

1.0 INTRODUCTION

Phytoremediation is a relatively “new” technology that utilizes plants to treat contaminated soil and water *in situ*. While plants themselves are not new to maintaining the health of the environment, their potential to remove contaminants is now being studied in more detail. Previously the main focus of this work has included only non-aquatic plants such as poplar trees. Recently, however, aquatic plants have received more attention in this regard and attempts are now being made to detail the uptake mechanisms and rates of these plants in wetland settings. The main focus of this paper is to provide the reader with a basic understanding of phytoremediation as applied in constructed treatment wetlands. Accordingly, a general description of constructed treatment wetlands, contaminants they are commonly used for, methods for modeling and designing wetlands are presented.

Wetlands have been used in Europe and the United States to treat wastewaters since the 1970's (Ohlendorf et al., 1999). As their popularity has grown, so has the amount of information on their typical use, design, and construction. Laws and regulations have also been introduced and modified as more information about constructed wetlands is generated. The use of constructed wetlands to treat domestic wastewater is well-documented for the most part, but their application to hazardous waste sites and industrial wastewaters that contains hazardous material is still an emerging field. To date, most of the constructed wetlands treating hazardous wastes are found in industries such as petroleum. They are also commonly used in stormwater runoff, water management, and landfill leachate collection systems. A few wetlands are being used to treat acid mine drainage and radionuclides.

There are several pathways that a number of contaminants can be degraded or removed from the water and soil of a constructed wetland system. Some of these include reduction, oxidation, volatilization from the water surface, dilution, adsorption to sediments, bioremediation, and phytoremediation. While these processes are all briefly mentioned or discussed throughout this paper, phytoremediation is discussed in depth more than the others. Likewise, wetlands have been shown to effectively remove contaminants including heavy metals, some halogenated solvents such as TCA, hydrocarbons, radioactive material, and explosives. However, only heavy metals and select organic compounds are discussed.

In order to evaluate the effectiveness of removing these contaminants through wetlands, a review of current research on wetland plants and their potential for phytoremediation is presented. With this data, it is possible to develop a model that will produce a conservative estimate of the surface area required for the wetland. The model is based on several parameters including hydraulic flow and which plant species are used. While pollutant removal is more dependent on hydraulic loading and influent concentration than plant species, water depth, or hydraulic efficiency (Ohlendorf et al., 1999), a basic model for evaluating wetland efficiency is presented as a function of plant species, plant density, and influent concentration. However, since this model is not very practical to field applications, pilot studies are recommended.

Lastly, the construction of the wetland is discussed. It includes items such as siting, plant selection, construction, operation and maintenance, laws and regulations, costs, and team planning suggestions. This is to give the reader a preview of what obstacles and considerations he or she will have to overcome to build a successful wetland.

2.0 PHYTOREMEDIATION: TECHNOLOGY DESCRIPTION

2.1 Basis

Plants enhance contaminant removal in three ways: (1) enhancement of microbial degradation of the contaminant by excretion of enzymes into the soil which are used by microbes; (2) intra- or extracellular catalysis of the contaminants within the root and/or shoot tissues by enzymes; (3) movement of the contaminant through the roots and/or shoots accompanied by sorption to plant tissues or volatilization into the atmosphere through plant stomata (Vroblecky et al., 1999). Schematics of phytoremediation are shown in Appendix B.

The technology has been proven successful for low concentrations of certain contaminants. As a general guideline, organic contaminants that have a moderate octanol-water partition coefficient ($\log K_{ow} = 1$ to 3.5) can diffuse through the root tissues of plants. Contaminants with a larger coefficient will stick to the soil before they will diffuse into the root tissues while those with a smaller K_{ow} value will tend to readily dissolve and remain in the ground water where it will not be bioavailable for the plants to uptake. However, contaminants that tend to adsorb to soil (those with large K_{ow} 's) may still be remediated through a type of phytoremediation in which plant enzymes stimulate microbial degradation (Schnoor, 1997).

