Key Words: **Wetlands**
Metal
Waste Water Treatment

Review of Constructed Subsurface Flow vs. Surface Flow Wetlands

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SRS
savannah river site
TM

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LIST OF ACRONYMS

BOD   Biochemical Oxygen Demand

CERCLA   Comprehensive Environmental Response Compensation and Liability Ac

cwt   Hundredweight, unit of weight equivalent to 100 pounds

ENR   Engineering News Record

ha   Hectare

MR   Monitor and Report

NPDES   National Pollution Discharge Elimination System

O&M   Operations and Maintenance

RCRA   Resource Conservation and Recovery Act

SF   Surface Flow

SRS   Savannah River Site

SSF   Subsurface Flow

su   Standard Units

TSS   Total Suspended Solids

EXECUTIVE SUMMARY

The purpose of this document is to utilize existing documentation to review the effectiveness of subsurface flow and surface flow constructed wetlands in treating wastewater and to demonstrate the viability of treating effluent from Savannah River Site outfalls H-02 and H-04 with a subsurface flow constructed wetland to lower copper, lead and zinc concentrations to within National Pollutant Discharge Elimination System (NPDES) Permit limits. Constructed treatment wetlands are engineered systems that have been designed and constructed to utilize the natural functions of wetlands for wastewater treatment. Constructed wetlands have significantly lower total lifetime costs and often lower capital costs than conventional treatment systems.

The two main types of constructed wetlands are surface flow and subsurface flow. In surface flow constructed wetlands, water flows above ground. Subsurface flow constructed wetlands are designed to keep the water level below the top of the rock or gravel media, thus minimizing human and ecological exposure. Subsurface flow wetlands demonstrate higher rates of contaminant removal per unit of land than surface flow (free water surface) wetlands, therefore subsurface flow wetlands can be smaller while achieving the same level of contaminant removal.

Wetlands remove metals using a variety of processes including filtration of solids, sorption onto organic matter, oxidation and hydrolysis, formation of carbonates, formation of insoluble sulfides, binding to iron and manganese oxides, reduction to immobile forms by bacterial activity, and uptake by plants and bacteria. Metal removal rates in both subsurface flow and surface flow wetlands can be high, but can vary greatly depending upon the influent concentrations and the mass loading rate. Removal rates of greater than 90% for copper, lead and zinc have been demonstrated in operating surface flow and subsurface flow wetlands.

The constituents that exceed NPDES limits at outfalls H-02 and H-04 are similar in nature and within typical concentrations found in municipal wastewaters, mine drainage and landfill leachate, all of which have been successfully treated in constructed wetlands. Contaminant-specific removal rates required to bring outfall H-02 and H-04 effluents to within NPDES limits have been achieved by various types of wetlands, including SSF wetlands. Therefore a constructed wetland would be a viable approach for treating effluent from the two outfalls.

SSF wetlands generally can be smaller than SF wetlands for a particular wastewater flow, but can cost more per acre. Thus the potential range of costs for constructing a SSF system may overlap with the cost range predicted for a SF system. However, capital costs and operations and maintenance costs for both SSF and SF wetland treatment systems are lower than for conventional wastewater treatment systems. Preliminary scoping level cost estimates for a SSF and a SF system for outfalls H-02 and H-04 are presented in this document using a range of values found in the literature.

INTRODUCTION

The purpose of this document is to utilize existing documentation to review the effectiveness of subsurface flow and surface flow constructed wetlands in treating wastewater and to demonstrate the viability of treating effluent from Savannah River Site (SRS) outfalls H-02 and H-04 to meet National Pollutant Discharge Elimination System (NPDES) Permit limits using a subsurface flow constructed

wetland.   Concentrations of copper, lead and zinc currently exceed the final limits specified in the NPDES Permit for one or both of these outfalls.

Wetland systems have always served as natural water treatment systems. During the past few decades people have seriously studied and utilized wetland systems for meeting wastewater treatment and water quality objectives in a controlled manner. The role of wetlands as a passive approach to improving water quality is a compelling argument for preserving natural wetlands and, in recent years, constructing wetlands systems for wastewater treatment.

Increasingly, studies have provided evidence that wetlands systems can effectively improve water quality while providing many benefits, including food and habitat for wildlife. However, there are concerns over potential harmful effects from toxic constituents and pathogens in many wastewater sources. Also, there are concerns that using natural wetlands for wastewater treatment may result in long-term degradation of the wetlands due to the added nutrients and altered hydrologic conditions of these systems. These potential benefits and concerns have promoted a growing interest in the use of constructed wetlands for wastewater treatment (USEPA 1993c).

Constructed treatment wetlands are engineered systems that have been designed and constructed to utilize the natural functions of wetland vegetation, soils, and their microbial populations to treat contaminants in surface water, groundwater, or waste streams (ITRC 2003, USEPA 1993c). Constructed wetlands can be considered treatment systems that use natural processes to stabilize, sequester, accumulate, degrade, metabolize, and/or mineralize contaminants. Although constructed wetland applications were limited to treating primarily storm water and municipal wastewaters, they are now being used in new applications and on new contaminants. Constructed wetlands are proving to be a valid treatment option for acid mine drainage, hazardous waste site wastewaters, petroleum refinery wastes, compost and landfill leachates, agricultural wastes and pretreated industrial wastewaters, such as those from pulp and paper mills and textile mills (ITRC 2003, USDA 1995). The technology is now mature and tested.

Constructed wetland treatment systems use rooted wetland plants and shallow, flooded or saturated soil to provide wastewater treatment. Constructed wetlands are designed to take advantage of the chemical and biological processes of natural wetlands to remove contaminants from the wastewater (Skousen 2004). Wetlands possess a rich microbial population in the sediment to bring about the biochemical transformation of pollutants, are biologically productive, and are self-sustaining. Constructed wetlands also have significantly lower total lifetime costs and often lower capital costs than conventional treatment systems (ITRC 2003). Compared to conventional systems, natural systems can be operated using less electricity and less labor (USEPA 1988).

Additionally, constructed wetlands:
- tolerate fluctuations in flow and pollutant concentrations,
- provide flood protection,
- can be built to fit into the landscape,
- provide habitats for plants and wildlife,
- enhance aesthetics of open spaces,
- provide recreational and educational opportunities, and
- are an "environmentally sensitive" approach viewed favorably by the general public and regulatory agencies (ITRC 2003)

Because the wetland constructed for the A-01 outfall has successfully brought the outfall into compliance with the NPDES permit limits, wetland treatment can be considered a potential option for other outfalls at

SRS. Constructed wetland treatment is being considered as an appropriate passive treatment of effluent at outfalls H-02 and H-04.

OUTFALL H-02 AND H-04 NEEDS

Outfall Characterization

The H-02 outfall receives non-process cooling water, steam condensate, and storm water runoff from storm drains and roof drains associated with the Replacement Tritium Facility. The H-02 outfall has a long-term average flow of 0.12 million gallons per day (mgd) (450 m^3/d) and a maximum daily flow of 2.13 mgd (8,060 m^3/d). The discharge from H-02 flows for approximately 200 meters before entering the headwaters of Crouch Branch. Crouch Branch, a tributary of Upper Three Runs, enters Upper Three Runs approximately 0.9 miles (1.5 km) downstream from Road F. Biological and chemical analyses conducted in Crouch Branch indicate that the stream ecosystem is impaired due to heavy metals (primarily copper) (Specht 2004). See Figure 1 for a map of the area.
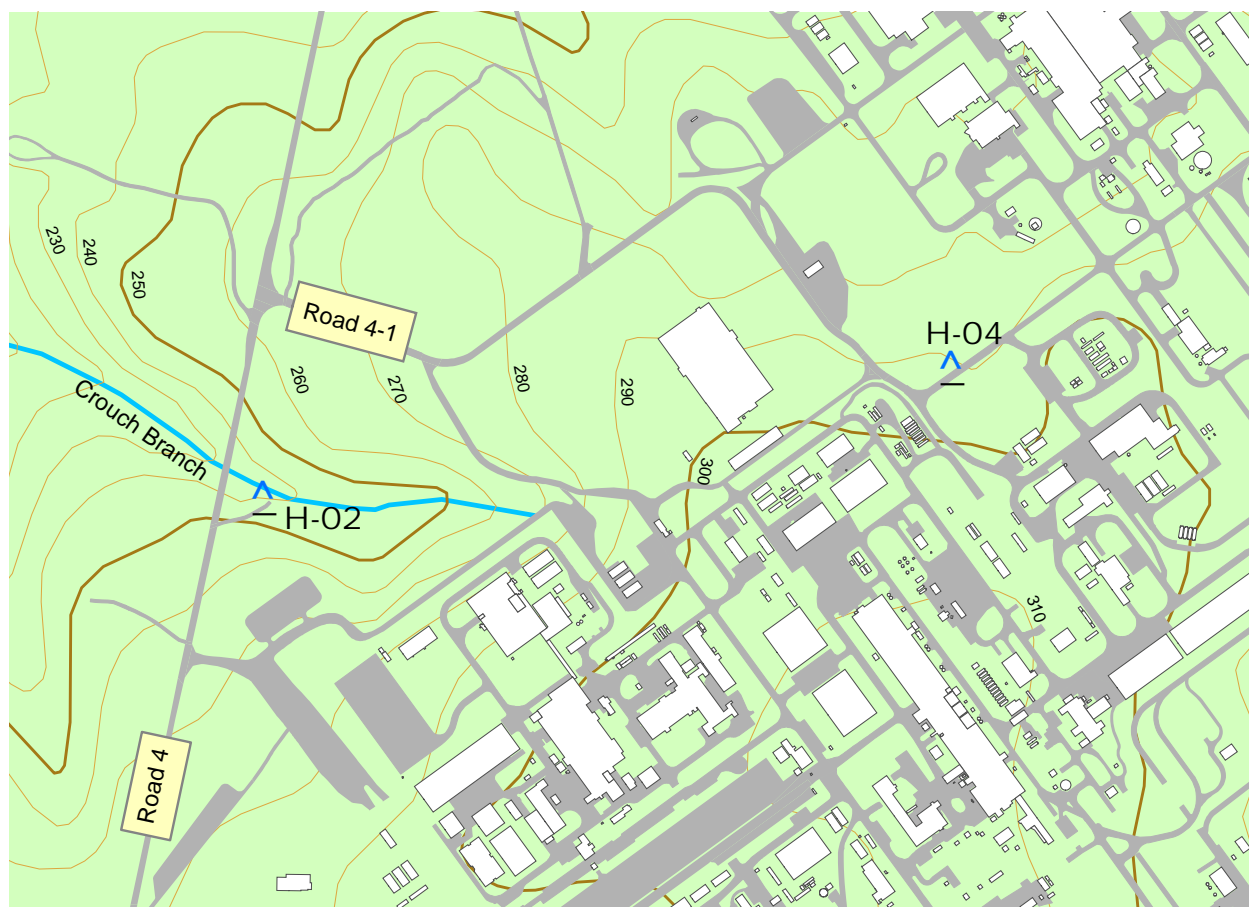
   Figure 1.   Location of Outfalls H-02 and H-04

The H-04 outfall receives nonprocess cooling water from the H Canyon, Canyon auxiliary steam condensate and storm water runoff. The H-04 outfall has a long-term average flow of 0.01 mgd (40 m^3/d)

and a maximum daily flow of 0.2 mgd (800 m^3/d). The discharge from H-04 flows 410 m in an open ditch to an unnamed tributary of Crouch Branch (Specht 2004). See Figure 1 for a map of the area.

Flow and monitored pollutant concentrations for the two outfalls are shown in Table 1. Results of metals, anions and other analyses on samples collected at outfall H-02 in June are shown in Table 2.

The NPDES permit conditions for the H-02 outfall specify Interim Limits (Table 3), which are in effect until October 31, 2008 and Final Limits (Table 4), which are in effect from November 1, 2008 through the expiration date of the NPDES permit. The NPDES permit conditions for the H-04 outfall specify Interim Limits (Table 3), which are in effect until November 30, 2006 and Final Limits (Table 4), which are in effect from December 1, 2006 through the expiration date of the NPDES permit.

