University Curriculum Development for Decentralized Wastewater Management

Constructed Wetlands: A Critical Review of Wetland Treatment Processes

by

Robert W. Seabloom, P.E.
Emeritus Professor of Civil and Environmental Engineering
Dept. of Civil and Environmental Engineering
University of Washington

Adrian T. Hanson, PE
Professor of Environmental Engineering
Frank M. Tejeda Center

September 2004
NDWRCDP Disclaimer

This work was supported by the National Decentralized Water Resources Capacity Development Project (NDWRCDP) with funding provided by the U.S. Environmental Protection Agency through a Cooperative Agreement (EPA No. CR827881-01-0) with Washington University in St. Louis. These materials have not been reviewed by the U.S. Environmental Protection Agency. These materials have been reviewed by representatives of the NDWRCDP. The contents of these materials do not necessarily reflect the views and policies of the NDWRCDP, Washington University, or the U.S. Environmental Protection Agency, nor does the mention of trade names or commercial products constitute their endorsement or recommendation for use.

CIDWT/University Disclaimer

These materials are the collective effort of individuals from academic, regulatory, and private sectors of the onsite/decentralized wastewater industry. These materials have been peer-reviewed and represent the current state of knowledge/science in this field. They were developed through a series of writing and review meetings with the goal of formulating a consensus on the materials presented. These materials do not necessarily reflect the views and policies of University of Arkansas, and/or the Consortium of Institutes for Decentralized Wastewater Treatment (CIDWT). The mention of trade names or commercial products does not constitute an endorsement or recommendation for use from these individuals or entities, nor does it constitute criticism for similar ones not mentioned.

Acknowledgements

The authors would like to thank the following persons for reviewing the materials in this module:

Mark Gross
Mike Hoover
Jim Kreissl
Richard Otis
Scott Wallace
Citation of Materials

# Table of Contents

I. Introduction ........................................................................................................ 1  
   A. Definition ......................................................................................................... 1  
   B. History ........................................................................................................... 1  

II. Pretreatment ..................................................................................................... 3  

III. Types of Passive Constructed Wetland Treatment Systems ......................... 3  

IV. Free Water Surface (FWS) Constructed Wetlands ........................................ 3  

V. Removal Mechanisms on Free Water Surface (FWS) Wetlands .................... 6  
   A. Removal of Biochemical Oxygen Demand (BOD) and Total Suspended Solids (TSS) .......................................................... 6  
   B. Nitrogen Removal Mechanisms ................................................................... 6  
   C. Phosphorous Removal Mechanisms ............................................................... 8  
   D. Sulfur Removal Mechanisms ......................................................................... 8  
   E. Pathogen Removal .......................................................................................... 9  
   F. Metals ............................................................................................................ 9  
   G. Synthetic Organics ....................................................................................... 10  

VI. Performance .................................................................................................... 10  

VII. Design Considerations .................................................................................. 11  

VIII. Vegetated Submerged Bed (VSB) Constructed Wetlands ....................... 11  

IX. Removal Mechanisms in Vegetated Submerged Bed (VSB) Constructed Wetlands ............................................................... 12  
   A. Removal of Biochemical Oxygen Demand (BOD) .................................. 12  
   B. Nitrogen Removal Mechanisms ................................................................... 12  
   C. Phosphorous Removal Mechanisms ............................................................... 16  
   D. Pathogen Removal .......................................................................................... 16  
   E. Metals ............................................................................................................ 16  
   F. Synthetic Organics ....................................................................................... 17  

X. Performance .................................................................................................... 17  

XI. Construction, Operation, and Maintenance ................................................ 17  
   A. Containment Structures ............................................................................... 17  
   B. Inlet and Outlet Devices ............................................................................... 19  
   C. Media ............................................................................................................ 19  
   D. Vegetation Establishment ............................................................................. 19  
   E. Operation and Maintenance ....................................................................... 22
XII. Design Considerations .................................................................23
    Constructed Wetlands – Common Misconceptions ....................24

XIII. Performance ..............................................................................25

XIV. Conclusions ...............................................................................27

    References ..................................................................................28
    List of Figures ............................................................................30
    List of Tables .............................................................................31
Constructed Wetlands:
A Critical Review of Wetland Treatment Processes

Introduction

Definition
Constructed wetlands are a relatively new technology used in the small scale wastewater management field. These small artificial wastewater treatment systems consist of one or more shallow treatment cells, either ponds or channels, with emergent herbaceous vegetation that flourish in saturated or flooded soils. They employ the same biological processes found in larger natural wetland ecosystems, to provide treatment of residential septic tank effluent for discharge to the soil. If the lot is large enough, the effluent may be applied directly to the soil within the residence property lines, and if the wetland serves multiple sources, such as from a cluster of homes, the application to the soil may be to a nearby community drainfield. The treatment expected from these small constructed wetland units is to raise the quality of the wastewater up to secondary effluent standards or better. This is in contrast to the widely used and naturally occurring large polishing wetlands which receive secondary effluent and provide further tertiary treatment before discharging to the environment. Thus the distinction between the widely used large polishing wetlands and small constructed wetlands is based upon the strength of the wastewater entering the systems. The wastewater treatment trains for constructed wetlands, as contrasted to large polishing wetlands, are shown in Figure 1. Septic tank effluent is the primary wastewater considered in this discussion. Therefore, if allowed by local regulators, constructed wetlands may be an appropriate alternative technology to the conventional soil adsorption system.

The use of constructed wetlands as a traditional technology has a certain degree of risk due to possible human dermal contact with septic tank effluent and possible transmission of disease. This possible exposure to primary effluent is greater than that in the large polishing wetlands where the influent has already met effluent quality standards. Also constructed wetlands may present conditions favorable for the growth of mosquito populations of which certain species may carry a health risk as well as an annoyance. In any treatment system receiving septic tank effluent, inevitably during the natural process of anaerobic decomposition of the organic waste matter and other biological solids will result in the generation of foul odors, such as hydrogen sulfide and mercaptans: These odors usually will be concentrated in areas around inlet structures. And while there is a relatively large area for dilution, the odor generation at times may be a major operational concern. Because they require relatively large land areas they may be especially suited for rural areas and small communities where inexpensive land is available.