2.2 Definitions

While there are three general ways in which plants remediate toxic compounds, phytoremediation can currently be classified into six different types based on which of the three mechanisms is used; the fate of the contaminant; and the location within the plant where the remediation occurs. The six types of phytoremediation are: rhizosphere bioremediation, phytotransformation, phytoextraction, phytovolatilization, rhizofiltration, and phytostabilization.

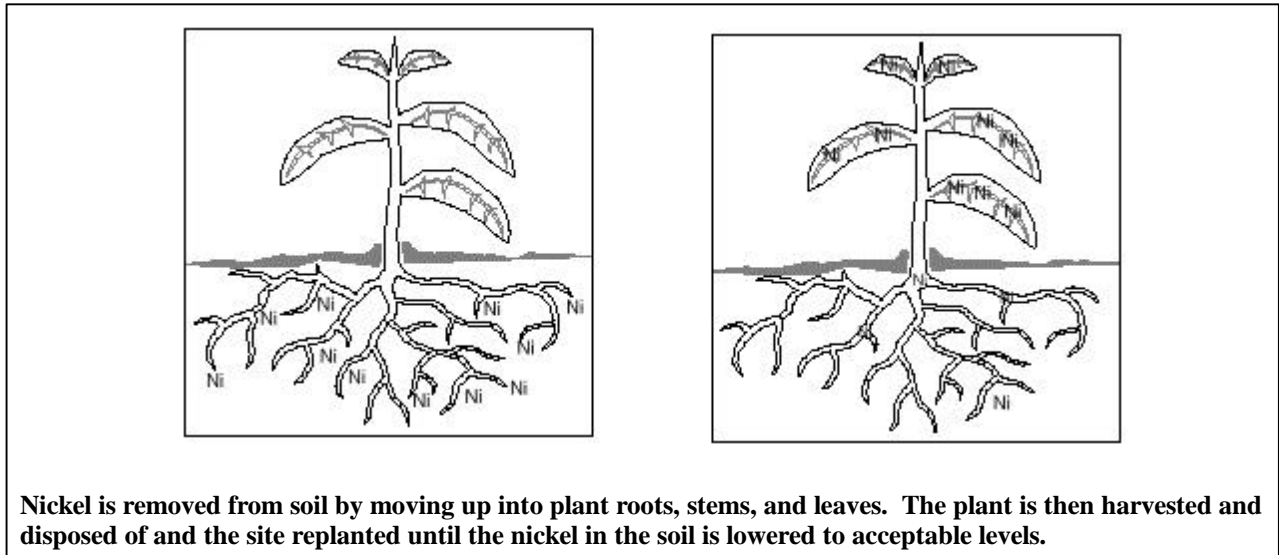
Rhizosphere Bioremediation. This refers to the breakdown of contaminants in soil through microbial activity in the presence of the root zone (rhizosphere). Certain microorganisms can digest hazardous organic substances such as fuels or solvents and break them down into harmless products. Natural substances released by plant roots (sugars, alcohols, and acids) contain food and additional nutrients for soil microorganisms, thereby enhancing their activity.

Phytovolatilization is the uptake and transpiration of a contaminant by a plant, with release of the contaminant or a metabolite of the contaminant into the atmosphere. Phytovolatilization occurs as growing plants take up water and the organic contaminants in the water. Some contaminants can pass through the plant and evaporate, or volatilize into the atmosphere.

Phytoextraction. Also called phytoaccumulation, refers to the uptake and translocation of metal contaminants by plant roots into the stems and leaves. Certain plants, called hyperaccumulators, absorb unusually large concentrations of metals. These hyperaccumulators are selected and planted based on the types of metals