Table 1. General Characterization of the Outfalls H-02 and H-04

Outfall	Wastewater Stream Flow Rates, Average (Maximum)	Pollutant Concentrations, Mean (Range)					
		pH	TSS	Cu	Pb	Zn	Hg
			mg/l	µg/l	µg/l	µg/l	µg/l
H-02	0.12 (2.13)[a] mgd 450 (8,060) m^3/d	7.2 (6.7-7.6)[b]	2 (<1-5)[b]	30.7 (15-87)[a]	3.7 (<2-12)[a]	109 (18-230)[a]	0.011 (0.010-0.012)[b, c]
H-04	0.01 (0.2)[a] mgd 40 (800) m^3/d	6.8 (6.1-8)[b]	<1[b]	Not sampled	23.8 (9-61)[a]	236 (61-799)[a]	0.004 (0.002-0.005)[b, c]

Sources: a Specht 2004
          b Discharge Monitoring Report data for January 2003 - April 2004.
          c Based on only two data points

Table 2. Results of June Sampling at Outfall H-02

Constituent, units	</>	Result	Constituent, units	</>	Result
Conductivity		66	Ca, µg/l		1475
pH		7.12	Cr, µg/l		2.095
NH4, mg/l	<	0.5	Mn, µg/l		39.09
NO3, mg/l		0.9	Co, µg/l		0.526
NO2, mg/l	<	1.0	Ni, µg/l		1.979
Cl, mg/l	<	1.0	Cu, µg/l		39.19
PO4, mg/l		1.8	Zn, µg/l		127.1
SO4, mg/l		1.7	As, µg/l		0.659
Fe, µg/l		499.9	Sr, µg/l		7.726
Li, µg/l		1.629	Mo, µg/l		0.801
Be, µg/l		0.102	Ag, µg/l		0.001
B, µg/l		8.101	Cd, µg/l		0.580
Na, µg/l		8832	Sb, µg/l		0.312
Mg, µg/l		396.8	Ba, µg/l		10.03
Al, µg/l		970.1	Au, µg/l		-7.073
P, µg/l		378.5	Pb, µg/l		4.921
K, µg/l		1160			

Table 3. Interim NPDES Limits for Outfalls H-02 and H-04

	Concentration	
Parameter	**Monthly Average**	**Daily Maximum**
Outfall H-02		
Flow	MR mgd	MR mgd
pH (su)		4.8 to 8.5
Copper, total (mg/l)	MR	MR
Lead, total (mg/l)	MR	MR
Mercury, total (µg/l)	MR	MR
Zinc, total (mg/l)	MR	MR
Outfall H-04		
Flow	MR mgd	MR mgd
pH (su)		4.8 to 8.5
Lead, total (mg/l)	MR	MR
Mercury, total (µg/l)	MR	MR
Zinc, total (mg/l)	-	MR
TSS (mg/l)	20	40

MR - Monitor and Report

Table 4. Final NPDES Limits for Outfalls H-02 and H-04

	Concentration	
Parameter	**Monthly Average**	**Daily Maximum**
Outfall H-02		
Flow	MR mgd	MR mgd
pH (su)		4.8 to 8.5
Copper, total (mg/l)	0.007	0.009
Lead, total (mg/l)	0.001	0.02
Mercury, total (µg/l)	0.051	0.07
Zinc, total (mg/l)		0.10
Outfall H-04		
Flow	MR mgd	MR mgd
pH (su)		4.8 to 8.5
Lead, total (mg/l)	0.00083	0.02
Mercury, total (µg/l)	0.051	0.07
Zinc, total (mg/l)	-	0.10
TSS (mg/l)	20	40

MR - Monitor and Report

Treatment objectives

Constituents exceeding NPDES permit limits must be reduced to within those NPDES permit limits. Based on recent data, the concentrations of copper, lead and zinc in the H-02 effluent (Table 1) all exceed the Final Limits specified in the NPDES Permit (Table 4). In the H-04 effluent, the mean concentrations of lead and zinc (Table 1) exceed the Final Limits specified in the NPDES Permit (Table 4). Constituents above the NPDES limit and the required removal rates to meet the NPDES limits are shown in Table 5.

Table 5. Constituents Above NPDES Limits and Required Removal Rates

Constituent	NPDES Limit	Existing Concentration	Removal Rate Required
H-02			
Copper, total	7 µg/l avg.	30.7 µg/l avg.	77%
	9 µg/l max.	87 µg/l max.	90%
Lead, total	1 µg/l avg.	3.7 µg/l avg.	73%
	20 µg/l max.	12 µg/l max.	0%
Zinc, total	100 µg/l max.	230 µg/l max.	57%
H-04			
Lead, total	0.83 µg/l avg.	23.8 µg/l avg.	97%
	20 µg/l max.	61 µg/l max.	67%
Zinc, total	100 µg/l max.	799 µg/l max.	87%

TREATMENT WETLAND SYSTEM DESCRIPTION

General Information

Constructed wetlands can treat contaminants such as total suspended solids (TSS), biochemical oxygen demand (BOD), nutrients (nitrogen and phosphorus), organic compounds, and inorganic constituents (such as metals) to meet regulatory targets. The two main types of constructed wetlands are surface flow (SF) and subsurface flow (SSF). A SF wetland typically consists of a basin or channels with a barrier layer to prevent seepage, soil to support rooted vegetation, and relatively shallow water flowing through the system. The water flows primarily horizontally and above ground. The SRS A-01 constructed wetland is a good example of a SF wetland. The SSF wetland also consists of a basin or channel with a seepage barrier, but the bed is filled with porous media, such as rock and gravel. The media supports the vegetation root structure. SSF wetlands are designed to keep the water level below the top of the rock or gravel media. The flow path through the operational SSF systems in the U.S. is usually horizontal, but may be vertical (USEPA 1993b).

There are more than twice as many SF systems in the United States than SSF systems. In Europe SSF systems outnumber SF systems. In general, SF wetlands require more land to achieve the same pollution reduction as SSF wetlands, but are easier and cheaper to design and build (USEPA 1993a, ITRC 2003).

Constructed wetlands have many advantages compared to conventional treatment techniques. They:
- have significantly lower total lifetime costs and often lower capital costs than conventional treatment systems.
- tolerate fluctuations in flow and pollutant concentrations,
- are capable of treating multiple or mixed contaminants,
- provide flood protection,

- have lower air and water emissions and secondary wastes,
- can be built to fit into the landscape,
- provide habitat for plants and wildlife,
- provide recreational and educational opportunities, and
- are environmentally friendly and are viewed favorably by the general public and regulators (USDA 1995, ITRC 2003).

There are some limitations to the use of constructed wetlands in treating wastewater:

- They generally require larger land areas than conventional wastewater treatment systems, so adequate land must be available.
- They may be relatively slow to provide treatment compared to more conventional treatment technologies.
- Performance may be less consistent than in conventional treatment; constructed wetlands depend on climate and, thus, may have reduced efficiencies during colder seasons.
- Surges in flow or pollutants may temporarily reduce treatment effectiveness.
- They require a base flow of water; they can tolerate temporary water level drawdowns, but not complete drying.
- They may provide breeding grounds for mosquitoes and other pests, though proper design can reduce this problem.
- Anaerobic conditions might produce disagreeable odors associated with natural biological functions, though proper design can reduce this problem.
- Long-term maintenance may be required.
- The biological components are sensitive to toxic chemicals.
- Contaminant accumulation must be monitored to maintain ecological health of the system (USDA 1995, ITRC 2003).

SF and SSF wetlands are discussed further below. Advantages and disadvantages or each are shown in Table 6.

Surface-flow (SF) wetlands

SF wetlands consist of shallow basins partially filled with soil, peat or any other media that will support plant roots. SF wetlands generally have a soil bottom, emergent vegetation, and a water surface above the substrate (Figure 2). The design may or may not include areas of open water in addition to the vegetated areas. SF wetlands are sometimes called free water surface wetlands or aerobic wetlands. The water moves slowly through the wetland above the substrate. The near-surface layer of water is aerobic while the deeper waters and the substrate are usually anaerobic (USDA 1995, ITRC 2003). The vegetation is usually cattails, reeds, sedges, and rushes (Hurtado 2004). Plants in these SF systems can tolerate continuously saturated soil conditions and the resulting anaerobic soils (USDA 1995, ITRC 2003). Figure 3 shows the elements of a SSF wetland system.

SF wetlands are densely vegetated and typically have water depths less than 1.3 ft (0.4 m) (Kadlec and Knight 1996). Typical hydraulic loading rates are between 0.3 and 2 in/day (0.7 and 5.0 cm/day), which corresponds to a wetland of 18.7 to 131 acres per mgd of flow (2 to 14 ha per 1000 m^3/day of flow) (Kadlec and Knight 1996). Typical flow depths for SF systems are 0.3 to 2.0 ft (0.09 to 0.6 m) (Tchobanoglous and Burton 1991).

Table 6. Advantages and Disadvantages of Surface Flow and Subsurface Flow Wetlands

Surface Flow Wetland	
Advantages	Disadvantages
Less expensive to construct (on a cost per acre basis) and operate and simpler to design than SSF wetlands and conventional treatment methods.	Lower rates of contaminant removal per unit of land than SSF wetlands, thus they require more land to achieve a particular level of treatment than SSF wetlands.
Can be used for higher suspended solids wastewaters.	Requires more land than conventional treatment methods.
More operating data in the United States than for SSF wetlands.	Risk of ecological or human exposure to surface-flowing wastewater.
Offer greater flow control than SSF wetlands	May be slower to provide treatment than conventional treatment
Offer more diverse wildlife habitat.	Odors and insects may be a problem due to the free water surface.
Provides habitat for plants and wildlife.	
Subsurface Flow Wetland	
Advantages	Disadvantages
Higher rates of contaminant removal per unit of land than SF wetlands, thus they require less land to achieve a particular level of treatment than SF wetlands.	Requires more land than conventional treatment methods.
Lower total lifetime costs and capital costs than conventional treatment systems.	May be slower to provide treatment than conventional treatment
Less expensive to operate than SF systems.	More expensive to construct than SF wetlands on a cost per acre basis.
Minimal ecological risk due to absence of an exposure pathway.	Waters containing high suspended solids may cause plugging.
More accessible for maintenance because there is no standing water.	
Odors and insects not a problem because the water level is below the media surface.	
Provides habitat for plants and wildlife.	
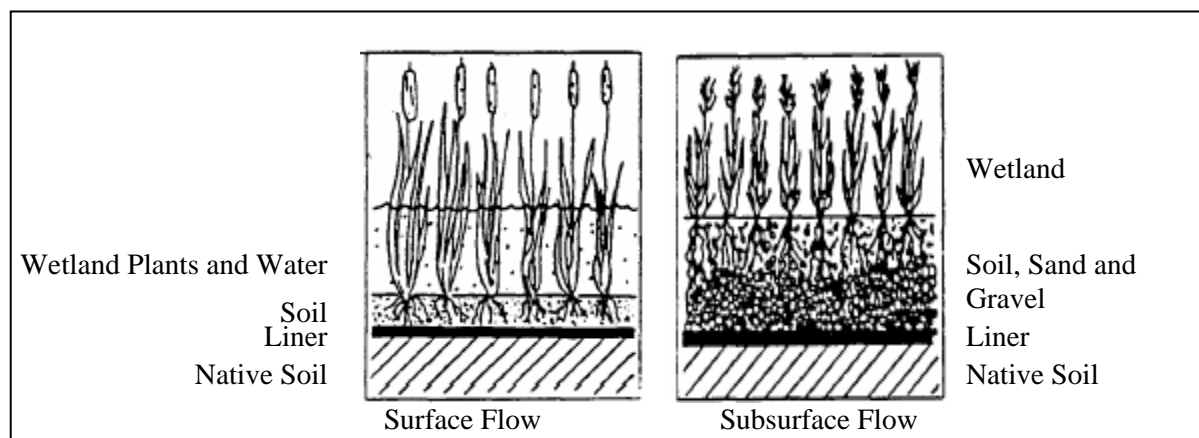
Source: USDA 1995

Figure 2. Surface Flow vs. Subsurface Flow Constructed Wetland
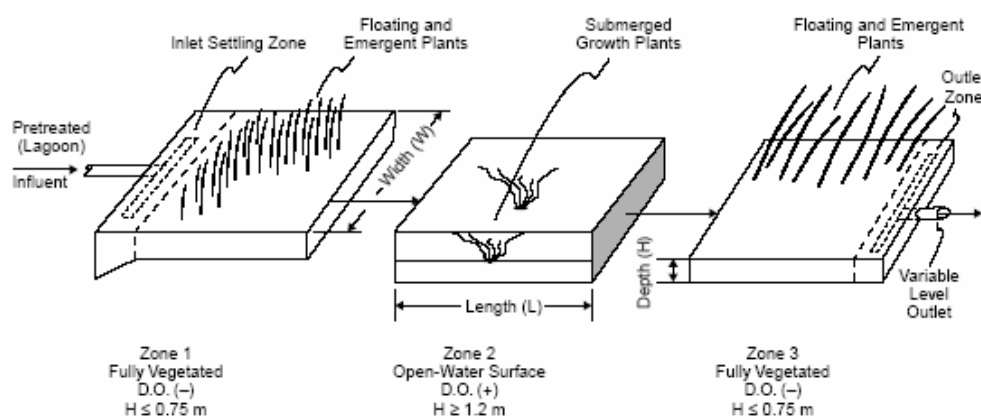
Source: USEPA 2000a

Figure 3. Elements of a SF Wetland System

SF wetlands are generally cheaper to construct (on a cost per acre basis) and are simpler to design than SSF wetlands. They are easy to construct, operate and maintain. They also provide more diverse wildlife habitat due to areas of free water surface. SF wetlands offer greater flow control than SSF wetlands (USDA, 1995, ITRC 2003). The main disadvantage of SF systems is that they generally require more land than SSF systems (Lorion 2001, USDA 1995).