History
Natural wetlands as the name implies are in simplest terms transitional areas between dry land and wet areas, such as swamps, marshes, and bogs and are extremely valuable and protective ecosystems. The small constructed wetlands described herein are designed to mimic the natural
processes occurring in nature. In 1970 the U.S. Army Corps of Engineers and the U.S. Environmental Protection Agency formally defined wetlands for regulatory purposes as follows:

*Wetlands are areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas.*

Figure 1

**WASTEWATER TREATMENT TRAINS FOR CONSTRUCTED WETLANDS AND LARGE POLISHING WETLANDS**

**CONSTRUCTED WETLANDS TREATMENT TRAIN**

Primary Treatment  | Secondary Treatment
--- | ---
Raw Wastewater  | Septic Tank Effluent  | Constructed Wetland Effluent  | Secondary Effluent
Septic Tank  |

**LARGE POLISHING WETLAND TREATMENT TRAIN**

Primary Treatment  | Secondary Treatment
--- | ---
Raw Wastewater  | Sedimentation Effluent  | Primary Biological Effluent  | Secondary Polishing Wetland Effluent  | Tertiary Effluent
Primary Effluent  | Biological Effluent  | Polishing Wetland Effluent  |

Because natural wetlands have a natural water quality improvement function, and typically are at the lowest point in the topography and receive surface runoff, it was only natural to attempt to utilize this capability to protect downstream rivers and lakes. Thus, these large natural polishing wetlands have been used to further treat surface runoff and water of secondary effluent quality. This is in contrast to the constructed wetlands, which receive primary effluent from septic tanks, and treat it to secondary standards. These nature wetlands are home to many species of fish and birds, retain flood waters, filter runoff, and provide varied recreational opportunities.
Natural wetlands have probably been used to enhance wastewater quality since 1912. (US EPA, 2000) Research studies on the use of wetlands to enhance water quality began in Europe in 1950, in 1960 in the U.S. and then increased throughout the 1970’s and 1980’s, with major involvement by the Tennessee Valley Authority (TVA) and the US Department of Agriculture. (US EPA, 2000) These constructed enhancement wetlands, are similar to natural marshes and ponds and are built to benefit the community by reclamation and storage of water, provision of wildlife habitat and opportunities for recreation and environmental education. (US EPA, 2000). Small constructed wetlands differ in scale from natural polishing wetlands, typically occupying a few hundred square feet as contrasted with the large area of natural ponds and marshes. (US EPA, 2000)

The use of constructed wetlands seems to have an inherent aesthetic appeal to the general public (US EPA, 2000). This may be a valuable asset and powerful argument in public debate on environmental issues.

**Pretreatment**

It is critical that the residential wastewater receive primary treatment before flowing into constructed wetlands. This would, at a minimum, include screening, floating and suspended solids reduction, such as that provided by a septic tank. Under no circumstances, would it be appropriate to directly discharge raw residential wastewater into constructed wetlands. The typical composition of septic tank effluent is shown in Table 1.

**Types of Passive Constructed Wetland Treatment Systems**

As previously stated, constructed wetlands provide secondary treatment for primary effluent. There are two types that share many of the same characteristics, but are distinguished by the location of the hydraulic grade line, (US EPA, 2000) they are the Free Water Surface (FWS) and Vegetated Submerged Bed (VSB) constructed wetlands.

**Free Water Surface (FWS) Constructed Wetlands**

Free Water Surface Constructed Wetlands (FWS) closely resemble natural wetlands, such as marshes, swamps, and bogs (US EPA, 2000). They have a combination of open water areas with some floating vegetation as well as emergent plants rooted in the soil bottom (see Figures 2 and 3). Depending upon local regulations and soil conditions, berms, dikes, and liners are used to control flow and infiltration. As the wastewater flows through the leaves and stems of plants it is treated by the processes of sedimentation, filtration, digestion, oxidation, reduction, adsorption, and precipitation (US EPA, 2000). A free water surface (FWS) wetland may be described as a shallow attached growth biological reactor with a combination of floating aquatic plants, such as duckweed, water hyacinth, water fern, and water lettuce. In addition they have rooted plants growing in a floating form including penny wort, frogs pit, and pond weed (US EPA, 2000).
Since FWS constructed wetlands closely resemble natural wetlands it should be no surprise they invariably attract a wide variety of wild life, namely, protozoa, insects, mollusks, fish, amphibians, reptiles, birds, and mammals (US EPA, 2000). Although most species of animals are beneficial, some may be a nuisance, particularly burrowing rodents which may disrupt berms and dikes and consume beneficial emergent vegetation (US EPA, 2000). Water fowl in large numbers may stir up sediments, and add excessive nutrients from their droppings (US EPA, 2000).

Generally FWS are more suitable in warmer climates, because biological decomposition rates are temperature dependent, decreasing with decreasing water temperature. In addition if ice covers the open water surface the transfer of oxygen from the atmosphere is reduced (Vassoe, 1999; Wallace, 1998).

Usually, it is necessary to fence off and isolate the FWS wetland against animals and humans.

<table>
<thead>
<tr>
<th>Source</th>
<th>Flow (gal/capita/day)</th>
<th>BOD₅ (mg/l)</th>
<th>TSS (mg/l)</th>
<th>Grease (mg/l)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kreissl</td>
<td>242 (64)</td>
<td>218</td>
<td>114</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lawrence-Home 1</td>
<td>117 (31)</td>
<td>224</td>
<td>130</td>
<td>26</td>
<td>7.5</td>
</tr>
<tr>
<td>Lawrence-Home 2</td>
<td>185 (49)</td>
<td>124</td>
<td>70</td>
<td>8.5</td>
<td>7.2</td>
</tr>
<tr>
<td>Otis et al</td>
<td></td>
<td>125</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Otis et al</td>
<td></td>
<td>130</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U. Wisconsin</td>
<td></td>
<td>158</td>
<td>51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bennett, ASAE</td>
<td></td>
<td>134</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schmidt-(two)</td>
<td>151 (40)</td>
<td>90</td>
<td></td>
<td></td>
<td>7.1</td>
</tr>
<tr>
<td>Bounds, 1982-STEP-(one)</td>
<td>189 (50)</td>
<td>118</td>
<td>52</td>
<td>16</td>
<td>6.9</td>
</tr>
<tr>
<td>PHS 2nd Series</td>
<td></td>
<td>178</td>
<td>111</td>
<td></td>
<td>7.4</td>
</tr>
<tr>
<td>PHS 3rd Series</td>
<td></td>
<td>92</td>
<td>112</td>
<td>19</td>
<td>7.5</td>
</tr>
<tr>
<td>PHS 4th Series</td>
<td></td>
<td>151</td>
<td>128</td>
<td></td>
<td>7.5</td>
</tr>
<tr>
<td>Barshied</td>
<td></td>
<td>223</td>
<td>39</td>
<td></td>
<td>7.1</td>
</tr>
<tr>
<td>Ronayne, 1982-(two)</td>
<td>208 (55)</td>
<td>217</td>
<td>146</td>
<td></td>
<td></td>
</tr>
<tr>
<td>USEPA 1980 On-Site</td>
<td>167 (44)</td>
<td>155</td>
<td>88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ziebell, 1974</td>
<td></td>
<td>158</td>
<td>51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eastsound, WA, Bounds 1996</td>
<td></td>
<td>214</td>
<td>117</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loon Lake, WA, Bounds 1996</td>
<td></td>
<td>90</td>
<td>45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cagle, 1993, Placer, CA-(two)</td>
<td></td>
<td>160</td>
<td>73</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Average**                                   | **180 (48)**          | **156**     | **84**     | **17**        |    |

