L and 16 mg/L, respectively) were similarly low in the outlet, much better reduction of ammonia (85.1%) was achieved due to better oxygen transfer among the beds due to aeration of the water as it moved between beds down the slope. Conversely only 16.4% of the nitrate and nitrite concentration was removed since that requires an anaerobic environment (Cooper, 2009). The long experience with horizontal flow wetlands in Europe, as demonstrated by the Chez and British example above, demonstrates the long term effectiveness and reliability of this technology.

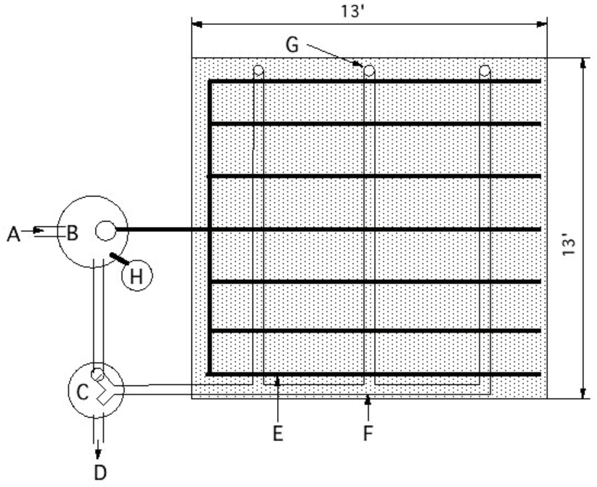

Figure 4 Vertical Subsurface Flow Wetland, Plan. A – Inflow from residence. B – Septic tank C – Recycling tank with V-notch weirs. D - Effluent. E- 1 ½” perforated PVC distribution piping, capped, 3’ spacing. F – 4” perforated PVC drainage piping, 3’ spacing. G – Aeration pipes connected to bottom drain H - Aluminum polychloride dosing chamber with air-lift pump in septic tank, for phosphorus removal. Source: Adapted from Brix, 2005

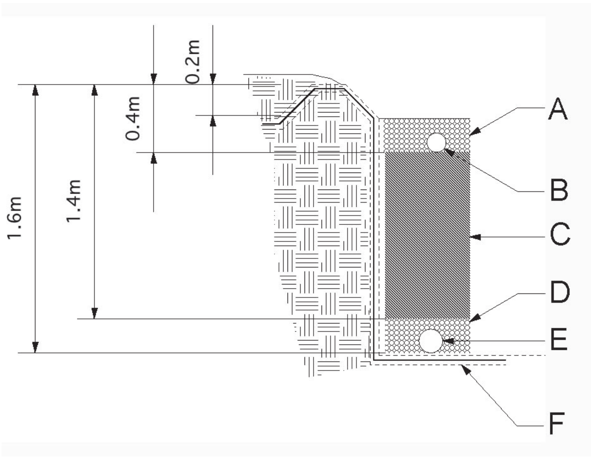

Figure 5 Vertical Subsurface Flow Wetland, Section. A - Wood chips. B – 1 ½” PVC distribution pipes, space 3’ max. C - Uncompacted filter sand, .125-4 mm with clay and silt <.5%. D- ½ “ drain rock. F - .5 mm waterproof membrane between two geotextile layers. E – 4” perforated PVC, space 3’ max. At one end connect to aeration pipes that extend above surface. Source: Adapted from Brix, 2005.

VERTICAL SUBSURFACE FLOW WETLANDS

Introduction

The vertical subsurface flow (VSF) wetland (Figure 3, right, Figure 4 and 5) receives periodic doses of pretreated water over its entire top surface but beneath a layer of mulch or gravel so that no water is ever exposed to human contact. Then the water flows down through a sand bed and out of the wetland through a bottom drain. Air replaces water in the sand pore spaces after the water flows through. This system creates an oxygen rich environment where bacteria reduce BOD, TSS and convert ammonia to nitrates. VSF wetlands require only 21.5 ft2 (2 m2) per person but they sometimes require energy input for pumps, and more regular attention from an operator (Tuncsiper, 2009).