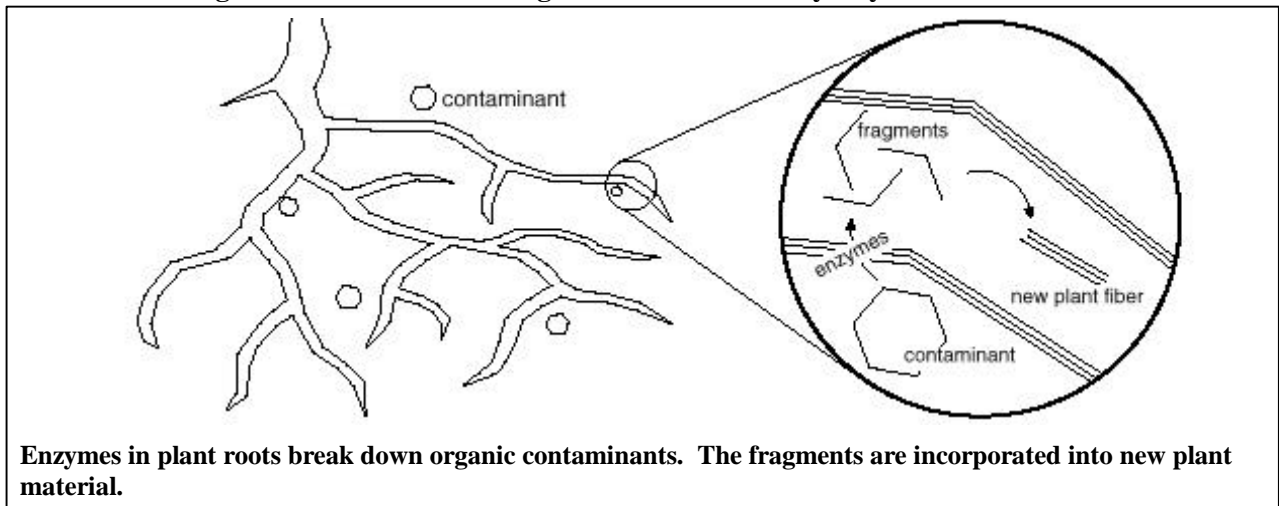
present and other site conditions. After a period of time, the plants are harvested and incinerated or composted to recycle the metals. This procedure may be repeated until the contaminants reach acceptable levels in the soil.

Figure 1. Uptake of Metals (Nickel) by Phytoextraction



Phytotransformation. Also called phytodegradation, this refers to the uptake and subsequent transformation of a contaminant by a plant. This includes both the breakdown of contaminants through metabolic processes within the plant, or the breakdown of contaminants external to the plant through the effect of compounds such as enzymes produced by the plants. Enzymes are complex chemical substances (proteins), that cause rapid chemical reactions to occur. Pollutants can be degraded into simpler molecules and incorporated into plant tissues to help them grow faster.

Figure 2. Destruction of Organic Contaminants by Phytotransformation



Rhizofiltration. This refers to the adsorption or precipitation of contaminants onto plant roots, or the absorption into the roots of contaminants that are in solution surrounding the root zone. Rhizofiltration is similar to phytoextraction, but the plants are used primarily to cleanup contaminated groundwater rather than soil. Often the plants used for remediation are hydroponically raised in greenhouses. Once a large root system has been developed, the plants are acclimated by being watered contaminated water from a waste site. The plants are then planted in the contaminated area where the roots take up the water and the contaminants along with it. As the roots become saturated with pollutants, they are harvested.

Phytostabilization. Phytostabilization utilizes certain plant species to immobilize contaminants in the soil and ground water through absorption and accumulation within roots, adsorption onto roots, or precipitation within the root zone of plants. Although this process does not transform or remove the contaminant, it reduced the mobility of the contaminant and prevents migration to the groundwater, air, and the food chain. This technique is applied to sites where natural vegetation is lacking due to high metals concentration in surface soils. Metal tolerant species can then be used to restore vegetation to the site, preventing wind erosion of contaminants or surface pollutants leaching into the groundwater (EPA technology fact sheet, 1998).

2.3 Benefits

At sites where phytoremediation is a feasible option, it offers several benefits over traditional remediation technologies. A few examples are reduced cost, improved aesthetics, low maintenance, and long term capabilities. At some large sites, it may be the best option since it can be applied over a large area at much lower costs than other non-passive technologies. For example, when comparing remediation technologies with phytoextraction for heavy metals, it is estimated that landfilling would cost \$100-\$400 per cubic meter, soil extraction with leaching would cost \$250-\$500 per cubic meter, while phytoextraction would cost merely \$15-\$40 per cubic meter (Schnoor, 1997). It is ideal for sites where only “polishing treatment” is required, especially if it is required over a long period of time. Thus, it can often be used at sites as a final closure after the site has been treated with another remediation technology.