From Bounds, 1997
Fig. 2: Free water surface (FWS) constructed wetland

Fig. 3: Free Water Surface (FWS) Constructed Wetland
Adapted from Reference 1. No scale
Figure 3. Free water surface (FWS) constructed wetland cross section
Removal Mechanisms in Freewater Surface (FWS) Wetlands

Removal of Biochemical Oxygen Demand (BOD) and Total Suspended Solids (TSS)

Discrete and Flocculent Settling.
Gravity produced settling is categorized as discrete and flocculent, both of which are influenced by particle size, specific gravity, shape, and the viscosity of the fluid. Discrete particle settling means the particles settle independently without a change in size or shape. Flocculent settling results from the movement and collision of particles resulting in growth and change of shape of the particle. To be removed, it is necessary that a settling velocity of a particle be great enough to reach the bottom of the wetland before reaching the outlet zone. While it is clear that the removal of TSS and insoluble BOD by a FWS wetland is a reality, it is much too complex to be fully explained by discrete settling theory alone (US EPA, 2000).

Filtration/Interception
The stems from emergent plants are likely too far apart to effect entrapment and filtration of the particle sizes found in septic tank effluent (US EPA, 2000). It is possible; the plant surfaces in the water column which are coated with an active biofilm of periphyton may by interception and adhesion remove particulate matter.

Resuspension
The relatively quiescent conditions in FWS wetlands allow a large amount of sediment detritus to accumulate on the bottom among the root mats. Because water velocities in FWS wetlands are minimal, the resuspension of settled particles from bottom sediments is unlikely. On the other hand, oxygen generated by submerged plants, as well as nitrogen oxides and nitrogen gas from denitrification may enhance the resuspension of particulates (Kadlec, 1996).

Nitrogen Removal Mechanisms
The chemistry of nitrogen in wastewater is extremely complicated because it exists in so many oxidation states, which may be altered by the biochemical operations of microorganisms. In nature, nitrogen is cycled between organic and inorganic forms by the pathways shown in Figure 4. The nitrogen present in wastewater is in the organic form primarily as proteinacious matter and urea. After undergoing anaerobic decomposition biochemical operations in the septic tank, the nitrogen form is changed to ammonia, (NH$_3$) nitrogen gas by a process referred to as ammonification. As the aqueous form known as ammonium (NH$_4^+$) flows into the FWS it undergoes many alterations. In Zone 2 Open Water Surface Zone, if dissolved oxygen is present, the ammonium may be converted to nitrite (NO$_2^-$) and then to nitrate (NO$_3^-$) in a two-step process called nitrification.
Figure 4. The nitrogen cycle (Sawyer and McCarty, 1978)

The first step is conversion of the ammonium ion to nitrite by the bacteria genus nitrosomonas as follows:

$$\text{NH}_4^+ + 1.5 \text{O}_2 \rightarrow 2 \text{H}^+ + \text{H}_2\text{O} + \text{NO}_2^-$$

The second step is conversion of nitrite to nitrate by the bacteria genus nitrobactor as follows:

$$\text{NO}_2^- + 0.5 \text{O}_2 \rightarrow \text{NO}_3^-$$

The denitrification step which requires a carbon source takes place in the absence of oxygen and produces gases N$_2$ and N$_2$O. The loss of these gases to the atmosphere represents a removal of nitrogen from the wastewater.

The carbon source is from plant litter and natural detritus. The denitrification reaction takes place primarily in the wetland sediments and in the periphyton films on the submerged vegetation (US EPA, 2000). The nitrogen gas then may be fixed, that is converted to organic
nitrogen, by organisms in the water column, in the sediment, in the oxidized rhizosphere of the plants, and on the stem surfaces of submerged plants (US EPA, 2000). It is well to note that any nitrogen assimilation by plant uptake in the operation of FWS wetlands, if considered to be removed, must be harvested and carried away from the wetland. As such any attempt to utilize nutrient removal by harvesting and subsequent offsite disposal is unlikely to be worth the considerable time and labor involved. Thus, without sufficient area for aerobic and anaerobic zones in the FWS wetland, they cannot be counted upon for any nitrogen removal in the wastewater. It has been reported that when temperatures are favorable for nitrification in the intermediate open water zones, significant nitrogen removal rates > 50% may be possible. (Kreissl, 2002)

**Phosphorus Removal Mechanisms**

Phosphorus is one of the most important elements in the natural ecosystem, and occurs in wastewater primarily as phosphates. They typically are called orthophosphates and may be assimilated in soluble or particulate form (US EPA, 2000). Phosphorus is often the limiting nutrient in the eutrophication of fresh water systems. Basically, phosphate removal in a FWS wetland is by accretion on and burial in the bottom sediments (US EPA, 2000).

**Physical Chemical Separations**

Since phosphorus has no important gaseous form in the biogeochemical cycle, sedimentation is the primary mechanism for removal from the wastewater in the wetland (US EPA, 2000) (Crites and Tchobanoglous, 1998). Plant uptake of soluble phosphate by sorption onto plant biofilms is part of the process for their removal. At startup, there may be some sorption of negatively charged phosphate particles, to bottom soil liner particles (US EPA, 2000). This removal mechanism may be abnormally high at the outset, but will diminish and essentially disappear with time as sites on the absorbent surface become scarce (US EPA, 2000).