Two Stage Vertical Flow Constructed Wetland

An Austrian demonstration wetland featured two VSF stages operated in series. Each of the wetlands was 108 ft2 (10 m2) and was planted with Common Reed (Phragmites australis). The first cell of the two-stage system included a 20” (50 cm) deep bed filled with sand ranging from 0.08” - .12” (2 - 3.2 mm) and an impounded basin of water below the filtration bed. The second stage included a .002” - .016” (.06 - 4 mm) sand layer above a conventional coarse aggregate drainage layer. Sewage, pretreated in a septic tank, flooded the top of the wetland to a depth of .64” (16.2 mm) every three hours. The demonstration wetland was operated and monitored from September 2005 to May 2007. Inlet BOD was high at 340 mg/L while the effluent was 4 mg/L in summer and 12 mg/L in winter. The removal efficiency for BOD was 98.7% (Langergraber, 2009). Both were well below the US EPA target of 30 mg/L.

Ammonia and Nitrate Removal

Average ammonia concentrations of the influent were high at 59.3 mg/L in summer and 53.4 mg/L in winter. The ammonia effluent average was .29 mg/L in summer (a 99.5% reduction) and 17.5 mg/L in winter (a 64% reduction). This two-stage VSF wetland removed 46% more of the ammonia concentration than a single cell VSF wetland with no impoundment of water below the filter bed (Langergraber, 2009). The US does not regulate ammonia discharge but aquatic organisms are sensitive to constant levels in excess of 1.8 mg/L at ph-8 and 25 degrees Centigrade (EPA, 2009).

The concentration of nitrates entering the two-stage wetland averaged .37 mg/L in summer and .30 mg/L in winter. Nitrates in the effluent were 30.9 mg/L in summer and 21.1 mg/L in winter. This large increase indicates complete conversion of ammonia (Langergraber, 2009).

Elimination of total nitrogen was 53.2% in summer and 37.1% in winter. This high performance in the removal of nitrogen is attributed to the nitrification of about 80% of the ammonia in the first stage wetland with the water impoundment but with enough carbon remaining to allow conversion of some of the nitrate to nitrogen gas in the impoundment, although not all of the nitrate was removed. The elimination of total nitrogen over the entire study was 2.7 g/m^2 or 986 g/m^2 per year (Langergraber, 2009). This nitrogen removal represents a 30% increase over the average VSF wetland and even better compared to FWS and HSF wetlands (Vymazal, 2007). The second stage of the two-part system is required to provide full nitrification of ammonia and elimination of the remaining organic matter. This two-stage wetland removed 64% more total nitrogen than a single cell VSF wetland (Langergraber, 2009). This improvement is attributed to the increased nitrification and de-nitrification.

Removal of Pathogenic Bacteria

The log influent concentration of heterotrophic bacteria was 6.32 with an effluent concentration of 3.45 representing a log removal of 2.87. For *E. coli* the influent concentration was 6.18 while the effluent concentration was 3.2, representing a log removal of 3.31. For total coliform bacteria, average concentration of the influent was 6.56 while the effluent concentration was 3.49 representing a log removal of 3.42. For *Enterococci* the influent concentration was 5.94 while the effluent concentration was 2.76 representing a log removal of 3.36 (Langergraber, 2009). In summary, numbers of pathogenic bacteria were reduced about 99.9%. However, the remaining number of *E. coli,* for example, is 1,585 cfu/100 mL, which is still much higher than the 126 cfu/100 mL recommendation of the US EPA for primary contact. Additional treatment in another wetland stage or ultra violet light disinfection would be required before this effluent could be used for intensive recreation.

This two-stage VSF constructed wetland with impoundment but without recirculation of water performed consistently better in removal of nutrients than a single stage system without impoundment. The single stage and two-stage constructed wetlands were similarly effective in the removal of microbes although the hydraulic loading of the two-stage system was twice as high as that of the one stage system (Langergraber, 2009).

Widespread Application

Austria, France and Denmark all have ordinances defining the size, construction materials and performance standards for subsurface flow wastewater treatment (Cooper, 2009, Brix, 2005). Most of these are horizontal subsurface flow wetlands but vertical subsurface flow wetlands are becoming more popular because they require less land and perform well in removal of ammonium in addition to BOD and TSS. Figure 2 and 3 illustrate both of the subsurface types and how they can be used in sequence. The HSF and VSF wetlands are presented as panels of dense vegetation that could be treated aesthetically to contribute to the public landscape. The potential for dispersed constructed wetlands that treat wastewater, rather than the current centralized, industrial approach, has great promise. Placing these constructed wetlands at institutions, like schools, or within new subdivisions or adjacent to multifamily buildings would contribute to the green infrastructure networks promoted by landscape architects. As the data presented above on the performance of each constructed wetland type indicates, none by itself is capable of fully treating wastewater for all water quality parameters. Combinations of the wetland types are more effective for advanced wastewater treatment.