For wastewaters containing contaminant metals, SF wetlands are generally used to collect water, provide aeration, and retain the water long enough that metals in the water can precipitate. The extensive water surface and slow flow in SF wetlands foster metal oxidation and hydrolysis. The compounds precipitate and are retained in the wetlands. The extent of metal removal depends on dissolved metal concentrations, dissolved oxygen content, pH, retention time of the water in the wetland and other factors. For metals removal, SF wetlands are best used with water that contains net alkalinity to neutralize metal acidity and allow metals precipitation to continue (Skousen 2004).

Subsurface-flow wetlands (SSF)

SSF wetlands are generally constructed with a porous material (e.g. soil, sand, or gravel) as a substrate for growth of rooted wetland plants (Figure 2) in addition to various microbes. SSF wetlands are also known as reed beds, rock-reed filters, gravel beds, and vegetated submerged beds (USDA 1995, ITRC 2003). They can also be known as anaerobic wetlands (Skousen 2004). SSF wetlands are designed so that water flows horizontally or vertically through the substrate and below the ground surface (USDA 1995, ITRC 2003). Distinct aerobic and anaerobic treatment zones become established, which improves wastewater treatment (Dusel and Pawlewski 2004). The emergent vegetation, mostly bulrush, reeds, and sometimes cattails, supplies oxygen to the substrate and allows biological growth to accumulate on its roots (Hurtado 2004). Bacteria and beneficial fungi live in the substrate as biofilm attached to the substrate particles (ITRC 2003). Flow is maintained by either a sloping bottom and/or an adjustable outlet structure which allows the water level to be lowered at the end of the bed, producing the pressure head required to overcome flow resistance through the substrate media. An adjustable outlet provides greater flexibility and control and is the recommended method (USEPA 1993b). Figure 4 shows the elements of a SSF wetland system. Figure 5 shows a typical cross section of a SSF wetland cell.

Bed depth for SSF wetlands is generally less than 2 ft (0.6 m) (Kadlec and Knight 1996). Typical flow depths vary from 1.6 to 2.6 ft (0.49 to 0.79 m) (Cooper et al. 1998). Typical hydraulic loading rates are between 0.8 - 8 in/day (2 and 20 cm/day), which corresponds to a wetland of 4.7 to 47 acres per mgd of flow (0.5 to 5 ha per 1000 m^3/day of flow) (Kadlec and Knight 1996).

SSF wetlands can be classified into two basic flow systems: horizontal flow and vertical flow. Horizontal flow systems are more common, therefore more operations data exist for horizontal flow wetlands than for vertical flow systems. Horizontal and vertical flow systems have similar contaminant removal mechanisms, but different hydraulics. In horizontal subsurface flow wetlands, the wastewater flows only through the substrate. SSF wetlands should have no continuous free surface water or the flow will short-circuit, moving quickly across the surface of the wetland and resulting in incomplete treatment. Vertical systems are constructed so that water moves uniformly down or up through the substrate. Water is generally ponded on the surface to help maintain anaerobic conditions in the substrate and to provide hydraulic head to encourage flow. Vertical flow systems are more common in mining applications. Some vertical flow systems combine an organic substrate with the inorganic permeable media (ITRC 2003).

SSF wetlands support metal oxidation and hydrolysis in aerobic surface layers and chemical and microbial reduction reactions in the subsurface layers to precipitate metals. The water infiltrates through the subsurface sediment, becoming anaerobic due to high biological oxygen demand. Several treatment mechanisms are enhanced in the anaerobic conditions, including formation and precipitation of metal sulfides and metal exchange and complexation reactions (Skousen 2004).

The SSF type of wetland is thought to have several advantages over the SF type. SSF wetlands demonstrate higher rates of contaminant removal per unit of land than SF wetlands (Lorion 2001, USDA 1995). The substrate provides more surface area for bacterial biofilm growth than a SF wetland, resulting in increased treatment effectiveness, which may translate to a smaller wetland (USDA 1995, ITRC 2003, USEPA 2000b). If the water surface is maintained below the media surface there is little risk of odors, lack of mosquitoes and other insect vectors, and minimal risk of public or animal exposure or contact with the water, (USEPA 1993b, Lorion 2001). In several locations, SSF wetlands are operating in parks (USDA 1995). Many industrial waste streams containing hazardous substances can be treated in SSF wetlands with minimal ecological risk due to absence of an exposure pathway. SSF wetlands are better suited for cold weather operation than the SF wetlands because they are more insulated by the earth and accumulated plant debris on the surface of the SSF bed (Lorion 2001, ITRC 2003). Also, SSF wetlands are more accessible for maintenance because there is no standing water (ITRC 2003). However, SSF

wetlands are best suited to wastewaters with relatively low solids concentrations to prevent clogging of the substrate (USDA 1995).

Hundreds of horizontal SSF wetlands operate dependably in Europe. SSF systems are preferred for their simple technology and reliable operating conditions (Kuschk et al. 2003). About 40 percent of the operational SSF systems in the U.S. use only bulrushes (*Scirpus*) for vegetation. Common reed (*Phragmites*) is widely used in European systems (USEPA 1993b, USDA 1995). A number of systems in the Gulf States have used flowering plants for aesthetic reasons (USEPA 1993b).
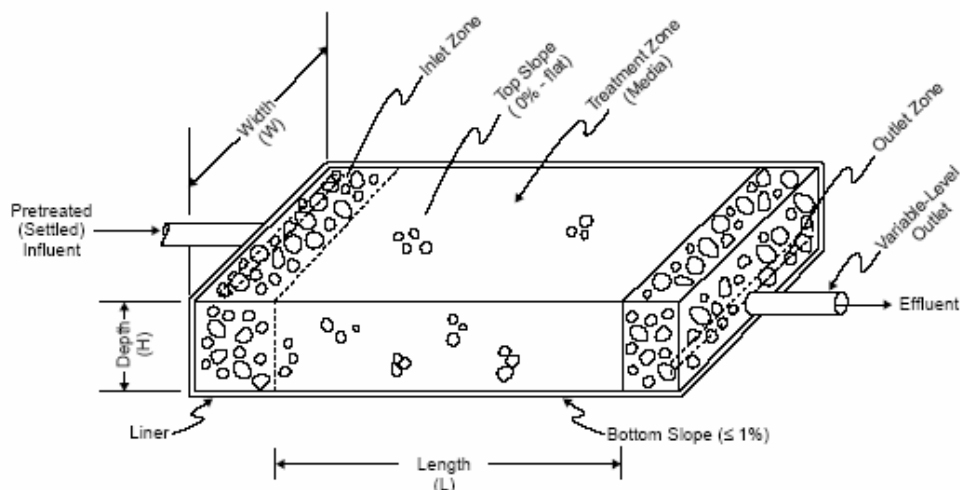
Source: USEPA 2000a

Figure 4. Elements of a SSF Wetland System
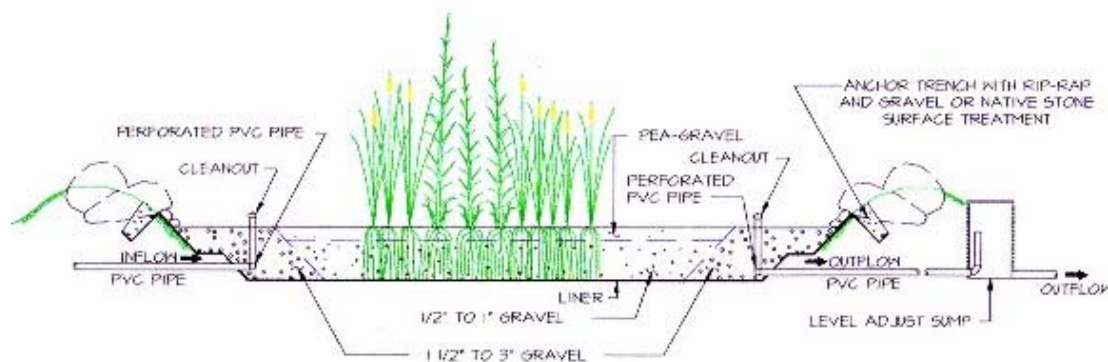
Source: NAHB 2004

Figure 5. Typical Cross-Section of a SSF Wetland Cell

TREATMENT MECHANISMS AND PERFORMANCE

Heavy metals are common environmental pollutants. Metal contamination of soils and waters has a severe impact on the environment and human health. Industrial and mining wastes are major sources of heavy metal environmental pollution (ITRC 2003). Heavy metals also can be found in municipal

wastewater, even in the absence of major industrial input. The treatment goal is to remove the metals from the larger environment and from the food chain, especially in rivers and oceans. Constructed wetlands can accomplish the same level of removal at lower labor and energy costs than conventional wastewater treatment processes (USEPA 1988).

General Removal Mechanisms

A wetland is composed of water, substrate, plants, plant litter, invertebrates (mostly insect larvae and worms), and microorganisms (most importantly bacteria). Processes controlling contaminant retention in a constructed wetland sediment may be abiotic (physical and chemical) or biotic (microbial and phytological (i.e. botanical)) and are often interrelated (USDA 1995 and ITRC 2003).

The primary abiotic processes that are responsible for removing wastewater contaminants in a constructed wetland include the following:
- settling & sedimentation - which achieve efficient removal of particulate matter and suspended solids
- sorption - including adsorption and absorption, the chemical process occurring on the surfaces of plants, substrate, sediment, and litter that results in short-term retention or long-term immobilization of contaminants
- chemical oxidation/reduction/precipitation - conversion of metals in the influent stream, through contact of the water with the substrate and litter, to an insoluble solid form that settles out, an effective means for immobilizing toxic metals in the wetland
- photodegradation/oxidation - degradation/oxidation of compounds in the presence of sunlight
- volatilization - which occurs when compounds with significant vapor pressures partition to the gaseous state (USDA 1995, ITRC 2003).

Biotic processes like biodegradation and plant uptake are also responsible for contaminant removal, in addition to the abiotic processes. Some microbial and phytological processes taking place in a wetland are given below:
- aerobic/anaerobic biodegradation - metabolic processes of microorganisms, which play a significant role in removing organic compounds in wetlands
- phytoaccumulation - uptake and accumulation of inorganic elements in plants
- phytostabilization - the ability to sequester inorganic compounds in plant roots
- phytodegradation - plant-produced enzymes break down the organic and inorganic contaminants that enter into the plant during transpiration
- rhizodegradation - plants provide exudates that enhance microbial degradation of organic compounds
- phytovolatilization/evapotranspiration - uptake and transpiration of volatile compounds through the leaves (ITRC 2003).

Some of these processes that can treat inorganic pollutants, such as metals, are shown in Figure 6.

The pollutant-transforming chemical reactions generally occur in the wetland water, detritus, and rooted soil zones as a result of the diverse microbial populations and high microbial activity that occurs in these layers. Flowing water contacts the microbes attached to the submerged substrate, providing opportunity for the microbes to remove the contaminants and use them as a nutrient source (ITRC 2003). In the case of SF wetlands these substrates are the submerged parts of the vegetation, the plant litter, and the benthic soil layer. In SSF wetlands the submerged substrate includes the plant roots and the surfaces of the media (gravel and soil) themselves. Because the media surface area in a SSF wetland exceeds the available substrate in a SF wetland, the microbial reaction rates in a SSF wetland can be higher for most

contaminants. Thus a SSF wetland can be smaller than a SF wetland for the same flow rate (USEPA 2000b).