**Biological Transformation of Phosphates** (US EPA, 2000)

Both dissolved organic phosphate and insoluble organic phosphate are not usually available to plants unless transformed to a soluble form. Fortunately, microbes suspended in the water column of a FWS are able to transform these phosphates into a soluble inorganic form. Once available to the plants, phosphate uptake occurs during the growing season, but during plant senescence in the fall and winter, plant death is followed by its decomposition. Thus, the FWS wetland cannot be relied upon for phosphorus removal because the early plant uptake will be negated by the plants’ senescence.

**Sulfur Removal Mechanism**

Sulfur is an important component of all living matter, and the principal forms that are of special significance in water quality are organic sulfur, hydrogen sulfide ($\text{H}_2\text{S}$), elemental sulfur ($\text{S}$), and sulfate ($\text{SO}_4^{2-}$). In the sulfur cycle it is taken up by plants and microorganisms for the production of cell tissue, and in turn the microbes are consumed by animals. (Crites and Tchobanoglous, 1998) Sulfate reduction is an indicator of anaerobic conditions and sulfide oxidation is an indicator of aerobic conditions. In the absence of oxygen these anaerobic bacteria convert sulfate to sulfide and to hydrogen sulfide in accordance with the following equations:
\[ \text{SO}_4^{2-} + \text{organic compounds} \rightarrow \text{S}^2+ + \text{CO}_2 + \text{H}_2\text{O} \]

\[ \text{S}^2+ + 2 \text{H}^+ \rightarrow \text{H}_2\text{S} \]

The H$_2$S is a colorless gas with the characteristic odor of rotten eggs, and if aerobic conditions ever prevail, bacteria will oxidize the H$_2$S to sulfuric acid as shown:

\[ \text{H}_2\text{S} + 2 \text{O}_2 \rightarrow \text{H}_2\text{SO}_4 \]

The sulfuric acid is a strong acid and will corrode any concrete pipes, inlet or outlet works of the CWS. Also the oxidation of sulfide to sulfate consumes significant amounts of oxygen.

**Pathogen Removal**

It is always presumed that the septic tank effluent entering a FWS wetland will contain waterborne pathogens. Since it is very difficult and expensive to isolate and identify these organisms, it is common to test for indicator organisms. These indicator organisms are normal non-pathogenic inhabitants of the intestinal tract of warm blooded animals. Their presence in water may be presumptive, but not definite, evidence of the presence of pathogens. The most common indicators of fecal contamination are the coliform groups. Since these organisms are excreted in large numbers by warm-blooded animals residing in the wetlands, it is obvious the test is not specific and may produce false positive results for human contamination. Further, there are conflicting data whether the presence of fecal coliform organisms are reliable indicators of the presence of pathogenic bacteria, viruses, and protozoa (Crites and Tchobanoglous, 1998).

**Removal Mechanisms**

Intestinal organisms entering the FWS wetland, immediately find themselves in a very hostile environment. Thrust into lower temperature and lower substrate waters with intense predation, most will not survive for a long period of time. Some may be incorporated within TSS and be removed by sedimentation, interception, and sorption (US EPA, 2000). It has been found that there is a correlation between pathogen (indicators) and TSS removal (Crites, 1997). In addition, if the organisms are at or near the water surface, UV radiation will reduce their numbers significantly. Undoubtedly, all of the mechanisms taken collectively will significantly reduce the numbers of indicators of pathogenic organisms in FWS effluent, but it is unlikely that the effluent will consistently meet regulatory standards. Thus, the need for subsurface disposal of the effluent, or further disinfection if surface discharged.

**Metals**

Metals are required for plant and animal growth, but only in trace quantities, these include barium, baron, chromium, cobalt, copper, iodine, magnesium, manganese, molybdenum, nickel, selenium, sulfur, and zinc (US EPA, 2000). Metals known to be toxic at trace concentrations are arsenic, cadmium, lead, mercury, and silver (Gersberg et al., 1999). Normal domestic wastewater does contain a variety of heavy metals from household and personal products used in the home. However, their concentrations are not normally considered excessive.
Removal Mechanisms
In the unlikely event trace metals do gain entrance to wastewater entering the FWS, there are indications that the metals will be trapped and adsorbed on plant and debris surfaces and be effectively removed by sedimentation. (US EPA, 2000; Crites and Tchobanoglous, 1998). Any metals entering the FWS wetland as insoluble forms would likely be as suspended solids and would be removed similar to TSS. Limited data indicates metals removal efficiency correlates with TSS reduction (US EPA, 2000).

Synthetic Organics

Removal Mechanisms
Although normal household activities can produce significant concentrations of these compounds, their fate in both septic tanks and FWS systems is not well documented. Removal mechanisms will vary with the chemical characteristics of each compound introduced.

Performance
There are many design and site factors which may have an effect on the effluent quality of a FWS constructed wetland. The design variables include, total area, the number, size, and shape of cells, hydraulic retention time, vegetation types, and inlet and outlet devices (US EPA, 2000) (Gearhart, 1993). As expected the performance reveals a wide range of treatment capabilities. Table 2, depicts a summary of the removal treatment effectiveness for a number of water quality parameters. It is noteworthy that colloidal and particulate BOD are removed primarily by flocculation and sedimentation, but BOD can also be removed by aerobic oxidation in the open zone. (Kadlec and Knight, 1996) Because plants take up phosphorus in the growing season and release some during senescence, over a full season analysis it is possible there will be an apparent increase rather than a reduction. Indeed, as shown in Table 2, the total P increased from a mean of 1.39 to 2.42 mg/l. Since all forms of nitrogen in wastewater are biochemically interconvertible, any meaningful analysis of FWS wetland performance of nitrogen removal would require a mass balance analysis on the total number of nitrogen species. None the less as shown, the FWS wetland accomplished a 33% reduction on Total Kjeldahl nitrogen. Finally, that the FWS wetland is an unfavorable environment for intestinal organisms is shown in Table 2, by the 99% reduction in fecal coliforms. As previously mentioned, intestinal organisms require a rich and high temperature substrate, and most will be unable to compete and survive in the wetland, particularly if they happen to drift through a sun drenched open water column.
Table 2. Performance of (FWS) Constructed Wetland