TREATMENT OF CONTAMINANTS BY HYBRID SYSTEMS

Introduction

In addition to the indirect measures provided by removal of BOD and TSS (secondary level of treatment), wastewater treatment and stormwater discharge permits are requiring discharge maximums for ammonium, nitrates, phosphorus, heavy metals and pathogenic bacteria into sensitive water

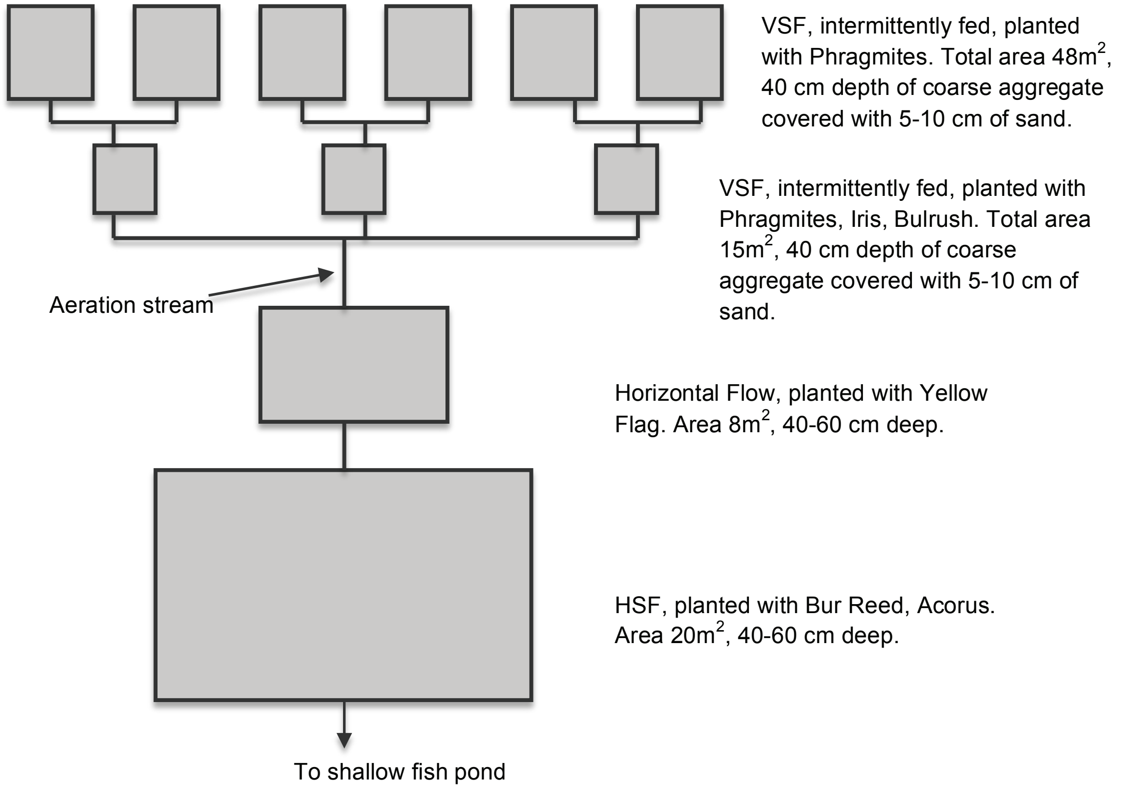

Figure 6 Plan view diagram of the hybrid wetland at Oaklands Park, UK for treatment of domestic sewage. Source: adapted from Burka, U.; Lawrence, P. 1990

bodies and recreation areas. Since many of these contaminants are also problematic in stormwater runoff, much is to be gained by studying the effectiveness of constructed wetland treatment chains and their ability to reduce the concentration of these pollutants.

Hybrid constructed wetlands (some combination of FWS, HSF and VSF) are able to significantly reduce ammonium and nitrate levels. Ammonia is highly toxic to aquatic organisms and nitrate is harmful at elevated levels.