The transition from aerobic to anaerobic zones in the detritus, sediment, and soil layers promotes microbial diversity. Both zones support a unique and diverse community of microorganisms. Plants and microbes have a complex symbiotic relationship, often benefiting each other by exchanging nutrients or exudates or by other mechanisms (ITRC 2003).
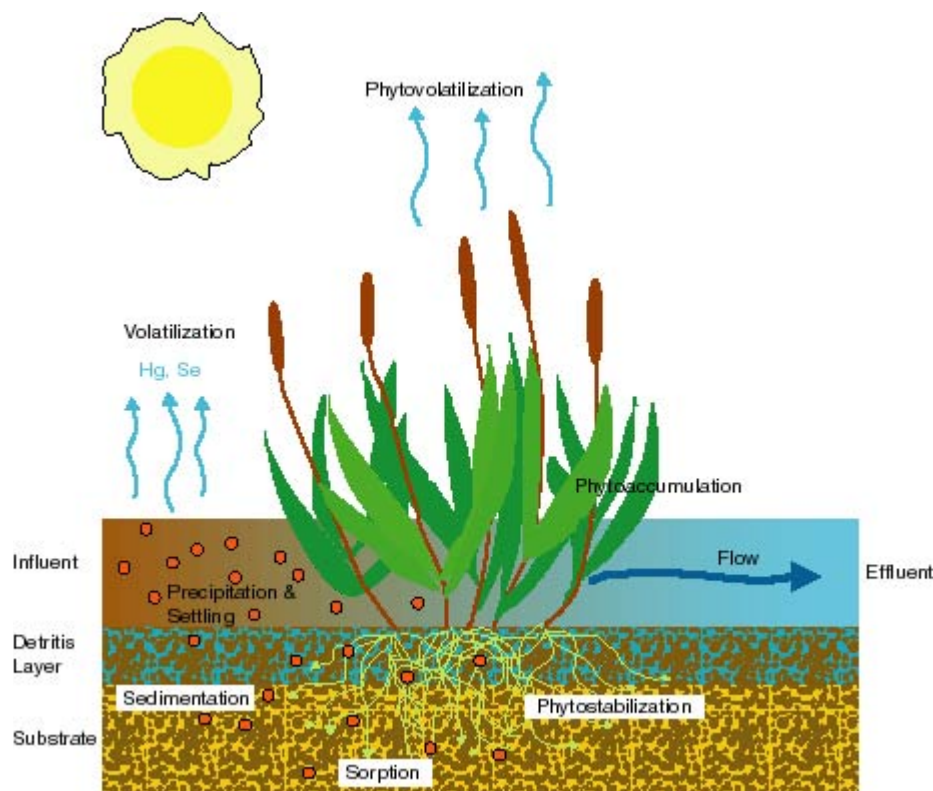
Adapted from ITRC 2003

Figure 6.   Mechanisms Treating Inorganic Compounds in Wetland Treatment Systems

Metal Removal Mechanisms

Metal removal processes occurring in wetlands involve a series of mechanisms (see Figure 7):

- filtration of solids - suspended solids, including adsorbed metals, are easily filtered and retained in wetlands
- sorption onto organic matter - several metals (e.g., copper, uranium and nickel) have a high affinity to bind to organic matter
- oxidation and hydrolysis - generally the main processes responsible for removal of aluminum, iron, and manganese
- formation of carbonates - which play an important role in the initial trapping of metals such as copper, manganese and nickel
- formation of insoluble sulfides - metals such as silver, cadmium, mercury, arsenic, copper, lead and zinc form highly insoluble sulfide compounds
- binding to iron and manganese oxides - which has been effective for arsenic, copper, iron, manganese, nickel, cobalt, lead, uranium, and zinc

- reduction to nonmobile forms by bacterial activity - effective for chromium, copper, selenium and uranium
- biological methylation and volatilization of mercury - the methylation creating additional environmental problems (ITRC 2003)
- uptake by plants (e.g. algae) and bacteria (Kadlec and Knight 1996).

Most of these are discussed in further detail below.

Adapted from ITRC 2003
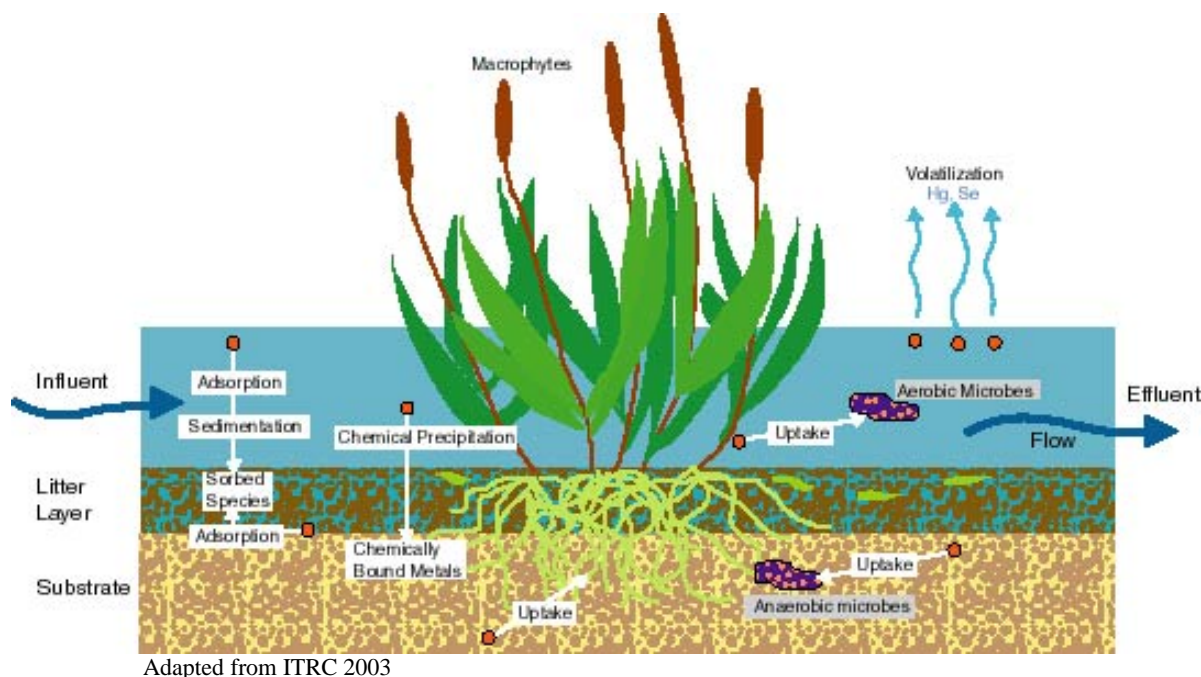
Figure 7.   Mechanisms for Metals Removal in Wetlands

Sorption of Metals onto Organic Matter
Sorption, which includes adsorption and precipitation reactions, is the transfer of ions from the solution phase (water) to the solid phase (soil). In the organic substrate, adsorption (the attachment of ions to soil particles) seems to be the dominant mechanism for metals removal (Fitch and Burken 2004). Kadlec and Keoleian (1986) and Drever (1988) have documented that several metals, including copper, uranium and nickel, easily bind to organic matter, which is plentiful in wetland systems, especially in the detritus layer. The interactions involve the carboxyl and phenolic hydroxyl groups from organic matter, such as humic acid (Tipping and Hurley 1992), resulting in formation of stable complexes. Constructed wetlands may be designed to mimic the organic matter loading of natural wetlands by using an organic substrate such as peat to foster these reactions. But over time the adsorbed material may transform to metal sulfides (Fitch and Burken 2004). Also, organic matter can biodegrade and eventually release adsorbed metals (ITRC 2003). Boyle (1965) and Berner (1980) identified alternatives to prevent this release of metals, including formation of colloidal complexes and insoluble sulfides (ITRC 2003).

Oxidation and Hydrolysis of Metals
Aluminum, iron, and manganese can form insoluble compounds — oxides, oxyhydroxides, and hydroxides — via hydrolysis and/or oxidation (Karathanasis and Thompson 1995). Oxidation and hydrolysis are generally the main removal mechanisms for these three metals (ITRC 2003). Copper can also be removed from solution in this manner (Lehman et al. 2002).

Formation of Metal Carbonates
Metals may form carbonates in the presence of high ambient bicarbonate concentrations. Carbonate formation can take place if limestone occurs in the flow path or with extensive bacterial production of bicarbonate alkalinity in the sediments. Carbonates can be important in initially capturing metals. Carbonate compounds are not as stable as sulfides, but may be transformed to more stable forms following the initial formation (ITRC 2003). Considerable quantities of copper and manganese carbonates have accumulated in some natural wetlands (Sobolewski 1999).

Sulfate reduction and Formation of Insoluble Metal Sulfides
Anaerobic conditions in wetlands promote the growth of sulfate-reducing bacteria, which generate hydrogen sulfide. Most transition metals react with hydrogen sulfide to form highly insoluble sulfides (Stumm and Morgan 1981). The organic-rich detritus of wetlands increases sulfate reduction. Silver, cadmium, mercury, arsenic, copper, lead and zinc form highly insoluble sulfide compounds in contact with even low concentrations of hydrogen sulfide (ITRC 2003).

Binding of Metals to Iron and Manganese Oxides
Iron and manganese will precipitate as oxides, oxyhydroxides, or hydroxides in an oxidizing environment, such as at the wetland surface. Metals may bind with the iron and manganese oxides (Stumm and Morgan 1981; Drever 1988) via adsorption or co-precipitation processes. These redox sensitive oxides may redissolve following changes in oxygen concentration (ITRC 2003). However, the copper, iron, manganese, nickel, cobalt, lead, uranium, and zinc that were bound to iron oxides in Northern Australian wetlands have shown no sign of dissolution from the wetland (Noller et al. 1994, Eapaea et al. 1995). A natural wetland in North Wales, England effectively retained arsenic, cobalt, nickel and zinc in association with iron oxides (Horsnail et al. 1969). Arsenic and zinc were reported to be bound to iron plaques at the surface of plant roots (Otte at al. 1995).

Reduction of Metals to Nonmobile Forms by Bacterial Activity
Some metals (chromium, copper, selenium and uranium) can be reduced to immobile (e.g., metallic) forms by bacterial activity controlled by factors such as Eh-pH and sulfide concentrations in some wetlands (Sobolewski 1999). Copper was immobilized in slightly acidic wetlands (Boyle 1977), selenium was immobilized in natural wetlands where its soluble oxyanion was reduced to elemental, insoluble selenium (Oremland 1994), and chromium and uranium were immobilized when reduced through processes catalyzed by microorganisms (Fude et al. 1994) or by hydrogen sulfide (ITRC 2003).

Biological Methylation and Volatilization of Mercury
Mercury acts differently from other metals in wetland environments. In nature, mercury (Hg) exists in three principal forms: elemental mercury [Hg(0)], mercuric mercury [Hg(II)], and methyl mercury (Me-Hg). Under anaerobic sediment conditions in wetlands, mercuric ions are biomethylated by anaerobic microorganisms to methyl (mono- and dimethyl) mercury. Methyl mercury is a serious problem in aquatic ecosystems because it is highly toxic and readily biomagnifies in the food chain, thereby creating additional environmental problems. As a result, wetlands are generally not recommended for treating elevated levels of mercury unless pilot studies can demonstrate effective removal of mercury with limited methyl mercury production (ITRC 2003).

Treatment Efficiency for Metals

Metal removal rates can be high, but also can vary greatly depending upon the influent concentrations and the mass loading rate (Kadlec and Knight 1996). Table 7 summarizes the metal removal mechanisms discussed above and the removal efficiencies actually achieved for a number of existing treatment wetlands. Additional data on SSF wetland removal rates for the three metals of concern for outfalls H-02 and H-04 — copper, lead and zinc — are shown in Table 8.

Table 7. Examples of Metals Removal in Wetland Treatment Systems

Metal	Removal mechanism	Removal %	Case study	References
Cd	• Formation of insoluble sulfides • Filtration of solids and colloids	98.7	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al. 1979
		75	Bulrushes in gravel	Sinicrope et al. 1992
		79	SSF wetlands	
		99.7	SF cattail	Noller et al. 1994
Cr	• Reduction to nonmobile form by bacterial activity	87.5	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al. 1979
		40	Freshwater marsh receiving urban storm water, Orlando, FL	Schiffer 1989
		84	Bulrushes in gravel	Sinicrope et al. 1992
		68	SSF wetland	
		>65	SRS A-01: retention basin, bulrush SF Cells, hydrosoils amended w/ gypsum	Nelson et al. 2002 Gladden et al. 2003
Cu	• Sorption onto organic matter • Formation of insoluble sulfides • Binding to iron and manganese oxides • Reduction to nonmobile form by bacterial activity	96	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al. 1979
		87.5	Freshwater marsh receiving urban storm water, Orlando, FL	Schiffer 1989
		70.1	Carolina bay receiving municipal effluent, Myrtle Beach, SC	CH2M Hill 1992
		88	SSF Wetland	Sinicrope et al. 1992
		36	Typha SF	
		78 - 83	SRS A-01: retention basin, bulrush SF Cells, hydrosoils amended w/ gypsum	Knox et al. 2004
Fe	• Oxidation and hydrolysis • Formation of carbonates • Binding to iron and manganese oxides	66.7	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al. 1979
		58.2	Average for 137 acid mine drainage constructed wetlands	Wieder 1989
		98	Acid mine drainage wetland, KY (Fabius IMP1)	Edwards 1993
		97	Acid mine drainage wetland, KY (Widows Creek)	
		9	Natural wetland, TN	
Pb	• Formation of insoluble sulfides • Filtration of solids and colloids • Binding to iron and manganese oxides	83.3	Freshwater marsh receiving urban storm water, Orlando, FL	Schiffer 1989
		26	Acid mine drainage wetland, KY (Widows Creek)	Edwards 1993
		86	Bulrushes in gravel	Sinicrope et al. 1992
		80	SSF Wetland	
		98	Typha SF	Noller et al. 1994
		94	Typha/Melaleuca SF	
		77 - 87	SRS A-01: retention basin, bulrush SF Cells, hydrosoils amended w/ gypsum	Knox et al. 2004