2.4 Limitations

Phytoremediation does have limitations that may render it unfeasible for use at a site. The timescale required by phytoremediation to reach below action levels can be lengthy. It will not work if contaminants are deep within the soil since plants will only remediate the first meter of soil while trees will not treat beyond the first three meters of soil (Schnoor, 1997). The fate of the contaminant may be a concern during dormant months when trees loose their foliage and when the plant uptake is suspended. Along these lines, animals that consume the plants could become poisoned by the contaminant stored within the plant. In these instances, harvesting or installing wildlife control devices is recommended. Also, if the levels of contaminants are toxic, plants will die. It is important that non-native plant species are not introduced to a new region. Finally, phytoremediation is not considered an EPA

approved technology. Therefore, if it fails to remediate the site the law requires that a proven technology such as pump and treat be implemented. This can lead to unexpected additional costs. These are all considerations that are site specific and help to determine if phytoremediation is a viable option.

3.0 WETLANDS

3.1 General

Wetlands are generally characterized by shallow water, low dissolved oxygen, and saturated soils. Wetlands can be classified according to their salinity and the predominate type of vegetation. A freshwater wetland contains salinities less than 1000 mg/L, whereas a saltwater wetland has a total salinity greater than 1000 mg/L. The predominant type of vegetation present also aids in classification of wetlands. A marsh is dominated by emergent herbaceous vegetation, whereas a swamp is dominated by tree species adapted to flooded conditions (Kadlec and Knight, 1996). Both natural wetlands and constructed wetlands can be used for wastewater treatment, although constructed wetlands are most often preferred because of regulations and system control.

Constructed wetlands may also be classified according to their hydraulic design. Free water surface (surface flow) mimic natural wetlands in their hydraulic characteristics as the water flows in from a pipe over the soil to an outlet point. In subsurface flow (vegetated submerged bed) systems, the wastewater flows vertically or horizontally through a constructed media bed that has been planted with aquatic plant species. The main benefit of subsurface flow is minimal risk of human or wildlife exposure to the wastewater (Ohlendorf et al., 1999).

3.2 Wetland Plants

The selection of plants for a wetland is a major consideration where phytoremediation is to be applied. Wetland species can be split into two categories: emergent (floating) or submerged. Emergent species are used for phytotranspiration, phytoextraction, and phytovolatilization and are easy to harvest if so desired. Submerged species do not transpire water, but they do provide more biomass for the uptake and sorption of the contaminants through phytoextraction. When trying to remove metals from waste water, generally submerged plants are able to better accumulate metals in their tissues than rooted emergent plants because their foliage is exposed to the water. Because of this observation, it is suggested that a good metal accumulator would be a plant that has the ability to adsorb the metals through leaf uptake (Qian et al., 1999). Since leaf uptake is directly related to the amount of leaf surface area that is exposed to the water, plants that have a higher surface area and have a high planting density (plants/m²) make good accumulators. Also, the rate at which a plant accumulates biomass is critical to predicting if it will be a good accumulator of metals. The higher the rate of biomass accumulation, the better accumulator a plant will be. Qian et al demonstrated this correlation by observing that among a number of selected species, smartweed had the highest biomass accumulation rate and the highest rate of element accumulation (1999).

It is important to establish standard criteria for identifying aquatic plants that are well suited for phytoremediation. Because the practice of using wetlands and their aquatic plants for phytoremediation of hazardous wastes is still emerging, few standardized methods for comparing good contaminant accumulators are available. One method suggested by Zayed et al. (1998) defines a good accumulator according to the following:

1. The ability to take up more than 0.5% dry weight of a given element
2. The ability to bioconcentrate the elements in its tissues to a bioconcentration factor (BCF) of more than 1000.