Oaklands Park Wetland

The case of the Oaklands Park wetlands illustrates the complex biological, chemical and energy transformations required to reduce ammonia and nitrates in sewage effluent (these nutrients are also problematic in landfill leachate, food processing, livestock operations and fish farms as well as agricultural and suburban runoff).

The wetland diagramed in Figure 6 was built in the England to serve a population of 65 people. Pretreatment in a septic tank, with a 12-hour retention time, was followed by 6 vertical flow wetland cells, only one of which was active at any time. The vertical flow cell in the first stage was operated for two days and then allowed to rest for ten days. In the second stage, the vertical flow cell was operated for 4 days and then rested 8 days. This rest period was thought to be necessary to avoid clogging the sand media in the cell. However, refinements illustrated in the Austrian VSF wetland, discussed above, shows that VSF cells can be operated with resting periods of only a few hours. Two stages of HSF wetlands followed the vertical flow cells. The final step was a fishpond. The vertical flow wetlands significantly reduced BOD and TSS. The oxygen rich environment allows aerobic bacteria populations to consume organic carbon and create ammonia, nitrite and nitrate. Anaerobic bacteria in horizontal flow wetlands convert the nitrate to nitrogen gas, which escapes to the atmosphere. However, if too much carbon was to be removed in stages 1 and 2, there would not enough carbon to fuel de-nitrification in the horizontal flow wetlands (Burka, 1990; Gaboutloeloe, 2009).

The data in Table 1 illustrates the excellent performance of the Oakland Park system. Outlet concentrations of BOD and TSS are 7 and 4 mg/L respectively. Ammonia and nitrate concentrations are reduced by 78% and 68%, respectively. The data for pond effluent is not shown but it resulted in further reductions in ammonia, nitrate and phosphorus. Phosphorus declined from 19.8 in septic tank effluent to 8.2 mg/L (a 58.5% reduction) at the pond outlet. As expected, BOD and TSS increased between the pond inlet and outlet but remained within the EPA standards. Total coliform bacteria (an indirect measure of pathogenic bacteria) dropped from 2,310,000 in the septic tank effluent to 680 colony forming units per 100 milliliters (cfu/100mL) at the pond outlet. *E. coli* dropped from 500,000 to 0 and fecal *Streptococci* dropped from 22,000 to 25 cfu/100mL. The pond contributed significantly to the reduction of harmful bacteria suggesting that the increase in BOD and TSS in the pond effluent does not indicate an increase in pathogens (Burka, 1990; Gaboutloeloe, 2009). The pond water met EPA standards for primary contact.

Notice that the Oaklands Park treatment wetland requires no artificial energy source in contrast to the system illustrated in Figures 2 and 3 where a pump is required to return water to the horizontal flow wetland to allow for de-nitrification after the vertical flow cell. In that example, the horizontal flow wetland is placed before the vertical flow wetland and would result in incomplete de-nitrification but excellent performance in other parameters.

Table 1 Treatment effectiveness of the hybrid wetland at Oaklands Park, UK. Source: Burka, U.; Lawrence, P. 1990 ; Gaboutloeloe, 2009.

Flow Form	Surface area m^2	Influent BOD_5	Effluent BOD_5	Influent TSS	Effluent TSS	Influent NH_4^+	Effluent NH_4^+	Influent NO_3^-	Effluent NO_3^-
Vertical	8	285	57	213.3	38.5	50.5	29.2	1.7	10.2
Vertical	5	57	14	38.5	17.7	29.2	14	10.2	22.5
Horizontal	8	14	15	8	8.2	14	15.4	22.5	10
Horizontal	28	15	7	9.2	4	15.4	11.1	10	7.2
			a		a		b		c

a – EPA discharge requirement less than 30 mg/L

b – No EPA discharge requirement for ammonia. In streams rainbow trout fry tolerate up to about 0.2 mg/L. Hybrid striped bass can handle 1.2 mg/l.

c - No EPA discharge requirement for nitrate. In streams concentrations above 5 mg/L inhibit growth in fish. Salmon are much more sensitive.