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Influent (mg/L)</th>
<th>Effluent (mg/L)</th>
<th>Percent Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min  Mean  Max</td>
<td>Min  Mean  Max</td>
<td></td>
</tr>
<tr>
<td>BOD₅</td>
<td>6.2  113  438</td>
<td>5.8  22   70</td>
<td>81</td>
</tr>
<tr>
<td>TSS</td>
<td>12.7 112 587</td>
<td>5.3  20   39</td>
<td>82</td>
</tr>
<tr>
<td>NH₃-N</td>
<td>3.2  13.4 30</td>
<td>0.7  12   23</td>
<td>10</td>
</tr>
<tr>
<td>TKN</td>
<td>8.7  28.3 51</td>
<td>3.9  19   32</td>
<td>33</td>
</tr>
<tr>
<td>TP</td>
<td>0.56 1.39 2.41</td>
<td>0.68 2.42 3.60</td>
<td>+74</td>
</tr>
<tr>
<td>FC</td>
<td>42,000 73,000 250,000</td>
<td>112 403 713</td>
<td>99</td>
</tr>
</tbody>
</table>

BOD = Biochemical Oxygen Demand (5 day)  
TSS = Total Suspended Solids  
NH₃-N = Ammonia Nitrogen  
TKN = Total Kjeldahl Nitrogen  
TP = Total Phosphorus  
FC = Fecal Coliform, cfu/100mL

Adapted from US EPA, 2000

**Design Considerations**

It has been shown that FWS wetlands can reliably produce an advanced secondary effluent as well as potentially removing significant amounts of nitrogen. The effluent quality is excellent for a subsurface wastewater infiltration system (SWIS), but would need additional treatment, such as disinfection if used for direct surface discharge. The design considerations for an FWS design are shown in Table 3.

**Vegetated Submerged Bed (VSB) Constructed Wetlands**

Vegetated submerged Bed (VSB) constructed wetlands (formerly known as subsurface flow wetlands) consist of gravel and soil beds planted with wetland vegetation. They are designed to treat primary effluent up to secondary standards. As previously explained, the VSB has many of the same features of the FWS, but is distinguished by its subsurface hydraulic gradeline. A typical VSB has inlet and outlet structures to control the distribution of the wastewater with berms or concrete chambers to enclose the water in treatment cells. The contained wastewater undergoes physical, chemical, and biological processes while in contact with gravel/stone media,
and to a lesser extent plants, roots, and detritus. In contrast to the FWS wetland, the wastewater stays beneath the surface of the media, flows in contact with the roots and rhizomes of the plants and is invisible or unavailable to animals. However, it is again emphasized that the VSB described herein receives septic tank or primary sedimentation effluent, and treats it to secondary effluent standards as defined by BOD and TSS. This is in contrast to the natural polishing wetland which received secondary effluent and provides further treatment before the wastewater is discharged to the environment. A typical conventional VSB, as depicted in Figures 5 and 6, contains inlet piping, clay or synthetic membrane liner, filter media, planted vegetation berms, and outlet piping with water level control. (US EPA, 2000) They are generally low in cost and maintenance requirements, and by providing somewhat of a natural appearance, they have a certain aesthetic appeal. However, similar to the FWS, they require relatively large land areas, 4 to 25 acres per million gallons of wastewater per day. (US EPA, 2000) Thus, they may be especially well suited for small communities where inexpensive land and low cost media are readily available. (US EPA, 2000)

**Removal Mechanisms in Vegetated Submerged Bed (VSB) Constructed Wetlands**

**Removal of biochemical Oxygen Demand (BOD) and Total Suspended Solids (TSS)**

The primary removal mechanisms for BOD and TSS are flocculation, settling, and filtration. As the wastewater slowly flows horizontally through the VSB, it acts as a horizontal gravel filter, there by providing opportunities for TSS separation by sedimentation, physical straining and capture, and adsorption on biomass attached to the gravel and root system. (US EPA, 2000) Inevitably some material will accumulate in the interstices of the VSB and tend to clog, although recent findings indicate the trapped organic material will degrade over time. (Bavor et al., 1939, Fisher, 1990) Since it has been found that the dominant fraction of the wastewater flow occurs below the root system the role of root surfaces in TSS removal has yet to be proven (US EPA, 2000). At this time, the potential of VSB constructed wetlands systems for TSS and BOD removal is known, but removal of other parameters needs better definition through improved databases.

**Nitrogen Removal Mechanisms**

As previously stated, the nitrogen present in the incoming wastewater, as it enters the septic tank, will be primarily in the organic form from the proteinaceous matter and urea. After exiting the anaerobic septic tank a great majority (80-90%) of the nitrogen would be in the NH₄⁺ form. The continued anaerobic environment in the VSB will cause it to approach 100% NH₄⁺ by ammonification of any remaining organic nitrogen. Unfortunately, the lack of oxygen and carbon sources limits any reliable nitrogen removal by denitrification. In addition, as with the FWS wetland, any dependence on plant uptake of nitrogen for removal would require harvesting and would account for no more than 25% removal.
Table 3. Recommended Design Criteria for FWS Constructed Wetlands

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effluent Quality</td>
<td>BOD ≤ 20 or 30 mg/L</td>
</tr>
<tr>
<td>Pretreatment</td>
<td>Oxidation Ponds (lagoons)</td>
</tr>
<tr>
<td>Design Flows</td>
<td>$Q_{\text{max}}$ (maximum monthly flow) and $Q_{\text{ave}}$ (average flow)</td>
</tr>
</tbody>
</table>
| Maximum BOD Loading (to the entire system) to Meet: | 20 mg/L : 45 kg/ha-d
|                                  | 30 mg/L : 60 kg/ha-d                                                            |
| Maximum TSS Loading (to the entire system) to Meet: | 20 mg/L : 30 kg/ha-d
|                                  | 30 mg/L : 50 kg/ha-d                                                            |
| Water Depth                      | 0.6-0.9 m Fully vegetated zones<br>1.2-1.5 m Open-water zones<br>1.0 m Inlet settling zone (optional) |
| Minimum HRT (at $Q_{\text{max}}$) in Zone 1 (and 3) | 2 days fully vegetated |
| Maximum HRT (at $Q_{\text{ave}}$) in Zone 2 | 2-3 days open-water zone (climate dependent) |
| Minimum Number of Cells          | 3 in each train                                                                  |
| Minimum Number of Trains         | 2 (unless very small)                                                            |
| Basin Geometry (Aspect Ratio)    | Optimum 3:1 to 5:1, but subject to site limitations. AR > 10:1 may need to calculate backwater curves |
| Inlet Settling Zone Use          | Where pretreatment fails to retain settleable particulates                       |
| Inlet                            | Uniform distribution across cell inlet zone                                      |
| Outlet                           | Uniform collection across cell outlet zone                                       |
| Outlet Weir Loading              | ≤ 200 m$^3$/m-d                                                                  |
| Vegetation Emergent              | Typha or Scirpus (native species preferred)                                      |
| Submerged-Design Porosities      | Potamogeton, Elodea, etc                                                         |
|                                  | 0.65 for dense emergents in fully vegetated zones                               |
|                                  | 0.75 for less dense stand of emergents in same zones                             |
|                                  | 1.0 for open-water zones                                                         |
| Cell Hydraulics                   | Each cell should be completely drainable                                         |
| Flexible intercell piping to allow for required maintenance | Independent, single-function cells could maximize treatment |