The BCF is defined as follows:

$$\text{BCF} = \frac{\text{Trace element concentration in plant tissues (mg kg}^{-1}\text{) at harvest}}{\text{Initial concentration of the element in the external nutrient solution (mg L}^{-1}\text{)}}$$

A list of good accumulators is listed in Table 1 along with their respective BCF values. These values largely depend on eluent concentrations; therefore, while some plant species have high BCF values for low levels of certain heavy metals, others have high BCF values for high levels. There is no observable trend among aquatic species that can predict BCF values. Therefore, it is suggested that once the characteristics of a waste stream are determined, one should determine which plant species should be used based on BCFs for the a given influent pollutant concentration.

Plants also serve as a necessary hydraulic structure in a wetland. As noted by Demchik and Garbutt in their study of woolgrass to treat acid mine drainage, plants help to reduce soil erosion and increase the hydraulic residence time of the wastewater in the wetland (1999). Ohlendord et al. (1999) demonstrated the importance of using plants as flow barriers by using a wetland system that treated waste from a petroleum refinery in Surprise, Arizona. It consisted of a subsurface flow wetland system in which oil and grease concentration was reduced between 54% and 92% in the wetland outflow. However, an unvegetated control wetland showed no oil and grease removal. This suggests that constructed wetlands rely heavily on plants to prevent the water from short circuiting or flowing through the wetland too quickly.

3.3 Wetland Soils

Wetland soils, in addition to serving as a medium for plant growth, enhance pollutant removal in many ways. The mechanisms involved in the immobilization of pollutants in the soil component of a wetland system include biological oxidation and mineralization, nitrification and denitrification, adsorption on ion exchange sites, binding to organic matter, precipitation into insoluble compounds, complexation or chelation, and incorporation into lattice structures. Soil properties such as texture, pH, redox potential, concentrations of organic matter, Fe and sulfide, etc. would affect these binding mechanisms. Variations in salinities are common in wetlands, and can affect the binding of pollutants in soils (Tam and Wong, 1999).

Dissolved oxygen concentration is the main environmental factor that influences the nature of wetland soils. Vertical oxygen gradients are typically established in wetland soils due to bacterial respiration and chemical oxygen demand and due to the greatly reduced rate of oxygen diffusion in saturated soils compared to unsaturated soils. These oxidation-reduction gradients result in a chain of oxidation-reduction reactions that provide many wetlands with a profile of declining redox potentials with depth. Redox, in turn, affects the microbial processes that are important in most aspects of wetland use for water quality improvement (Kadlec & Knight, 1996).

4.0 COMMON WETLAND CONTAMINANTS

4.1 Heavy Metals

Heavy metal wastes are often found in industrial wastewaters. The removal of heavy metals by wetland systems is most significantly dependent on soil characteristics and the species of aquatic plants chosen. The efficiency of metal removal is highly dependent on influent concentrations and mass loading rates (Ohlendorf et al., 1999).

Wetland plants that are proven to be good accumulators of heavy metals are sometimes referred to as hyperaccumulators. Once the heavy metals have been accumulated in the plant tissues via phytoextraction, the plant may be harvested for disposal or for incineration to retrieve the metals from the plant.

Wetland plants may also have the ability to reduce certain heavy metals. In one study of water hyacinth by Norman et al., it was found that Cr(III) was accumulated in plant tissues when the feed solution contained Cr(VI). However, no Cr(VI) had been found in the plant tissues. Since plants have previously been shown to reduce Fe(III) to Fe(II) through a membrane-bound iron reductase prior to uptake, this has led to the theory that plants produce a reductase for Cr(VI) (Norman et al., 1998).

Within the soil, cation exchange capacity (CEC), organic matter content, and the presence of sulfides and carbonates, tend to have a major influence over the fate of heavy metals. Soils that are fine in texture and have high organic matter content will have a greater CEC and therefore heavy metals are more likely to adsorb to the surface of soil particles. Also the metals may precipitate out in the presence of sulfide and carbonate anions (Ohlendorf et al., 1999).