BOD = biological oxygen demand; TSS = total suspended solids; NH_4^+ = ammonium; NO_3^- = nitrate

CAPITAL AND OPERATING COSTS

Free water surface wetlands require about the same land area as HSF wetlands but the subsurface wetland requires a great deal of washed gravel increasing it's cost. The VSF wetland requires gravel as well but the area required is less than half that of the other two options. Comparing constructed wetlands to conventional systems, such as activated sludge process, is a matter of trading land cost for energy cost. Conventional systems are compact and perhaps an advantage where little land is available or where it's cost is high. Where land is less expensive then constructed wetlands would be require less capital investment. The capital cost of a Florida wetland of over 800 acres was approximately $23,000 per hectare (2.5 ac) (2006 dollars). Smaller wetland projects cost substantially more on a per acre basis (Kadlec, 2009).

Operating cost is much lower for constructed wetlands since most are powered by sunlight, gravity and biological process. Pumping or artificial aeration is rarely necessary. The primary operating cost is for water quality testing. For conventional systems substantial and continuous costs are accumulated for energy use, more operations personnel and equipment repair and replacement.

TREATING STORMWATER

Stormwater Characteristics

Variations in land-use, weather patterns and watershed characteristics, such as slope and soil make generalizations about the initial quality of stormwater runoff difficult. Nevertheless, research studies provide us with an understanding of land uses that typically contribute high concentrations of particular contaminants. For example, lawns (602 mg/L), commercial streets (468 mg/L), auto recyclers (335 mg/L), and industrial parking (228 mg/L) produce high levels of TSS. Landscaping (94,000 cfu/mL) and residential streets (37,000 cfu/mL) contribute significant concentrations of *E. coli* (Kadlec, 2009). Other species of pathogenic bacteria are also present in high concentrations in storm runoff. Fecal coliform, total coliform and the *E. coli* bacteria were highly correlated with one another and with turbidity and suspended sediment concentrations (Peters, 2009).

The greatest contributions of total phosphorus to stormwater runoff come from lawns (2.1 mg/L), driveways (.56 mg/L), residential streets (.55 mg/L) and urban highways (.32 mg/L). The heaviest contributors of total nitrogen are rural highways (22 mg/L), lawns (9.1 mg/L), driveways (2.1 mg/L) and urban highways (3 mg/L). Heavy metals are produced in the greatest concentrations by industrial roofs (62, 43, and 1390 um/L for copper, lead and zinc, respectively); heavy industrial land (148, 290, and1600 um/L of copper, lead and zinc, respectively); urban highways (54, 400, and 329 um/L of copper, lead and zinc, respectively); auto recycling yards (103, 182, and 520 um/L of copper, lead and zinc, respectively); and landscaping (94, 29, and 263 um/L of copper, lead and zinc, respectively) (Kadlec, 2009). Most of the concentrations of nutrients, bacteria and metals are far above EPA standards.

Stormwater Impacts

It seems clear that the pollution levels indicated above would degrade stream water quality. Water quality does diminish as urban and other human uses change watersheds from their natural state. In 2003 the city of Atlanta, Georgia developed a stream water quality monitoring network that annually gathered data from 21 stations. From 2003 to 2007 data was collected for more than 20 stream watersheds. The degree of watershed urbanization ranged from 69 to 93%. The data from urban watersheds was compared to a small forest watershed and a larger, lightly developed watershed as references (Peters, 2009).

The study indicates that urbanization impacts stream water quality but this impact is highly variable. Increased alkalinity and concentrations of calcium and magnesium in urban streams were thought to be associated with the weathering of concrete. High levels of chlorine were associated with combined storm and wastewater sewer outflow treated with sodium hypochlorite as well as drainage from swimming pools and road deicing salts ($CaCl_2$). The fecal coliform bacteria levels exceeded the EPA standard for primary or secondary use in more than 90% of the test samples taken from urban watershed streams. Nutrient levels in streams were high compared to streams in natural areas but lower than EPA standards.

The first flush of impervious surfaces resulted in high concentrations of copper, lead and zinc. Copper and zinc in most of the streams exceeded Georgia's chronic and acute standards (chronic levels damage aquatic organisms when exposure exceeds 4 days, acute levels damage aquatic organisms when exposure exceeds 1 hour). Lead was detected at chronic levels. These metals are common in highway runoff. Vehicle tire particles and decayed metal fittings used in building construction are the common sources of these metals. Cadmium exceeded state standards only in a small percentage of tests.