Table 7. Examples of Metals Removal in Wetland Treatment Systems (continued)

Metal	Removal mechanism	Removal %	Case study	References
Mn	• Oxidation and hydrolysis • Formation of carbonates • Binding to iron and manganese oxides	43	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al. 1979
		79	Acid mine drainage wetland, KY (Fabius IMP1)	Edwards 1993
		47	Acid mine drainage wetland, KY (Widows Creek)	
		40	Natural wetland, TN	
		98	Typha SF	Noller et al. 1994
		75	Typha/Melaleuca SF	
Hg	• Sorption to organics/silts • Possible immobilization as sulfides	85 (whole system) 75 (wetlands)	SRS A-01: retention basin, bulrush SF Cells, hydrosoils amended w/ gypsum	Nelson et al. 2002 Gladden et al. 2003
Ni	• Sorption onto organic matter • Formation of carbonates • Binding to iron and manganese oxides	70.7	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al. 1979
		25	Freshwater marsh receiving urban storm water, Orlando, FL	Schiffer 1989
		46	Carolina bay receiving municipal effluent, Myrtle Beach, SC	CH2M Hill 1992
		28	Carolina bay receiving municipal effluent, Conway, SC	CH2M Hill 1991
		63	Bulrushes in gravel	Sinicrope et al. 1992
		49	SSF Wetland	
		90	Typha/Melaleuca SF	Noller et al. 1994
Ag	• Formation of insoluble sulfides • Filtration of solids and colloids	75.9	Cypress-gum swamp receiving municipal effluent, Conway, SC	CH2M Hill 1991
Zn	• Formation of insoluble sulfides • Filtration of solids and colloids • Binding to iron and manganese oxides	89.5	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al. 1979
		66.7	Freshwater marsh receiving urban storm water, Orlando, FL	Schiffer 1989
		73	Carolina bay receiving municipal effluent, Myrtle Beach, SC	CH2M Hill 1992
		66	Carolina bay receiving municipal effluent, Conway, SC	CH2M Hill 1991
		33	Acid mine drainage wetland, KY (Widows Creek)	Edwards,1993
		79	Bulrushes in gravel	Sinicrope et al. 1992
		71	SSF wetland	
		96 - 98	Typha/Melaleuca SF	Noller et al. 1994
		54-68	SRS A-01: retention basin, bulrush SF Cells, hydrosoils amended w/ gypsum	Knox et al. 2004

Adapted from ITRC 2003

Table 8. Copper, Zinc and Lead Removal at Various SSF Wetlands

Site	Type of wetland	Contaminant	Influent Concentration	Effluent Concentration	Removal Efficiency
Burleigh Tunnel, Silver Plume, Colorado[a]	Upflow SSF Downflow SSF	Zn	-	-	70-77% >90%
Bioreactor System at West Fork Mine, Missouri[a]	SSF followed by aeration pond	Pb	0.4 - 0.6 mg/l	0.027 - 0.050 mg/l	>91%
Lab-scale system[b]	SSF	Cu Pb Zn	1 - 20 mg/l 1 - 20 mg/l 1 - 20 mg/l	-	82%-92% 76% - 95% 83% - 90%
Lab-scale system[c]	Vertical-flow SSF	Pb Cu	1.30 & 2.99 mg/l 0.99 & 1.93 mg/l	-	>96% - 100% >83% - <94%
Tennessee Copper Basin, Glenn Springs Holdings, Inc.[d]	SSF	Cu Zn	0.33 - 0.43 mg/l 1-2 mg/l	<0.025 mg/l 0.02 mg/l	>92% 85%
UK[e]	SSF	Cu Cr Ni Zn	- 	- 	67.3 69.8 87 60.6

Sources: a   Lorion 2001
            b   Mungur et al. 1997
            c   Scholz 2003
            d   Faulkner and Miller 2003
            e   Shutes et al. 2001

In surface waters, copper is generally found as chelated compounds of Cu(II). Copper forms relatively insoluble complexes with hydroxides, sulfides and carbonates, which can be efficiently retained in wetland systems without biomagnifying significantly in the food chain. Peat and humic substances have a high affinity for copper. Some plants uptake copper in the roots, shoots and rhizomes (Kadlec and Knight 1996). The reduction of copper concentrations in wetlands has been studied at a variety of sites (Hendrey et al. 1979; DeLaune et al 1981; Giblin 1985; Best 1987; Feijtel et al. 1989; Schiffer 1989; CH2M Hill 1991 & 1992; Sinicrope et al. 1992), as documented in Kadlec and Knight (1996) and ITRC (2003). Copper removal efficiency appears to correlate with inflow concentration up to 1,510 µg/l, with highest removal rates seen in wetlands with high influent concentrations (Table 7 and Table 8) (Kadlec and Knight 1996). Recent studies at the SRS A-01 wetlands indicated that copper was very strongly bound to the sediments, with only 1% being easily remobilized and bioavailable (Knox et al. 2004). SF and SSF wetlands have proved successful at removing copper from wastewaters (Table 7 and Table 8).

Lead in surface waters is most often found in Pb(II) form. This divalent lead forms salts with sulfides, carbonates, sulfates and chlorophosphates, which can be removed by wetland systems via sedimentation.

Lead solubility is generally less than 1 µg/l when pH is above 8.5, but is increasingly soluble with lower pH values and alkalinities. Some plants uptake lead, primarily in the roots (Kadlec and Knight 1996). Lead concentration reduction has been investigated at a variety of wetlands (DeLaune et al 1981; Giblin 1985; Feijtel et al. 1989; Schiffer 1989; CH2M Hill 1991 & 1992; Sinicrope et al. 1992; Edwards 1993; Noller et al. 1994), as documented in Kadlec and Knight (1996) and ITRC (2003). At the SRS A-01 wetlands, recent studies showed lead was very strongly bound to the sediments, with only 5% being easily remobilized and bioavailable (Knox et al. 2004). Lead removal efficiency has been seen to increase with increasing inflow concentration, though negative removal efficiencies have been seen in natural wetlands receiving low lead concentrations (Kadlec and Knight 1996). SF and SSF wetlands have been used to efficiently remove lead from their influent (Table 7 and Table 8).

The effect of wetlands on zinc has been studied at a variety of sites (Hendrey et al. 1979; DeLaune et al 1981; Giblin 1985; Best 1987; Feijtel et al. 1989; Schiffer 1989; CH2M Hill 1991 & 1992; Sinicrope et al. 1992; Edwards 1993; Noller et al. 1994), as documented in Kadlec and Knight (1996) and ITRC (2003). In surface water, zinc is present primarily as divalent Zn(II), which forms sulfides, hydrates, carbonates and organics. The sulfide form of zinc is highly insoluble and is responsible for much of the zinc removed in wetlands. At SRS, recent A-01 wetland studies indicated only 2% of the zinc can be easily remobilized and become bioavailable (Knox et al. 2004). Some plants also uptake zinc, primarily in the roots. As with other metals, zinc concentration and mass removal efficiency appears to correlate with inflow concentration up to 2200 µg/l and 124.5 kg/ha/yr (111 lb/acre/yr) (Kadlec and Knight 1996). SSF wetlands have proved successful at removing zinc from wastewaters (Table 7 and Table 8).

Constructed wetlands have been and are being used for a variety of wastewaters containing metal contaminants, including municipal wastewater, metal mine drainage and hazardous waste landfill leachate. Constructed wetlands have been used for years in treating municipal wastewater to remove suspended solids, BOD, organic compounds, and nutrients (nitrogen and phosphorous), in addition to metals. Contaminant removal is accomplished through the natural physical, chemical, and biological processes occurring in the wetlands. In the last 20 years, most municipal constructed treatment wetlands have been used for polishing treated wastewater (tertiary treatment), but SSF and SF wetlands are now being effectively used for secondary treatment also, alone or in combination with other technologies. More than 80% of these treat less than a million gallons of wastewater per day (ITRC 2003). Typical influent concentrations and removal efficiencies for municipal wastewaters are shown in Table 9.

Contaminated water draining from abandoned mines adversely impacts more then 19,000 km (12,000 miles) of rivers and streams and over 730 square km (180,000 acres) of lakes and reservoirs nationwide (Kleinmann 2000). In the 1980s, natural wetlands receiving mine drainage were found to be capable of removing significant amounts of metals from the water (Eger et al. 1980; Weider and Lang 1982; Eger and Lapakko 1988). Based on these findings, both SSF and SF wetlands began to be constructed in the mid-1980s to treat various types of mine drainage. More than a thousand wetlands have been built to treat mine drainage. These have ranged in size from less than an acre to over a thousand acres (ITRC 2003). Typical influent concentrations and removal efficiencies are shown in Table 9.

The use of constructed wetland treatment technology to treat wastewater, such as leachate, from hazardous waste sites managed under the federal Comprehensive Environmental Response Compensation and Liability Act (CERCLA), Resource Conservation and Recovery Act (RCRA) and state programs is increasing. These waste sites often have consistent, high flow, low concentration wastewater streams. Hazardous waste contamination treatable by constructed wetlands includes biochemical oxygen demand, chemical oxygen demand, petroleum hydrocarbons, polycyclic aromatic hydrocarbons, volatile organic carbons, some semi-volatile compounds, suspended solids, nutrients, and metals (ITRC 2003). Typical influent concentrations and removal efficiencies for RCRA/CERCLA treatment wetlands in New York are shown in Table 9.

Table 9. Typical Influent Concentrations and Removal Efficiencies for Three Types of Wastewaters

Pollutant	Municipal Wastewater		Metal Mine Drainage		RCRA/CERCLA Hazardous Waste Landfill Leachate	
	Influent Concentration [a]	Removal Efficiency [a]	Influent Concentration [b] (net acid drainage)	Removal Efficiency [b]	Influent Concentration [c]	Removal Efficiency [c]
Fe	-	-	10 - 1000 mg/l	80 - 90+%	51 mg/l	98%
Al	-	-	1 - 100 mg/l	90+%	-	-
Cd	10 µg/l	50 - 60%	50 - 1000 µg/l	75 - 90+%	-	-
Cu	50 µg/l	50 - 60%	1 - 100 mg /l	80 - 90+%	30 µg/l	89%
Mn			2 - 25 mg/l		-	-
Ni	-	-	-	-	65 µg/l	82%
Pb	50 µg/l	50 - 60%	0.5 - 10 mg/l	80 - 90+%	13 µg/l	100%
Zn	300 µg/l	50 - 60%	10 - 1000 mg/l	75 - 90+%	-	-
BOD	20 - 100 mg/l	67 - 80%	-	-	70 mg/l	95%
Suspended Solids	30 mg/l	67 - 80%	-	-	-	-
Ammonia Nitrogen	15 mg/l	62 - 84%	-	-	230 mg/l	91%
Total Nitrogen	20 mg/l	69 - 76%	-	-	-	-
Total Phosphorus	4 mg/l	48%	-	-	1.9 mg/l	99%
Sulfate	-	-	1,000 - 10,000 mg/l	10 - 30%		

a   Source: Kadlec and Knight 1996
b   Source: ITRC 2003
c   Mulamoottil et al. 1999

Fate and Transport

Constructed wetlands, like natural wetlands, are subject to fate and transport mechanisms, which could be a concern to regulators, stakeholders, and the public and must be understood and evaluated as part of the design processes. However, these same fate and transport mechanisms are what allow constructed wetlands to treat and remove pollutants from the influent (ITRC 2003).

Fate and transport mechanism questions identified in ITRC (2003) that must be answered during the design process include:
- Are the contaminants or contaminant byproducts bioavailable to ecological receptors?
- Can contaminants be converted into mobile forms that can impact groundwater?
- Is the contaminant being treated by the constructed wetland toxic to plants?
- Do the plants grown at the site pose additional risks for further ecological exposure or food chain accumulations?
- Is the contaminant transferred into the air or transformed into a more toxic form?

Contaminants entering a wetland can be eliminated, transformed, immobilized, or incorporated, and can pass out of the system. Pollutant concentrations may be reduced by more than one fate mechanism. Transport mechanisms include diffusion, gravity settling, hydraulic travel through the wetland, vegetative translocation, and transfer to groundwater flows in some cases. The chemical properties of the different pollutants influence the fate and transport mechanisms common to those pollutants (ITRC 2003).

Wetlands degrade and eliminate most organic pollutants, other organic matter, and nutrients through biological activity and other processes. Some chemicals will be transformed into less hazardous substances, while others will be moved, immobilized, or concentrated as a result of biological activity within wetland soils, sediment, and detritus layers. These layers bind organic chemicals, inorganic compounds, and metals. Bound biodegradable compounds are either fully degraded or transformed into less toxic compounds. For example, benzene is broken down into carbon dioxide and water through an aerobic microbial process (ITRC 2003).