4.2 Organics

Organics with a mild octanol-water partition coefficient such as oil, grease, hydrocarbons, solvents, and phenols are typically present in wastewater streams from the petroleum and manufacturing industries. Wetlands serve to remove non-volatile organic contaminants from wastewater typically by adsorption to the soil and subsequent degradation by microorganisms. Because soils in wetlands tend to have high levels of organic matter, hydrophobic organics tend to readily adsorb to the soil surface where microorganisms will degrade the contaminant. To improve the adsorption capabilities of a wetland, clays such as hectorite and montmorillonite can also be added

to the bottom of a constructed wetland. In general, the time that is required to break down various organics increases with increased molecule complexity. Microbes more easily break down short, single chained hydrocarbons than they do polycyclic aromatic hydrocarbons (Ohlendorf et al, 1999).

Some volatile organic contaminants can be removed by a wetland by escaping from the water surface or through phytovolatilization. A study conducted by Vrobley et al. (1999) suggested that baldcypress, a wetland tree, is effective at removing TCE from groundwater during the summer months through phytovolatilization. Because TCE can diffuse into the root system, it is transported within the water through the trees and will volatilize out of the leaves through the stomata. Thus, the removal rate of TCE can be approximated by rate at which water is transported through the plant multiplied by the TCE concentration in the root zone. Diffusion of TCE through the air voids in the soil account for 1% of the contaminant removal overall; therefore, if evapotranspiration makes a major contribution to the water budget for the site, then it can be a significant pathway for the removal of volatile organics.

Modeling the removal of organics from wastewaters using constructed wetlands is not well established. Estimates can be made based on published values of contaminants' hydrophobicity, sorption, and degradation rates by microorganisms.

5.0 MODELING CONSTRUCTED WETLANDS

5.1 Design Equations

The design of treatment wetlands centers on the question of size. The most important step in wetland design is selecting the appropriate area that will consistently achieve pollutant reduction goals. An area that is too small will result in permit violations, whereas an area that is too large is a waste of resources. In order to determine how large the wetland needs to be in order to accomplish a specified pollutant reduction, the wetland is viewed as a chemical reactor. Wetlands are complex dynamic ecosystems, and when considered for treatment purposes, it is desirable to predict the degree of treatment to be expected. A complete design model must predict wetland hydraulics, water budget, and chemical transformations and transfers that occur in wetlands.

A wetland may be partitioned into pieces, referred to as compartments. Plant stems and leaves, roots, litter, biofilms, soils, and water are the major compartments. The rates of movement of a chemical between these major compartments, together with the rates of accumulation of that chemical within them, could form the basis for rational design equations. If all rates were known, it would be possible to calculate the interaction between the wetland and the chemicals and water passing through it (Kadlec and Knight, 1996). However, there are a multitude of possible pathways for a contaminant to degrade or move in a wetland system. Although many of these pathways have been identified, the determination of rate expressions for each particular pathway is much more challenging.

If rate constants for a given wetland process can be experimentally determined, they are only directly applicable to the particular wetland the data was gathered from. For instance, a measured uptake rate by a particular plant is dependent on the initial concentration of the pollutant in the wastewater, the size of the plant, and the

hydraulic loading rate. In order to use this information in the design of another wetland, the uptake rate would have to be normalized to the new parameters of the proposed wetland. If it could be assumed in this case that phytoextraction is the dominant process, a first order rate constant could be calculated from the uptake rate and used in a reactor kinetics model. However, a model based only on plant uptake rates would provide an extremely conservative estimate of the required wetland area, since there are a number of other significant removal mechanisms. Attempts are being made to develop design equations based on mass transfer rates and chemical reactor engineering; however, the technology has not progressed enough to accurately do so at this time.