The Water Quality Storm

Biological wastewater treatment technology can be applied to stormwater runoff for water quality improvements. The most common response to stormwater pollution is the construction of a wet pond. This is defined as a basin containing a volume of water receiving biological treatment. The volume is often established to equal the two-year, 24-hour storm or a similar design storm that captures most of the runoff generated during the year. Selection of a design storm seems to be a better practice than treating the first flush. The first flush is defined by collection of 50% of the pollutant mass in the first 25% of the stormwater runoff. However, a second flush sometimes contributes more pollution to the stormwater volume than the first flush (Flint, 2007).

Retention Basin Batch Treatment

In general, stormwater treatment for water quality improvements in retention ponds or FWS wetlands follow the pattern of, 1) a volume of antecedent water is replaced by a new stormwater inflow, 2) a flow-through period, perhaps, 3) a volume of water retained and undergoing treatment. A higher number of replacement volumes stored in the wetland is associated with better water quality. A one to one replacement in the wetland will result in pollution removal of about 20% while a wetland that contains 6 replacement volumes will remove approximately 80% of the pollutants (Kadlec, 2009). Retention basins are often open water bodies with a margin of wetland plants but might be planted to densely vegetate the entire basin. In this case they are like free water surface wetlands.

Performance of Constructed Wetlands for Stormwater Treatment

Bulc and Slak reported on a constructed wetland to treat highway runoff for a 1.9 ac (.75 ha) drainage area and an inflow rate of 182 gpm (11.75 L/s). The system was initiated by a 388 ft2 (36 m2) sedimentation basin with a vertical wood and impervious membrane baffle at its midpoint. A similar pair of baffles contained a gravel gabion. After sedimentation, runoff was forced to flow up through the gravel gabion and into a 915 ft2 (85 m2) constructed wetland. The wetland functioned as a horizontal subsurface flow wetland during low-flow events, since water was directed through a bed of sand. However, at higher flow, water flowed over the surface of the wetland and through dense plantings as in a FWS wetland. Above the maximum design depth, the water overflowed into a riser with a sediment sump. BOD removal was low due to low organic matter in the inflow. This also limited nitrogen and phosphorous removal. TSS and particulates were removed at 69% and 97%, respectively. Iron was reduced 80%. Copper, zinc, cadmium, nickel and lead were reduced 90%, although each of these was already below regulatory standards in the inflow (Bulc, 2009).

A second study reveals the effectiveness of a FWS wetland for stormwater quality improvement. The North Carolina study compared a wet pond and a FWS wetland. The wet pond is 22 ac (8.82 ha) and receives stormwater runoff from a 935-acre (378.4 ha) drainage area composed of single and multi-family housing. It is 2,296' (700 m) long, 508' (155 m) wide and 6' (1.8 m) deep, resulting in a length to width ratio of 4.5 and a volume of 128 acre feet (158,760 m^3). The pond is heavily vegetated with submerged plants and contains two islands. There are three stormwater inlets, one of which was near the pond outlet. This pond achieved significant reductions in only turbidity and fecal coliform bacteria counts (56% reduction), but there were insignificant reductions in ammonium, nitrate, phosphorus and total nitrogen. Excessive water depth, lack of emergent vegetation and storm runoff inlets below the head of the pond are the most significant factors leading to the poor water quality performance of the pond (Mallin, 2002).

Improvements to the design of this system based on knowledge of constructed wetlands would include the addition of a sedimentation basin, piping all inflows to the head of the wetland, reducing water depth to 36 inches, dense planting of Cattail and Bulrush, and division of the wetland into several cells with water distribution piping at the head of each. An aeration waterfall between the FWS cells and a HSF wetland to finish TSS, nitrate and bacteria removal should follow the FWS wetland. Deepwater trenches could be installed instead of some cell berms, if increased fish and wildlife benefits were desired.

The second facility is 2.6 acres (1.04 ha) and received stormwater runoff from 71 acres (28.7 ha) composed of single and multi-family housing. It was 1,395' (425 m) long, 79' (24 m) wide and 2' (.6 m) deep, resulting in a higher length to width ratio of 17.7 and a volume of 5-acre feet (6,240 m³). The FWS wetland is composed of an upper basin, of which about 70% is vegetated with floating plants and emergent macrophytes, and a lower basin with about 40% vegetation coverage. There is a single stormwater inlet at the beginning of the pond. This marsh performed much better. There were significant reductions in fecal coliform bacteria counts (86%), ammonium (83%), nitrate (63%), orthophosphate (77%), and total nitrogen (86%). This pond, in its shape, depth and vegetation resembles a free water constructed wetland (Mallin, 2002).