From US EPA, 2000
Figure 5. Vegetated submerged bed (VSB) constructed wetland
Figure 6. Vegetated submerged bed (VSB) constructed wetland cross section
Phosphorous Removal Mechanisms

As explained previously, phosphorous is one of the most important elements in the natural ecosystem, and occurs in wastewater primarily as phosphates. Organic phosphates are formed primarily by biological processes and are found in raw sewage in fecal matter and food residues. Inorganic phosphorous compounds may also gain entrance to wastewater from household cleaning solutions.

Physical Chemical Separations.
Certainly in the early months sorption is the primary removal mechanism, but at a much lower rate throughout the performance of the VSB. For mature systems the P removal is low and happens through sedimentation and the mature lower level adsorption. Although, not very effective for long term phosphorous removal, the VSB media adsorption capacity does provide for minimal removal.

Biological Transformations.
Cycling of phosphorous in a VSB will produce seasonal results similar to those seen for FWS systems. Estimates of realistic long term phosphorous removal capacity by plant harvesting is very limited. (Kadlec and Knight, 1996) Finally, VSB systems should not be relied upon to remove P on a long term basis. (US EPA, 2000)

Pathogen Removal

As previously explained, it is always presumed the septic tank effluent, the influent to the VSB will contain water borne pathogens. However an advantage of the VSB over the FWS is that pathogen laden wastewaters are kept below the surface. Consequently, the potential for dermal contact is practically impossible unless there happened to be overflow or leakage from the inlet piping system.

Removal Mechanisms
Intestinal organisms entering a VSB wetland will immediately find themselves in a very hostile environment. Thus die off with time and predation are the primary mechanisms in microorganism removal. In addition, the coagulation and flocculation of suspended and colloidal particles, with the very high amount of surface area leads to adsorption and removal of the organisms by filtration. A two log reduction in fecal coliforms has been suggested as a reasonable estimate of VSB wetland performance. (US EPA, 2000).

Metals

Metals are required for plant and animal growth, but only in trace quantities. These include barium, baron, chromium, cobalt, copper, iodine, magnesium, manganese, molybdenum, nickel, selenium, sulfur, and zinc (US EPA, 2000). Metals known to be toxic at trace concentrations are arsenic, cadmium, lead, mercury, and silver (Gersberg et al., 1984). Fortunately, most normal household activities rarely involve the use of chemicals containing toxic metals, thus it is unlikely that the wastewater will contain such toxins.

Because many metals (Zn, Cr, Pb, Cd, Fe, Al) are associated with particles, a primary removal mechanism in a VSB wetland is particulate filtration (Heukelekian and Balmat, 1959; US EPA,
Secondly, if sulfide precipitation occurs due to reduction of sulfate to sulfide, some metals after being rendered insoluble will be removed (US EPA, 2000). Although small amounts of some metals may be taken up by the plants, any such removal should not be counted upon in the long term.

**Synthetic Organics**

**Removal Mechanisms**

Although normal household activities can produce significant concentrations of these compounds, their fate in both septic tanks and VSB systems is not well documented. Removal mechanisms will vary with the chemical characteristics of each compound introduced.

**Performance**

Vegetated submerged bed design factors differ from those for FWS systems. The primary design factors are retention time, pretreatment, media characteristics, and inlet and outlet designs. Some biological denitrification may occur if nitrates are present in the influent. Although plants may take up some of the nitrate, unless removed by harvesting the plants, it is insignificant and not worth considering. Phosphorous removal is minor and periodically positive and negative. As research has expanded, it has become increasingly clear, the impact of wetland plants on pollutant removal is minimal (US EPA, 2000). In fact, the selection of plant species should be based upon aesthetics, impacts on operation, and long-term plant health and survivability, rather than their capacity for pollutant removal (US EPA, 2000).

**Construction, Operation, and Maintenance**

To physically build constructed wetlands requires the same equipment and procedures as for other small decentralized wastewater treatment systems. However, there are aspects that are unique and need special attention, namely the establishment of the emergent vegetation and providing the necessary devices to ensure uniform flow through the wetland (US EPA, 2000).

**Containment Structures**

The structural and water tight integrity of berms, dikes, and bottom liners are absolutely essential. To prevent contamination of groundwater below the site, liner materials include 30 mil, polyvinyl chloride (PVC), polyethylene (PE) or high density polyethylene (HPE). Native clays may also be used if they achieve the necessary impermeability. Typically, the clay liner must be at least 0.3 m (1 ft) in thickness to provide an adequate hydraulic barrier (US EPA, 2000). In the FWS wetland, to prevent root penetration by emergent plants, the clay surface should be well compacted (US EPA, 2000). Exterior berms, dikes, and concrete walls should be designed to contain the liquid within the wetland. The side slopes should be a maximum of 3:1 with enough free board, usually around 0.6 to 1 m, to retain a local design rainfall event (US EPA, 2000). The width at the top of the berm should be large enough to permit access by maintenance vehicles. Since the interior berms are not used for water containment, the design considerations are much less stringent (US EPA, 2000). See Figure 7.
Figure 7. Examples of constructed wetland berms
From US EPA, 2000
Inlet and Outlet Devices

Inlet structures for both FWS and VSB vary, but they must provide uniform vertical and horizontal distribution of flow and be easily accessible for maintenance. See Figure 8. Outlet structures for both FWS and VSB systems must provide water level control, minimize short circuiting and be readily accessible for maintenance. See Figure 9. Several references describe these devices in detail, but for small (community/cluster/onsite) systems they are often slotted or perforated pipes. (Kreissl, 2002)

Media

In a FWS wetland, well loosened soils, such as sandy loam or loam gravel mix at least 150 mm (6 in) deep, should be placed on the bottom to protect the liner and provide plant footing (US EPA, 2000). Typically, the media for a VSB wetland should be gravel/rounded stone with diameters between 20-30 mm, and with coarser rock, 40-50 mm diameter adjacent to the inlet outlet structures. (US EPA, 2000)