Metals removal is often a combination of biological and physical processes. Metals and nondegradable compounds are removed from water and accumulate in wetlands, primarily in the soil and sediment layers. Because the metals tightly bind to the soils and sediments by cation exchange and chelation (the process of forming complex compounds that bind metal ions into stable ring structures), these layers can become the environmental endpoint (ITRC 2003, Kadlec and Knight 1996). Plants also intercept and uptake metals, mostly in the roots, but also in the stems, leaves and rhizomes. Upon root death, some portion of the metals may be permanently buried in the sediments (Kadlec and Knight 1996).

The fate of mercury is different from other metals. In reduced wetland sediments, elemental mercury forms and volatilizes, resulting in an atmospheric sink for mercury and subsequent deposition at a distant location (Kadlec and Knight 1996). The most common forms of mercury in aquatic systems are mercuric salts. In wetland systems under anaerobic sediment conditions, the mercuric ions are converted to mono- and dimethyl mercury by anaerobic microorganisms, which are more toxic than other forms of mercury. Methylated mercury is a serious problem in aquatic ecosystems because of its toxicity and because it bioaccumulates in the food chain, creating additional environmental problems (Kadlec and Knight 1996).

SUITABILITY OF SUBSURFACE-FLOW WETLANDS FOR THIS APPLICATION

The constituents that exceed NPDES limits at outfalls H-02 and H-04 (Table 5) are similar in nature and within typical concentrations found in municipal wastewaters, mine drainage and landfill leachate (Table 9), all of which have been successfully treated in constructed wetlands. Required removal rates for Outfalls H-02 and H-04 (Table 5) to bring the effluent to with NPDES limits have been achieved by various types of wetlands (Table 7, Table 8 and Table 9), including SSF wetlands. Therefore it seems likely that a constructed wetland would be capable of treating the flows of the two outfalls adequately.

TYPICAL DESIGN PARAMETERS & CONSIDERATIONS

In general, wetland designs attempt to mimic natural wetlands in overall structure while fostering those wetland processes that are thought to contribute the most to the improvement of water quality. The USDA (1995) recommends keeping the design simple. Complex technological approaches are more prone to failure. Design for minimal maintenance and use of gravity flow, and for the extremes of weather and climate. Design the wetland with the landscape, not against it, integrating the design with the natural topography of the site and mimicking natural systems.

The number of cells needed in a wetland system depends on topography, hydrology, and water quality. USEPA (1993b) recommends that all but the smallest systems divide the surface area required for treatment into two or more parallel cells to provide flexibility for operation and maintenance.

Residence time and the rate and depth of flow through a wetland are critical for adequate treatment and affect the design of a constructed wetland system. Required residence time depends upon contaminant types, degradation/removal rates, and treatment goals (ITRC 2003). Residence times for SF and SSF constructed wetlands are suggested to be from four to 15 days (Tchobanoglous and Burton 1991). Flow velocity should be low (less than 0.5 ft/second) and laminar to provide sufficient contact time to attain target removal rates. Flow depths typically range from 0.3 to 2.0 ft (0.09 to 0.6 m) for SF systems (Tchobanoglous and Burton 1991), and from 1.6 to 2.6 ft (0.49 to 0.79 m) for SSF systems (Cooper et al. 1998).

Constructed wetland design is an iterative process. Site conditions must be evaluated to assess the suitability and potential effectiveness of the proposed constructed wetlands. Site-specific data should be used for the design. Preliminary data required to begin the design process include:
- water budget and influent wastewater characterization
- treatment objectives
- site suitability
  - availability of consistent water source
  - available area
  - site topography
  - soils data
  - hydrogeology
  - climatic patterns
  - presence of endangered species (ITRC 2003)

Figure 8 is a decision tree that summarizes the preliminary stages of evaluating whether a constructed wetland is an appropriate treatment system to meet the treatment goals for any specific site.

Water Budget and Influent Characterization

The water budget quantifies all water flowing into and out of wetland cells. Inflows include natural flows, process flows, storm water runoff, precipitation, and groundwater. Outflows include evaporation, transpiration, the wetland outlet system, and possibly groundwater. The difference between all inflows and outflows is the required storage capacity. If the wetland is improperly designed, water could leave the wetland at a greater rate than the combined inflows for an extended period of time, causing the wetland to dry out and impacting overall treatment effectiveness. If the inflows are greater than outflows for an extended period of time, the wetland will flood and/or retention times will be too short for sufficient contaminant removal (ITRC 2003).
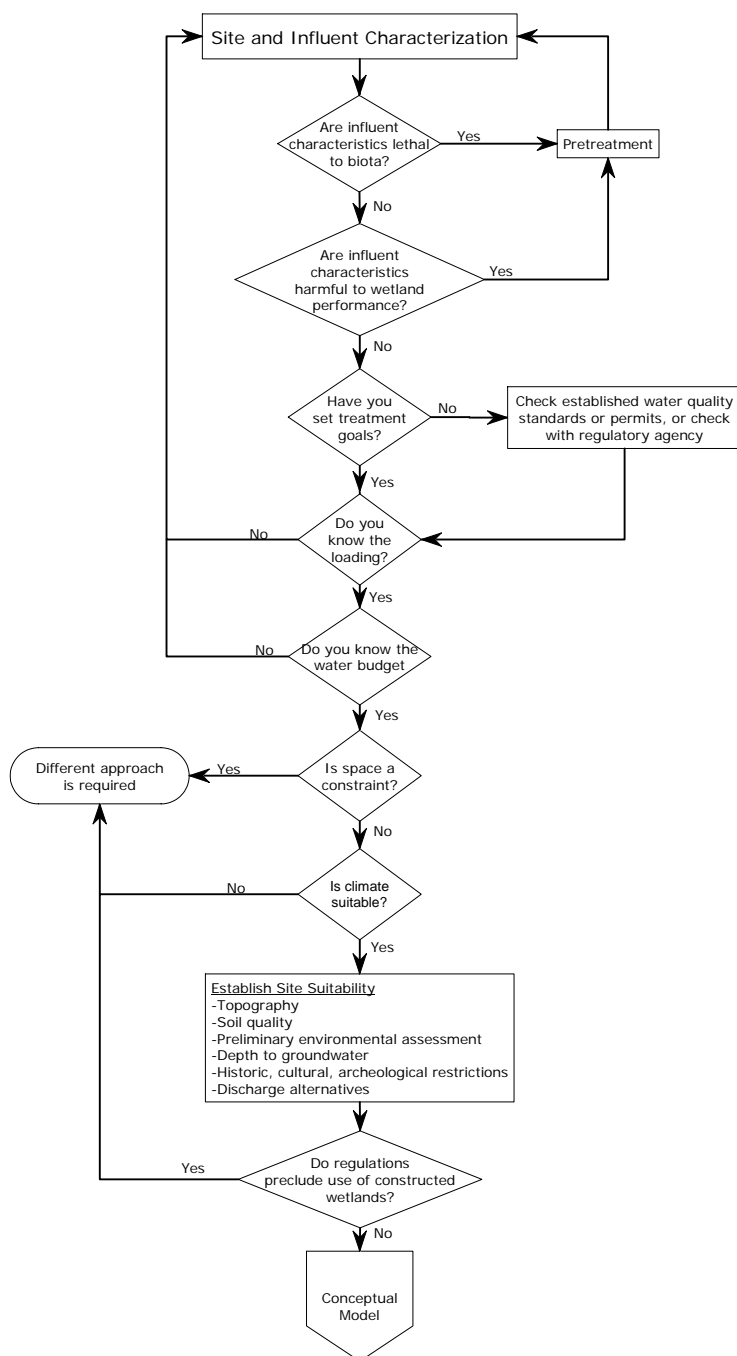
Adapted from ITRC 2003

Figure 8.   Constructed Wetland Site Selection Decision Tree

Influent characterization must be determined to understand whether a constructed wetland can effectively treat the influent. Influent characterization includes both water quantity and quality. Knowing the flow rate is critical to sizing the wetland. Low, average, and peak flow must be determined over a representative time interval. Water quality analysis reveals the contaminants and their concentrations,

which also vary over time. Some constituents may not be removed effectively in wetlands, and thus may not be suitable for wetland treatment. High concentrations of certain contaminants, even temporarily, can disable a treatment wetland or other biological treatment system for extended periods. The treatability of contaminants affects design retention times and, consequently, the size of a wetland. After flows have been estimated and contaminants have been identified and quantified, contaminant-loading estimates can be determined (ITRC 2003).

Treatment Objectives

Constructed wetlands are limited by the ability of the biota to withstand exposure to the influent contaminant concentrations and other water quality parameters. Contaminant concentrations within the wetland must be below biota survival threshold concentrations. The concentrations in the discharge after treatment must meet regulatory levels. High contaminant concentrations and low permissible effluent concentrations could require long retention times, which require large wetlands, especially if flows are high.

Wetland performance is often judged by removal efficiency, which is the effluent contaminant concentration divided by the influent concentration, but this value can be misleading. Removal efficiency must be coupled with influent concentration to determine whether sufficient treatment can be achieved. Low removal efficiencies do not necessarily result in unacceptable wetland performance. Wetlands can also add contaminants to water flowing through them; background concentrations of nitrogen, phosphorous, BOD, and other water quality parameters are not zero, and may exceed effluent standards in some cases. For example, waterfowl or other wildlife may introduce coliform bacteria exceeding effluent permit requirements. Therefore, removal efficiencies can be negative at times for some contaminants. This must be considered in cases where effluent limits are very stringent (ITRC 2003).

Site Suitability

Wetlands are best suited to sites having a relatively large amount of available land, a source of year-round water, a long growing season, and a wastewater with low to moderate contaminant concentrations. Depending on flow volumes, contaminant concentrations, and treatment goals, a treatment wetland may require a large tract of land. If the wetland is too small, it may not be able to handle increased flows from storm events in areas of high rainfall. The site should be relatively flat to minimize earth moving costs (ITRC 2003). Cells can be created with dikes on level sites and terraced on sloping sites (USDA 1995).

Site soils information is necessary for predicting the hydrology, determining the design, and determining suitability for wetland plants. Hydric soils can be valuable because they have already conformed to wetland (reduced) conditions. Upland soils can achieve adequate soil-reducing conditions within a few months of project startup. For intermittent flows, low-permeability soils may be desired to maintain saturated conditions. A location with a clay layer may not need a liner to protect groundwater. Highly permeable soils may require a liner so that adequate retention times are achieved and untreated contaminants do not reach groundwater. However, highly permeable soils may be an advantage if groundwater recharge is desired or where in-situ soils will be used for a SSF wetland. Depth to the bedrock at the site is also important because shallow bedrock could potentially cause problems with construction (ITRC 2003).

Wetland plants can be established and thrive most readily in loamy soils, composed of sand, silt, and organic matter. The ideal wetland condition would be a one to three foot layer of loamy soil for plant rooting and optimum microbial growth. The organic matter is important because binding sites on the organic soil particles may allow cation exchange, which removes metals from the water (ITRC 2003).

Hydrological issues also need to be considered. High groundwater may decrease the infiltration rate or act as a wetland water source, and may make construction difficult. Liners may be necessary to prevent groundwater infiltration, which may pose regulatory problems (ITRC 2003).

Aspects of climate that are important in treatment wetland design include daily and seasonal patterns of precipitation and temperature, both of which affect the biological and physical processes occurring in wetlands. Treatment effectiveness is generally lower in colder weather, so systems built in cold climates may need to be larger or otherwise modified to meet treatment goals. Hot climates may require additional sources of water to keep the wetland from drying out. Typical and extreme patterns of sunlight are also important because sunlight is the main energy source for most physical and biological wetland processes (ITRC 2003).