Stormwater Treatment and Pathogenic Bacteria

As suggested in the North Carolina study above, constructed wetlands are more effective than wet ponds for the removal of pathogens in stormwater runoff. An Australian study compared the effectiveness of a constructed wetland marsh and an open water retention pond for reductions in numbers of pathogenic bacteria. The constructed FWS wetland was 1.1 acres, preceded by a sedimentation basin and a trash rack. The wetland was divided into 5 elongated cells by 16" high coarse rock weirs. The wetland cells were 130' long and ranged from 8" – 24" in depth. Almost all of the wetland was vegetated with macrophytes. The marsh received stormwater runoff from a residential district.

A sedimentation basin and a trash rack preceded the 3.7 acre comparison wet pond that received stormwater runoff from a residential development. The pond was divided into three cells by 3' tall berms but the water ranged in depth from 6.5 to 16.4 feet. The pond edge was vegetated with macrophytes.

Fecal bacteria, *Entrococci* and heterotrophic bacteria reductions were much greater in the constructed wetland than in the deep water pond. For this FWS wetland, the outflow showed bacteria reductions of 79%, 85%, 87% for fecal coliform bacteria, *Entrococci* and heterotrophic bacteria, respectively (Davies, 2001). Despite the good removal rate for fecal coliform bacteria, the concentration in the effluent was 3,600 cfu/100mL; far above the maximum standard of 200 cfu/100mL for secondary recreation contact. Additional treatment or disinfection would be required depending on the use of the effluent.

At the wet pond outlet, the bacteria either increased or were reduced much less compared to the wetland marsh. The outflow showed bacteria reductions of -2.5%, 23%, 22% for fecal coliform bacteria, *Entrococci* and heterotrophic bacteria, respectively, compared to the inflow (Davies, 2001).

The soils in the areas around both of the stormwater facilities were slightly acidic clay. Water turbidity was much higher in the pond water than it was in the marsh wetland. This may be from fine sediment washing into the pond from the developing residential district or from reanimation of bottom sediment by stromwater inflow. Bacteria attach themselves to sediment particles, but preferentially to fine sediment particles, such as clay, and these particles settle more rapidly in the marsh environment than in open water. While the bacteria count is generally higher in sediment than in the water column, it is bacteria in the water that most impacts downstream ecosystems and people in downstream swimming areas. Reduction of bacteria in bottom sediment is increased when sediments are coarser that clay. The dense plant cover in the marsh may have stabilized the sediments. There is also a possible effect from antibacterial substances created by the wetland plants (Davies, 2001).

The wet pond in this study was poorly designed to achieve water quality improvements. The inadequate removal of suspended solids would be resolved by a horizontal subsurface flow wetland between the sedimentation basin and the open water zone. Marsh-like FWS cells after the proposed HSF wetland and just before the outlet would preserve the open water but would improve TSS and bacteria removal.

Removal of bacteria pathogens in FWS and other wetland types is highly dependent on residence time and internal flow patterns. Rotifers and protozoa are microorganisms that prey on bacteria. Rotifers are abundant in the effluent of wastewater wetlands. They are commonly present at 10 per mL. At this concentration rotifers can disinfect stormwater detained for 1.2 hours in a marsh wetland (Kadlec, 2009).

The effectiveness of FWS and VSF wetlands was confirmed by a study of two dry basins, a wet pond, two wetlands and one bioretention bed. The dry basins actually increased the concentration of harmful bacteria while one wetland met EPA recommendations for primary recreation contact for E. coli and fecal coliform. The bioretention bed, which is a VSF wetland, met EPA recommendations for primary recreation contact for E. coli and nearly met the standard for fecal coliform concentration (Hathaway, 2009). The study provided few details of the material or construction criteria leading to the success of failure of the systems.

Vertical Subsurface Flow Wetlands for Stormwater Treatment

Table 2 Bioretention Bed

Pollutant	Removal	Pollutant	Removal
Total Nitrogen	32%	Fecal Coliform Bacteria	69%
Total Kjeldahl Nitrogen	44%	E. coli	71%
Ammonium	73%	Zinc	77%
Nitrite and Nitrate	- 5%	Copper	54%
Total Suspended Solids	60%	Lead	31%
Biological Oxygen Demand	63%	Iron	330%
Total Phosphorus	31%		

Source: Hunt, 2008

Bioretention beds are designed similar to VSF constructed wetlands. Water filters vertically through a sandy substrate, fully saturating the filter material and even ponding on the surface temporarily before being drained by pipes below the bed. Like the VSF wetland they are intended to dry (and renew their oxygen content) between storms.