Vegetation Establishment

It has been found that the role of vegetation is absolutely essential for the FWS wetland systems. (US EPA, 2000) The primary role of emerged vegetation is to provide structure for enhancing flocculation, sedimentation, and filtration of suspended solids. (US EPA, 2000) However, the role of plants in VSB is not clear. Initially it was thought their translocation of oxygen was a major source of oxygen to the microbes growing in the VSB media. (US EPA, 2000) Recent data have not confirmed this belief, nevertheless, planted VSB systems are more desirable aesthetically, and the plants do not hinder their performance. (US EPA, 2000) A wide variety of aquatic plants have been used in wetland systems with the emergent aquatic macrophyte species being most prominent, namely, cattails, reeds, rushes, bulrushes, and sedges. (Vassoe, 1999) When selecting plants, it is prudent to consider only native macrophytes that grow locally, to increase the likelihood of plant survival and to prevent a significant rise in construction costs. However, macrophytes selected should (a) be active vegetative colonizers with spreading rhizome systems, (b) have considerable biomass and stem densities, and (c) be a combination of species that will provide coverage over various water depths (Allen et al., 1990). In temperate climates seedlings or clumps may be planted just after dormancy has begun, but before the first third of the summer growing season has passed (Allen et al., 1990). Start up periods are necessary to allow the vegetation to become established and will vary with the planting density, season of the year and type of wetland (US EPA, 2000).
Figure 8. Examples of constructed wetlands inlet designs
From US EPA, 2000
Figure 9. Examples of outlet devices
From US EPA, 2000
Operation and Maintenance

Since constructed wetlands are “natural systems”, operation involves mostly passive measures and requires little operator intervention. (US EPA, 2000) However, when operator intervention is necessary it is usually for one of the following:

- Maintenance of flow uniformity, across the wetland is vital to achieve the expected treatment level. Significant changes in water level should be investigated. The inlet and outlet manifolds should be checked routinely, and any debris or slime should be removed.

- Management of vegetation is primarily intended to keep the desired plant communities in their proper place. This can be achieved through small infrequent changes in the water levels and by harvesting of plants where necessary.

- Problems with odorous compounds may occur, most likely from the inlet and outlet structures, where the gases might be stripped from wastewater by turbulence. (Kreissl, 2002) In some cases certain chemicals in the wastewater may volatize. This will require careful analysis and elimination of the source or by dilution through recycling the effluent. (Kreissl, 2002) However, since VSB systems provide treatment in filter media that are not exposed to the atmosphere, there seldom is a nuisance odor problem.

- Control of nuisance pests and insects. Some of the nuisances that may occur in a FWS wetland, include burrowing animals, dangerous reptiles, and mosquitos. (US EPA, 2000) Burrowing animals use the vegetation for food and nesting materials, which can seriously damage the vegetation system. Control measures include raising and lowering the operating water level, and live trapping, and if necessary elimination of the animal (US EPA, 2000). In southeastern states, dangerous reptiles are common, including the water moccasin snake and alligator (US EPA, 2000). Because it is difficult to control these animals, fencing and raised boardwalks are recommended, to minimize human contact. Operators in particular, should be made aware of the danger, and be trained to take proper preventative actions (US EPA, 2000). In a FWS wetland, mosquito control is vital and must be addressed without delay. Natural control measures include, seeding the open water zone with mosquito fish and dragon fly larvae, and erecting bat and bird houses for purple martins and swallows. (US EPA, 2000) Other strategies that have been used to control mosquito populations are application of chemical and biological larvicides. (Kadlec and Knight, 1996) VSBs have similar problems with burrowing animals (muskrats, beavers, etc.) breaching berms and dikes. (Kreissl, 2002) In addition unwanted reptiles may find their way into inlet and outlet structures. (Kreissl, 2002)

- Maintenance of berms and dikes. The routine maintenance of berms and dikes, requires mowing, erosion control, and inspection for damage from burrowing rodents. Periodic removal of trees may be necessary if allowed to reach maturity and shade the emergent vegetation.
Design Considerations

Before any decision is made to utilize the constructed wetlands alternative treatment of primary treated residential wastewater, there are many design factors and site specific variables that need to be considered. The site specific factors include topography, available land, soil, water table, climate temperature variation, evapotranspiration, precipitation, wastewater characteristics, flows, and expected wildlife. The design criteria are summarized in Table 3. While these criteria are specifically listed for FWS wetlands, in the opinion of the writers, they apply equally to VSB wetlands. Design examples have been set forth in reference (US EPA, 2000; Kadlec and Knight, 1996; Crites and Tchobanoglous, 1998). It should be apparent that the design and operational experience of wetlands are in their infancy, and that much additional research, data gathering and analysis, must be accomplished before the design of constructed wetlands may be considered scientific. A list of the common misconceptions are shown on the following page.
CONSTRUCTED WETLANDS – COMMON MISCONCEPTIONS

1) Wetland design is based upon well characterized published design equations.

*Not so:* Due to lack of data, designers have been forced to derive design parameters from limited and unreliable information.

2) Vegetated Submerged Bed (VSB) constructed wetlands have aerobic as well as anaerobic treatment zones.

*Not so:* The ability of emergent wetland plants to transfer oxygen to their roots has been over estimated. The amount of oxygen leaked from plant roots is insignificant compared to the oxygen demand of septic tank effluent.

3) Vegetated Submerged Bed (VSB) constructed wetlands can remove significant amounts of nitrogen.

*Not so:* Uptake of nitrogen by plants must be followed by harvesting and removal of plants from the wetland, which generally is not feasible. Also because anaerobic processes dominate in VSB’s and in the vegetated portions of the FWS, nitrification of ammonia is unlikely to occur.

4) Constructed wetlands can remove significant amounts of phosphorous.

*Not so:* Phosphorous removal is limited to seasonal uptake by plants, which is very minor compared to the phosphorous load in septic tank effluent and is negated during the plants senescence. Sorption to solids in the wastewater, soils, and plant detritus is temporary and of limited capacity.

From US EPA, 2000
Performance

A summary of the principal removal and transformation mechanisms in constructed wetlands are shown in Tables 4 and 5.