Biological and ecological factors also need to be considered. As with any other construction project, the presence of endangered or threatened species may restrict construction activities. Wetlands located near human or ecological receptors may pose risk exposure pathways.   The presence of wetland indicator plants and animals at the project site provide information on the condition of the soil and depth to groundwater (ITRC 2003).
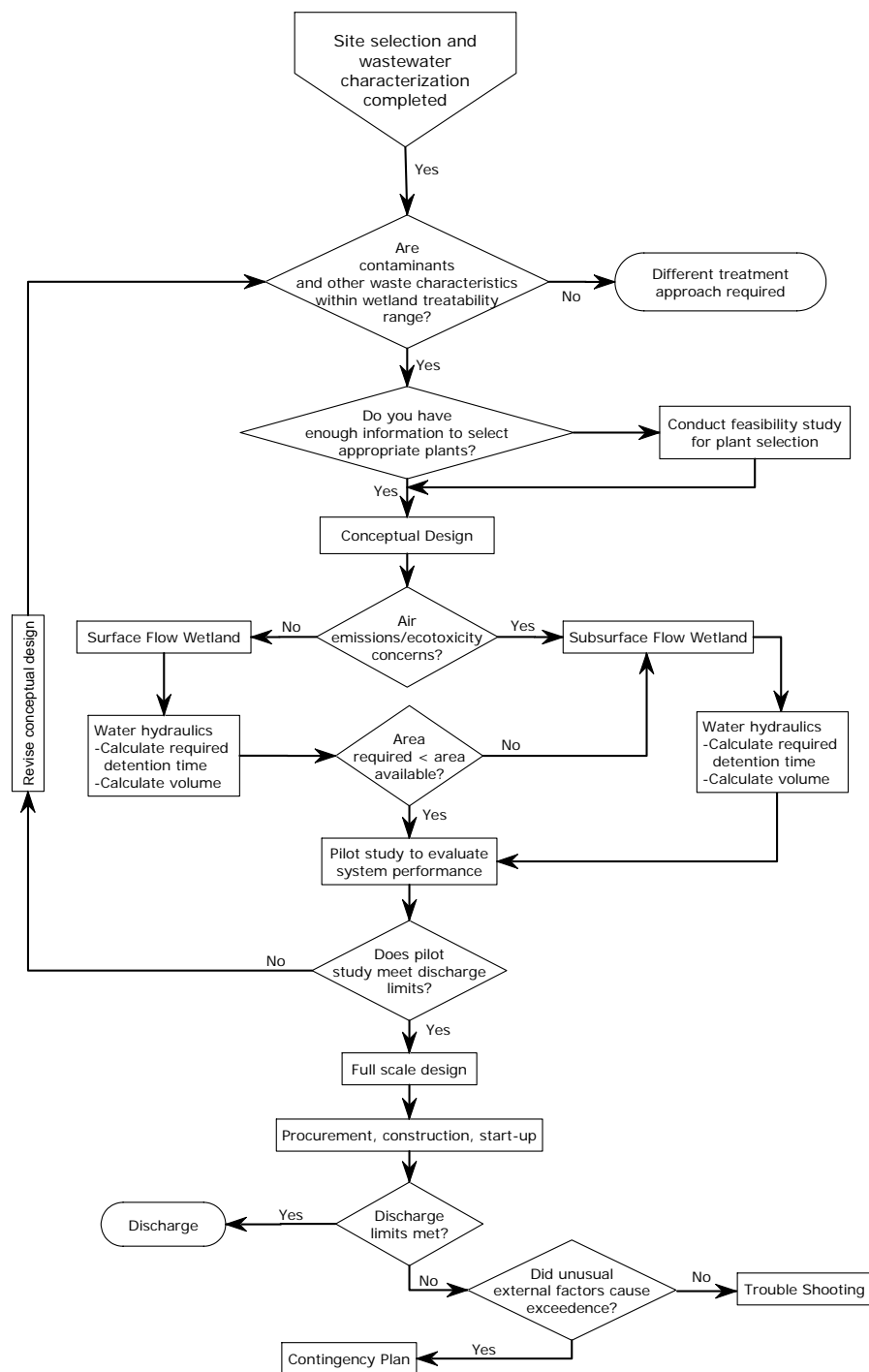
Decision Trees

Once it has been determined that a constructed wetland is appropriate for the waste stream and the site, the process would continue with the design and construction of the wetland system. ITRC (2003) developed decision trees for the construction of treatment wetlands for various applications. Figure 9 is a decision tree similar to the one shown in ITRC (2003) for remedial facility wastewater, which typically has contaminants similar to those discharged to Outfalls H-02 and H-04.

RESOURCES REQUIRED

Estimate of land requirements

Various methods can be used to determine the surface area required for subsurface flow wetlands: simple design models using rules of thumb, regression equations, first-order models and complex dynamic models. For this document, the simplest methods were used in order to obtain a rough estimate of surface area required for a subsurface wetland for Outfalls H-02 and H-04. Rules of thumb estimates are the fastest but also the roughest design methods. Because they are based on observations from a wide range of systems, climatic conditions and wastewater types, these rules of thumb show a large variation and uncertainty. Actual design of a wetland system would utilize more extensive calculations to determine design.

Residence time is the estimated average time for wastewater to flow completely through the wetland and is a function of the "reactive" volume of the wetland divided by the flow rate. The reactive volume is the volume of water above the substrate for SF wetlands, and the volume of water below the substrate for SSF systems. The required residence time for a treatment wetland is a function of the degradation and removal rates and the treatment goals. The residence time must be greater or equal to the reaction time needed to achieve desired effluent concentrations or treatment will not be adequate. Flow channeling will reduce the actual residence time to less than the calculated value. Treatment wetlands should be designed using a safety factor which increases the size of the wetland (ITRC 2003). As stated previously, suggested residence times for SF and SSF constructed wetlands are from four to 15 days (Tchobanoglous and Burton 1991), depending upon contaminant types, their degradation/removal rates, and treatment goals.

Adapted from ITRC 2003

Figure 9. Decision Tree for Remedial Wastewaters

Residence time is defined as:

(1) $T = V/Q$

where   T = residence time (days)
          V = wetland volume (m^3)
          Q = average flow rate (m^3/day)

A preliminary estimate of the land required for the wetland cells can be obtained using a variation of the above equation.

(2) $A = TQ \times 2.471 \text{ E-02} / d$

where   A = surface area for the constructed wetland (acres)
          d = depth of the wetland cell (cm)

Using typical wetland depths for subsurface flow wetlands (49 - 79 cm, or 1.6 to 2.6 ft) and surface flow wetlands (9 - 60 cm, or 0.3 to 2.0 ft), listed in ITRC (2003) and the residence times recommended by Tchobanoglous and Burton (1991) (4 to 15 days), ranges of estimated area required per unit of flow were calculated using equation (2). These are shown in Table 10 along with rule-of-thumb design criteria obtained from other sources.

A preliminary estimate of the amount of land required for a SSF or SF wetland also can be obtained using recommended hydraulic loading rates. The hydraulic loading rate (q), which is the flow rate per unit area, generally varies from 0.7–5 cm/d (0.3 and 2 in/day) for constructed SF wetlands and 2–20 cm/d (0.8 - 8 in/day) for constructed SSF wetlands (WPCF 1990). USEPA's North American Database, a compilation of data from actual treatment wetlands in the United States and Canada, lists median hydraulic loading rate values of 1.4 cm/d (0.5 in/d) and 17.4 cm/d (6.9 in/d) for SF and SSF wetlands, respectively (ITRC 2003). The estimated surface area required can be calculated from the hydraulic loading rate using equation (3) below:

(3) $A = Q \times 2.471 \text{ E-02} / q$

where   A = surface area for the constructed wetland (acres)
          Q = average flow rate (m^3/day)
          q = hydraulic loading rate (cm/day)

Using the typical hydraulic loading rates for SF and SSF wetlands, listed above, ranges of estimated area required per unit of flow can be calculated using equation (3). These are shown in Table 10 along with rule-of-thumb design criteria obtained from other sources.

Another parameter used in sizing wetlands is the areal loading rate (ALR). The ALR is the maximum removal rate of a pollutant mass per unit surface area of a wetland per daily input (ITRC 2003).

(4) $ALR = Q \times C / A$

where   ALR = areal loading rate (g/m^2/day)
          Q = influent flow rate (m^3/d)
          C = pollutant concentration ($mg/L = g/m^3$)
          A = surface area (m^2) of the SSF wetland.

Table 10.   Rule of Thumb Design Criteria for SSF and SF Constructed Treatment Wetlands

Criterion	Value range			
Method or Source	ITRC (2003) and Tchobanoglous and Burton (1991)	WPCF (1990)	Wood (1995)	Kadlec and Knight (1996)
SSF WETLAND				
Hydraulic retention time (days)	4 - 15	NA	2–7	2–4
Hydraulic loading rate (cm day^{-1})	NA	2 - 20	0.2–3.0	8–30
Cell depth (cm)	49-79	NA	n.g.	30–60
Calculated areal requirement (acre/m^3/day)	0.001 - 0.008	0.001 – 0.01	0.002 – 0.017	0.0008 – 0.003
SF WETLAND				
Hydraulic retention time (days)	4 - 15	NA	n.g.	7 – 10
Hydraulic loading rate (cm day^{-1})	NA	0.7 - 5	n.g.	1.5 – 6.5
Cell depth (cm)	9 - 60	NA	n.g.	15 – 45
Calculated areal requirement (acre/m^3/day)	0.002 - 0.04	0.005 - 0.03	n.g.	0.004 – 0.02

NA   not applicable
n.g.   not given by the source

Areal loading rates can be used to give sizing estimates for both planning and final design of wetlands systems from projected pollutant mass loads and effluent requirements.

Area requirements can also be calculated by reaction rate. Reaction rates are functions of the reactant concentrations and specific rate constants, which are a function of temperature. Removal rates are higher initially, when the concentration is at its highest, but the removal rates decrease as the water travels through the wetlands and the concentration decreases. A first order model used by Kadlec and Knight (1996) incorporated background concentrations and can be used for preliminary calculations of required wetland surface area (ITRC 2003):

(5) $A = -Q/k_A [\ln (([\text{Pollutant}]\text{outlet} – P^*)/ ([\text{Pollutant}]\text{inlet}-P^*))]$

Where   Q = average flow rate (cm3/day)
          k_A = areal rate constant (day^{-1})
          [Pollutant] = concentration of pollutant (g/L)
          P* =background pollutant concentration

For the purposes of this document, estimates of the wetland surface area required to treat effluents from Outfalls H-02 and H-04 are based on those parameters given in Table 10 rather than these last two calculation methods, which are pollutant-specific. Combined average flows for the two outfalls are approximately 0.13 mgd (Table 1) or 490 m^3/day, and maximum flows are 2.33 mgd or 8,800 m^3/day. Minimum wetland surface area required based on the average flow and using various calculation methods listed in Table 10 are shown below in Table 11. These areas do not take into account additional storm water influent or the safety factor discussed above. In comparison, USEPA (1993b) lists the sizes of operating subsurface flow wetlands receiving similar flow rates of municipal wastewater to be between 0.7 and 3.7 acres (0.3 - 1.5 ha).

Table 11.   Estimated Minimum Wetland Surface Area for Combined Outfalls H-02 and H-04
(Using Average Flows)

Criterion	Value range			
Method or Source	ITRC (2003) and Tchobanoglous and Burton (1991)	WPCF (1990)	Wood (1995)	Kadlec and Knight (1996)
SSF Surface Area Range (acres)	0.5 - 4	0.5 - 5	1 - 8	0.4 - 1.5
SF Surface Area Range (acres)	1 - 20	2 - 15	NA	2 - 10

Estimate of costs

A variety of factors affect the cost of constructed wetlands, including:
- detention time (longer detention time translates to a larger wetland),
- treatment goals (higher removal rates require longer detention times, thus larger wetlands),
- media type, source and availability,
- type of liner (if required)
- bed depth (deeper systems require less liner),
- pretreatment type,
- number of cells (more cells require more hydraulic control structures and liners), and
- terrain (which affects the amount of grading required) (ITRC 2003).

General cost estimates for constructed wetlands can be obtained from various sources. USEPA (1993b) reported that the capital costs averaged around $87,000/acre ($215,000/ha) for SSF wetland systems and about $22,000/acre ($54,000/ha) for SF systems. The major cost difference between the two types of systems was in procuring, transporting and installing the rock or gravel media, which is the most important factor influencing capital cost for a SSF wetland. Gravel accounts for approximately 40–50% of the total cost for a 50,000-ft^2 (0.5 ha or 1.1 acres) system, with the percentage increasing as the system gets larger. Gravel usually costs about $9.50/ton or $13/yd^3 ($17/m^3) throughout the United States. Delivered costs can exceed $20/yd^3 ($26/m^3). Some states, Florida for example, are considering the use of recycled concrete rubble as SSF wetland media (ITRC 2003).

The type of liner used, if any, can also significantly affect the cost. Liner costs depend on the quantity, thickness, and type of material specified. In general, liners account for approximately 15–25% of the total

cost, with the percentage declining as the system gets larger (ITRC 2003). The percentage increases when expensive liner materials are used and as the number of cells increases. In some cases, a liner can be eliminated if soils have high clay content. The addition of bentonite to the soil or the use of in-situ clay soils in lieu of a liner may seem desirable, but the additional costs of testing and compaction can add significant costs to the project and may even exceed the cost of a 30-mil PVC liner. However, because most liners are petroleum-based products, prices could easily rise with oil prices, making clay soils and bentonite more competitive. ITRC (2003) listed an installed cost for a 30-mil PVC liner of $38 – 40¢/ft^2$ ($4.10 – $4.30/m^2$) for small systems and $30 – 35¢/ft^2$ ($3.20 – $3.80/m^2$) in systems 100,000 ft^2 (9,000 m^2 or 2.3 acres) and larger. Other types of liners ranged from $35 – 90¢/ft^2$ ($3.80 – $9.70/m^2$) in systems 100,000 ft^2 (9,000 m^2 or 2.3 acres) and larger.