A bioretention bed was constructed in North Carolina to treat 1" (25.4 mm) of rainfall (the 2 year, 24 hour storm is 3.36"). The bioretention cell received water from a .92 acre (.37 ha) parking lot. The surface of the infiltration bed was 2,480 ft.^{2} (229 m^2) which represents 6% if the catchment area. The bed was composed of a 4'(1.2 m) depth of loamy sand (silt/clay = 5.7%) with a 6" diameter corrugated under drain. The soil permeability was .43 in/hr and the basin was planted with a variety of water tolerant species. For storms of less than 1.65" (42 mm) of rainfall (mean storm = 1.08" (27.4 mm), median storm = .95" (24.1 mm)) the bioretention cell decreased peak storm outflow dramatically (96% for storms less than 40 mm) (Hunt, 2008). The bioretention bed performed very well (Table 2). The low total nitrogen removal was due to low organic matter in the runoff. The increase in nitrite and nitrate to .43 mg/L indicates that the bed provides aerobic conditions for the conversion of ammonium to nitrite and nitrate but that there is no oxygen depleted zone (and probably too little carbon) for de-nitrification. If the bioretention bed had been designed to include an impounded drainage layer, as in the VSF wetland presented earlier, a significant amount of the nitrite and nitrate could have been prevented from exiting the bioretention bed. Even better, the well nitrified effluent from the biodetenton bed might have been directed through a HSF bed below the adjacent parking lot. A very similar bioretention bed was installed in Greensborough, North Carolina but the bottom 2' was saturated with water to form an anaerobic zone. This bed performed better with nitrate removal at 75% and total nitrogen removal of 40%.

The North Carolina study recorded performance below the suggested optimum levels according to a laboratory experiment that tested 125 biofilter configurations that varied the plant, filter media, media depth and pollutant concentrations typical of urban stormwater. The significant difference in the best performing biofilter was the presence of *Carex appressa,* which is characterized by deep and fine roots. Under various media and flow conditions, the biofilter removed 99% of TSS, 93% of ammonium, 85%-96% of nitrite and nitrate, 71%-79% of total nitrogen, 93%-96% of total phosphorus and 87% -98% of particulate phosphorus. Lessons from the study were to use sandy loam as the media, avoid compost or much in the media, since this increased total phosphorus in the effluent, and use plants that are known to remove ammonia and nitrate at accelerated rates (some plants actually increased total nitrogen and nitrogen species in the effluent). The biofilter performed to these standards when sized at 2% of the drainage area (for Melbourne, Australia's climate) (Bratieres, 2008).

Like biodetention beds green roofs and permeable pavements often offer stormwater improvements but these have also been shown to discharge nitrates into the environment. The nitrates could be removed if the concept of hybrid constructed wetlands is applied to treat the broadest range of nutrients and contaminants.

CONCLUSION

The three types of constructed wetlands for wastewater treatment can effectively meet secondary treatment standards for TSS and BOD. The required area per person served is 4.5 m^2 for FWS and HSF while 2 m^2 is needed for VSF wetlands. Nearly complete removal of both ammonium and nitrates by any of the three constructed wetland types alone is not possible. Hybrid wetlands that combine the three types of wetlands in various configurations are more effective in the removal of nitrogen species, total nitrogen and pathogenic bacteria.

HSF and VSF wetlands are effective and safe for wastewater treatment when placed in the green infrastructure of towns and cities where treated effluent could be reused for a variety of non-potable needs. Wastewater and stormwater constructed wetlands are potential contributors to green infrastructure and an important example of ecological services provided by green infrastructure.

While large constructed wetland systems for wastewater treatment may equal the capital cost of conventional activated sludge treatment, the operating cost and energy use are far lower.

The concepts and technology gained from biological wastewater treatment can be adapted to the treatment of stormwater to avoid incomplete treatment of nutrients and contaminants. The use of alternating stages of HSF and VSF for initial treatment followed by a FWS wetland are likely to produce the highest quality effluent while providing significant secondary benefits to the community open space system.

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