Table 4. Summary of Vegetated Submerged Bed Design Guidance

<table>
<thead>
<tr>
<th>Pretreatment</th>
<th>Recommendation for use after primary sedimentation (e.g. septic tank, Imhoff tank, primary clarifier) VSBs not recommended for use after ponds because of problems with algae</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface Area</strong></td>
<td>Based on desired effluent quality and areal loading rates as follows:</td>
</tr>
<tr>
<td>BOD</td>
<td>6 g/m$^2$-d (53.5 lb/ac-d) to attain 30 mg/L effluent</td>
</tr>
<tr>
<td>BOD</td>
<td>1.6 g/m$^2$-d (14.3 lb/ac-d) to attain 20 mg/L effluent</td>
</tr>
<tr>
<td>TSS</td>
<td>20 g/m$^2$-d (178 lb/ac-d) to attain 30 mg/L effluent</td>
</tr>
<tr>
<td>TKN</td>
<td>Use another treatment process in conjunction with VSB</td>
</tr>
<tr>
<td>TP</td>
<td>VSBs not recommended for phosphorus removal</td>
</tr>
<tr>
<td><strong>Depth</strong></td>
<td></td>
</tr>
<tr>
<td>Media (typical)</td>
<td>0.5 – 0.6 m (20 – 24 in.)</td>
</tr>
<tr>
<td>Water (typical)</td>
<td>0.4 – 0.5 m (16 – 20 in.)</td>
</tr>
<tr>
<td><strong>Length</strong></td>
<td>Minimum of 15 m (49 ft)</td>
</tr>
<tr>
<td><strong>Width</strong></td>
<td>Maximum of 61 m (200 ft)</td>
</tr>
<tr>
<td><strong>Bottom slope</strong></td>
<td>0.5 – 1%</td>
</tr>
<tr>
<td><strong>Top slope</strong></td>
<td>Level or nearly level</td>
</tr>
<tr>
<td><strong>Hydraulic Conductivity</strong></td>
<td></td>
</tr>
<tr>
<td>First 30% of length</td>
<td>1% of clean hydraulic conductivity K</td>
</tr>
<tr>
<td>Last 70% of length</td>
<td>10% of clean hydraulic conductivity K</td>
</tr>
<tr>
<td><strong>Media</strong></td>
<td>All media should be washed clean of fines and debris; more rounded media will generally have more void spaces; media should be resistant to crushing or breakage.</td>
</tr>
<tr>
<td>Inlet zone</td>
<td>40-80 mm (1.5 – 3.0 in)</td>
</tr>
<tr>
<td>Treatment zone</td>
<td>20-30 mm (3/4 – 1 in) [use clean hydraulic conductivity K = 100,000, if actual K not known]</td>
</tr>
<tr>
<td>Outlet zone</td>
<td>40-80 mm (1.5 – 3.0 in)</td>
</tr>
<tr>
<td>Planting media</td>
<td>5-20 mm (1/4 – 3/4 in)</td>
</tr>
<tr>
<td><strong>Miscellaneous</strong></td>
<td>Use at least 2 VSBs in parallel</td>
</tr>
<tr>
<td></td>
<td>Use adjustable inlet device with capability to balance flows</td>
</tr>
<tr>
<td></td>
<td>Use adjustable outlet control device with capability to flood and drain system</td>
</tr>
</tbody>
</table>
Adapted from US EPA, 2000

Table 5 – Summary of the principal Removal and Transformation mechanisms in constructed wetlands.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Free water system</th>
<th>Vegetated submerged bed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biodegradable organics</td>
<td>Bioconversion by aerobic facultative, and anaerobic bacteria on plant and debris surfaces of soluble BOD, adsorption, filtration, and sedimentation of particulate BOD</td>
<td>Bioconversion by facultative and anaerobic bacteria on plant and media surfaces</td>
</tr>
<tr>
<td>Suspended solids</td>
<td>Sedimentation, filtration</td>
<td>Filtration, sedimentation</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>Nitrification/denitrification, volatilization*</td>
<td>Nitrification/denitrification, volatilization</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>Sedimentation, soil sorption</td>
<td>Filtration, sedimentation, media sorption</td>
</tr>
<tr>
<td>Heavy Metals</td>
<td>Adsorption of plant and debris surfaces, sedimentation</td>
<td>Adsorption to media surfaces, sedimentation</td>
</tr>
<tr>
<td>Trace Organics</td>
<td>Volatilization, adsorption, biodegradation</td>
<td>Adsorption, biodegradation</td>
</tr>
<tr>
<td>Pathogens</td>
<td>Natural decay, predation, UV irradiation, sedimentation*</td>
<td>Natural decay, predation, sedimentation</td>
</tr>
</tbody>
</table>

Adapted from Crites and Tchobanoglous, 1998

*A properly designed FWS wetland with fortuitous conditions of sunlight, temperature, wind and wastewater strength may remove significant amounts of nitrogen and from 2 to 3 logs of coliforms (Kreissl, 2002)
Conclusions

It is becoming abundantly clear that the ability of constructed wetlands to remove nitrogen and phosphorous has been over-estimated. At the same time, their aesthetic appeal to the general public has tended to make them even more attractive in spite of their limitations. However, wetlands may be an appropriate technology for small communities where inexpensive land is available and skilled labor is scarce. There may be situations where it may be necessary for the designer to convince the public that wetlands are not a viable option, in spite of their inherent appeal (US EPA, 2000). Finally, it should be noted that the design process for constructed wetlands is still based upon empirical data, rather than scientific theories. (US EPA, 2000) However, there are a number of recent design approaches for establishing the size of wetlands and predicting their performance, which will be discussed in another section.
References


List of Figures

1. Wastewater Treatment Trains for Constructed Wetlands and Large Polishing Wetlands
2. Free Water Surface (FWS) Constructed Wetland
3. Free Water Surface (FWS) Constructed Wetland (Cross Section)
4. The Nitrogen Cycle
5. Vegetated Submerged Bed (VSB) Constructed Wetland
6. Vegetated Submerged Bed (VSB) Constructed Wetland (Cross Section)
7. Examples of Constructed Wetland Berms
8. Examples of Constructed Wetland Inlet Designs
9. Examples of Outlet Devices
List of Tables

1. Characteristics of Septic Tank Effluent (Unfiltered)
2. Performance of (FWS) Constructed Wetland
3. Recommended Design Criteria for FWS Constructed Wetlands
4. Summary of Vegetated Submerged Bed Design
5. Summary of the Principal Removal and Transformation Mechanisms in Constructed Wetlands