General construction costs have changed considerably over recent years. The Engineering News Record (ENR) Construction Cost Index can be used to adjust construction costs from previous years to current conditions. The Construction Cost Index is a representative construction cost composed of a fixed number of common labor hours and a specific set of materials costs, collected from across the country every month. The Construction Cost Index uses 200 hours of common labor, multiplied by the 20-city average rate for wages and fringe benefits, plus the 20-city average price for 25 cwt of fabricated standard structural steel, and local prices for 1.128 tons of bulk portland cement and 1,088 board-ft of 2x4 lumber. The Construction Cost Index measures how much it costs to purchase this hypothetical package of goods and labor compared to what it cost in the base year. Although this mix of labor and materials is not truly accurate for a constructed wetland because of the difference in construction materials needed for a wetland vs. those used in generating the index, the Construction Cost Index does provide a means to roughly update wetland construction costs reported in earlier years.

Using the average Construction Cost Index for 1993 (5210) and the Construction Cost Index reported for August 2004 (7188) (ENR 2004a), the costs reported in USEPA (1993b) can be roughly translated to 2004 costs by multiplying the 1993 cost by the ratio of the updated index to the 1993 index (in this case: 2004 cost = 1993 cost $\times$ 7188/5210). This approximation of 2004 costs is shown in Table 12.

USEPA (2000b,c) reported total calculated capital costs for a 3.2 acre (1.3 ha) wetland with a plastic membrane liner treating 0.1 mgd (380 m^3/d) to be $466,700 for a SSF wetland (USEPA 2000b) and $259,000 for a SF wetland (USEPA 2000c). Costs for constructing the same SSF and SF wetlands using a native soil liner were $362,500 and $154,800, respectively. In contrast, a conventional treatment system designed for the same size waste stream was reported to cost $1,104,500 (USEPA 2000b,c). Using the ENR Construction Cost Index listed in the USEPA document (6039, for June 1999) and the Construction Cost Index reported for August 2004 (7188) (ENR 2004a), the USEPA (2000b,c) costs can be updated to 2004 costs as discussed above.   These are shown in Table 12.

A cost estimate reported in ITRC (2003) for a 50,000 ft^2 wetland (4,600 m^2 or 1.1 acres) is itemized in Table 13 below. This cost estimate of $121,980 is roughly equivalent to an August 2004 cost of $131,000 (using the average Construction Cost index for 2003: 6694). This translates to $119,000/acre ($294,000/ha), which is close to the updated estimate from USEPA (1993b) (Table 12) of $120,000/acre ($297,000/ha).

Table 12.   Updated Estimate of Capital Costs

Item	Reported Cost	Updated 2004 Cost
Capital costs per acre for SSF wetland systems	$87,000/acre [a]	$120,000/acre [b]
Capital costs per acre for SF wetland systems	$22,000/acre [a]	$30,000/acre [b]
Capital costs for a 0.1 mgd SSF wetland system with a liner	$466,700 [c] or $146,000/acre	$555,000 [e] or $173,000/acre
Capital costs for a 0.1 mgd SF wetland systems with a liner	$259,000 [d] or $81,000 /acre	$308,000 [e] or $96,000/acre
Capital costs for a 0.1 mgd SSF wetland system without a liner	$362,500 [c] or $113,000/acre	$431,000 [e] or $135,000/acre
Capital costs for a 0.1 mgd SF wetland systems without a liner	$154,800 [d] or $48,000 /acre	$184,000 [e] or $58,000/acre
Capital costs for a 0.1 mgd conventional wastewater treatment system	*$1,104,500 [c]*	*$1,315,000 [e]*

a   Source: USEPA 1993b
b   Based on Construction Costs Indices found in ENR (2004a) for 1993 and for August 2004
c   Source: USEPA 2000b
d   Source: USEPA 2000c
e   Based on Construction Costs Indices listed in USEPA (2000b,c), which were for June 1999, and for August 2004

Table 13.   Cost of a Typical 50,000 ft^2 (4,600 m^2 or 1.1 acres) SSF Wetland

Component	Price/Unit	Total ($)
Excavation/Compaction	$1.75/yd^3 ($2.29/m^3)	13,000
Gravel	$16/yd^3 ($21/m^3)	51,900
Liner, 30-mil PVC	35¢/ft^2 ($3.80/m^2)	19,250
Plants, 18 inch centers	60¢/each	13,330
Plumbing		7,500
Control Structures		7,000
Other		10,000
Total		*121,980*

Source: ITRC 2003

Operation and maintenance costs include influent and effluent testing, water level adjustment, maintenance of inflow, outflow and distribution devices, weed control, odor control, control of nuisance pests and insects, and maintenance of berms and dikes. The largest single cost is generally the cost of testing influent and effluent, which depends on frequency of sampling, the number of water quality parameters, and the number of samples. Water levels should be checked periodically to ensure that water is flowing, that no surfacing has occurred in an SSF system, and that breaches have not occurred. Inlet and outlet piping must be inspected and maintained, removing clogs, debris and trapped sediment and periodically flushing pipes and manifolds. Flow splitters should be checked and cleaned periodically.

These activities will ensure proper water flow and water level. Weeds should be controlled around the edges, and large weeds should be removed. Odors can be reduced by lowering water levels below the substrate or reducing solid loading. A significant potential maintenance activity for SF systems is the control of nuisance pests, including beavers, mosquitoes, and other insects (ITRC 2003).

Reported costs for operations and maintenance (O&M) indicate that wetlands are very low-cost systems to operate. ITRC (2003) reported an annual operations and maintenance cost of $29,550 for a 3 mgd (11,000 m^3/day) SSF system, including the cost of operating the pre-treatment units. A smaller SSF system (0.4 mgd, or 1,500 m^3/day) had an annual operating budget of $10,000. This translates to operating cost of 2.7–6.8¢/1000 gallons treated (0.7–1.8¢/m^3). Crites and Ogden (1998) reported O&M costs of 4–8¢/1000 gallons (1.1–1.2¢/m^3) treated for SSF systems, compared to 10–30¢/1000 gallons (2.6–7.9¢/m^3) treated for SF systems (USEPA 2000a). The difference in cost between the two types of systems may be because SF systems are typically larger for a given flow rate than SSF systems. USEPA (2000b,c) reported a calculated O&M cost of $6,000/yr for 3.2 acre (1.3 ha) SSF and SF systems treating 0.1 mgd (380 m^3/day), or 16¢/1000 gallons. In contrast, O&M cost for a 0.1 mgd (380 m^3/day) conventional treatment facility was listed as $106,600/yr ($2.90/1000 gallons) (USEPA 2000b,c). These costs can also be updated in a manner similar to the capital costs using ENR's Common Labor Index, which is the labor component of ENR's Construction Cost Index and tracks the union wage, plus fringe benefits, for laborers. These updated costs are shown in Table 14.

Table 14.   Updated Estimate of O&M Costs

Type and Source of Data	Reported Cost	Updated 2004 Cost
SSF wetland system, ITRC (2003)	2.7 - 6.8¢/1000 gallons	2.8 - 7.1¢/1000 gallons [a]
SSF wetland system, Crites and Ogden (1998)	4 - 8¢/1000 gallons	5 - 10¢/1000 gallons [b]
SF wetland system, Crites and Ogden (1998)	10 - 30¢/1000 gallons	13 - 38¢/1000 gallons [b]
SSF or SF wetland system, USEPA (2000b,c)	16¢/1000 gallons	19¢/1000 gallons [c]
Conventional wastewater treatment system USEPA (2000b,c)	*$2.90/1000 gallons*	*$3.50/1000 gallons [c]*

a   Based on Common Labor Indices for average 2003 (14386) and for August 2004 (15038) (ENR 2004b)
c   Based on Common Labor Indices for average 1998 (12024) and for August 2004 (15038) (ENR 2004b)
c   Based on Common Labor Indices for June 1999 (12373) and for August 2004 (15038) (ENR 2004b)

These cost data can be used to develop a rough idea of the costs for constructing and operating a SSF wetland for outfalls H-02 and H-04. Based on a cost estimate of $120,000/acre (updated from USEPA 1993b, Table 12) and the sizing estimates shown in Table 11, costs for a SSF wetland using average flows for outfalls H-02 and H-04 could be very roughly predicted to be between $48,000 (0.4 acres or 0.16 ha) and $600,000 (5 acres or 2 ha), with an outside estimate of $960,000 (8 acres or 3 ha). Using a cost estimate of $173,000/acre (updated from USEPA 2000b, Table 12), the cost estimate ranges from $69,000 (0.4 acres or 0.16 ha) to $865,000 (5 acres or 2 ha). These costs are shown in Table 15. Using the range of dollars per unit flow O&M costs reported above (2.7–19¢/1000 gallons, or 0.7–5¢/m^3), annual O&M costs for a SSF wetland for outfalls H-02 and H-04 could be expected to be between approximately $1,300 and $9,000 using average outfall flows (Table 15). These estimates do not take into account any

additional acreage necessary to size the wetland to handle storm flows. Increasing the size of the wetland to handle such flows would necessarily increase both the construction and operations/maintenance costs. These estimates are intended for determining the initial feasibility of building a constructed wetland for these outfalls. More detailed estimates would be needed before proceeding with a constructed wetland project.

Rough cost estimates for a SF wetland for outfalls H-02 and H-04 can be calculated with these data also. Based on cost estimates of $30,000/acre ($74,000/ha) (updated from USEPA 1993b) to $96,000/acre ($240,000/ha) (updated from USEPA 2000c, Table 12) and the sizing estimates shown in Table 11 (1 to 20 acres or 0.4 to 8 ha), costs for a SF wetland using average flows for outfalls H-02 and H-04 could be very roughly predicted to be between $30,000 and $1,900,000 (Table 15). Using the range of dollars per unit flow O&M costs reported above (13 to 38¢/1000 gallons, or 3 to 10¢/m^3), annual O&M costs for a SF wetland for outfalls H-02 and H-04 could be expected to be between approximately $6,200 and $18,000 using average outfall flows (Table 15). Again, these estimates do not take into account any additional acreage necessary for handling storm flows, and more detailed estimates would be needed before proceeding with a constructed wetland project.

Table 15. Preliminary Cost Comparison of a SSF vs. a SF Wetland for Outfalls H-02 and H-04

Unit Cost	Range of Total Cost
SSF Unit Cost	
Capital Costs of $120,000/acre	$48,000 - $600,000[a]
Capital Cost of $173,000/acre	$69,000 - $865,000 [a]
Annual O&M Costs	$1,300 - $9,000[b]
SF Unit Cost	
Capital Costs of $30,000/acre	$30,000 - $720,000[c]
Capital Cost of $96,000/acre	$96,000 - $1,900,000 [c]
Annual O&M Costs	$6,200 - $18,000[d]

a Based on size estimate of 0.4 to 5 acres
b Based on range of 2.8 to 19¢/1000 gallons
c Based on size estimate of 1 to 20 acres
d Based on range of 13 to 38¢/1000 gallons

CONCLUSION

Constructed wetlands can be used to effectively treat a variety of types of wastewater, including those contaminated with metals, such as the effluent from outfalls H-02 and H-04. Such wetlands are designed to take advantage of the chemical and biological processes of natural wetlands to remove contaminants from the wastewater. Constructed wetlands also have significantly lower capital costs and total lifetime costs than conventional treatment systems.

The contaminants that exceed NPDES limits at outfalls H-02 and H-04 are similar in nature and within typical concentrations found in wastewaters that have been successfully treated in constructed wetlands. Required removal rates (>90%) to bring H-02 and H-04 effluent to within NPDES limits have been achieved by various types of wetlands, including both SF and SSF wetlands. Therefore it seems likely

that a constructed wetland would be capable of treating the flows of outfalls H-02 and H-04 sufficiently and cost effectively.

Land requirements and scoping-level costs for SSF and SF wetlands could be roughly predicted using size and cost per acre estimates from various sources. The wide range of costs reflects the variation in unit cost estimates reported in the literature and the flexibility in wetland design. Scoping-level costs for a SSF wetland for outfalls H-02 and H-04 were calculated to be between $48,000 (0.4 acres at $120,000/acre) and $865,000 (5 acres at $173,000/acre) when using average outfall flows to estimate the size requirements. Scoping-level costs for a SF wetland treating the same wastewater were calculated to be between $30,000 (1 acre at $30,000/acre) and $1,900,000 (20 acres at $96,000/acre). Annual O&M costs for a SSF wetland for outfalls H-02 and H-04 could be expected to be between approximately $1,300 and $9,000 using average outfall flows. Comparable O&M costs for a SF wetland could be expected to be between approximately $6,200 and $18,000.

These estimates do not take into account additional acreage necessary to size the wetland to handle storm flows. Increasing the size of the wetland to handle such flows would necessarily increase both the construction and operations/maintenance costs. These estimates are intended for determining the initial feasibility of building a constructed wetland. More detailed estimates would be needed before proceeding with a constructed wetland project.

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