In practice, design is most often based on the performance of existing analogous wetlands. For a particular pollutant, it is very easy to measure an inlet concentration, an outlet concentration, and an irreducible background concentration in the wetland. From these values, an overall first order areal rate constant can be calculated. This rate constant might then be applied to the design of a wetland with similar characteristics as the wetland from which the data was obtained. A two parameter first order model assuming plug flow kinetics, known as the k-C* model, is currently most often used in the design of constructed wetlands. The k-C* model is given as:

$$\ln \left[\frac{C_2 - C^*}{C_1 - C^*} \right] = -k / q$$

where C* is the irreducible background concentration in the wetland, C₁ is the pollutant inflow concentration (mg/L), C₂ is the outflow concentration (mg/L), k is the area based first order rate constant (m/yr), and q is the hydraulic loading rate (m/yr). Currently, the k-C* represents the highest level of complexity that can generally be calibrated with existing wetland data. It provides a reasonable approximation of performance for a wide range of pollutants. The k-C* model does not account for adaptation trends, the effects of dissolved oxygen and pH on performance, and many other factors that are known to affect the fate of pollutants. Rearrangement and a unit conversion give the area required for a particular pollutant.

$$A = \left(\frac{.0365 * Q}{k} \right) * \ln \left(\frac{(C_i - C^*)}{(C_e - C^*)} \right)$$

where A=required wetland area (ha) and Q is the average flow rate (m³/d) of the water (Ohlendorf et al., 1999).

5.2 Pilot Studies

If field or laboratory microcosms indicate that a contaminant could be effectively treated by a wetland, then a pilot treatment project is in order. However, short-term microcosm or mesocosm results should never be used as the sole basis for design. These have been notoriously bad predictors of the performance of full-scale wetlands. The reasons are many, and include edge effects, the wrong hydrology, environmental factors are constrained or absent, and the study period does not carry on to the sustainable limit. Microcosms are valuable because they allow us to understand process details, but the status of wetland science is not strong enough to synthesize and extrapolate to full-scale projects.

Because of these factors, pilot wetlands should be no less than 500 m² and should be run long enough to pass the startup transients and span all seasons. Key design variables include hydraulic loading rate, inlet

concentration, depth, and vegetation density. The cost of complete pilot projects is high, therefore designers have often opted for a demonstration project without experimental replication. This prototype is medium-sized and designed based on analogous wetlands and applications. If successful, the system is then scaled up in hopes of achieving results similar to the demonstration (Kadlec and Knight, 1996).

6.0 CONSTRUCTED WETLANDS DESIGN

6.1 Considerations

Overall, wetlands should be designed to have minimal impact on pre-existing waters of the U.S. (A water of the U.S. is defined as any body of water that has not been constructed). The local watershed and its water budget should be a consideration of the wetland design. Designs must take into consideration periods of drought and other possible sources of water to maintain the wetland. Surface waters and groundwater as well as the land uses upstream and in the surrounding areas all have major impacts on the water budget. The basins should be made of soft structures that incorporate the natural landscape and vegetation while avoiding the use of rigid structures such as rectangular basins or straight channels. Using gravity to maintain the flow through the wetland is the best option. Stagnant water, which promotes the growth of mosquitoes, should be avoided. In instances where the effluent is toxic, wildlife control devices such as fencing, netting, or noise-making devices must be installed. Forebays should be incorporated at the inflow to allow sediments to settle out. The use of multiple cells may allow for the system to be repaired and for the flow to be more easily managed without as much disruption to the normal system. Also multiple cells minimize the potential for short circuiting, which is the discharge of wastewater before it has completed its treatment. Finally, public concern over mosquito control, access to small children, drinking water contamination, unpleasant odors, and health effects should all be taken into consideration of the design (Guiding Principles for Constructed Treatment Wetlands, 1999).

6.2 Siting

Constructed wetlands should be located on uplands, or land higher than the surrounding area that are not within floodplains or floodways, to prevent damage to the surrounding environment or water resources. It has also been discovered that wetlands built on uplands are more easily modeled in terms of pollutant removal and hydraulic flow. These need to be taken into consideration when considering the desired hydraulic flow for the constructed wetland. Additionally, the impact on wildlife and/or endangered species, the possible introduction of non-native plant or animal species, zoning/land use consideration, and the local citizens' perception of the constructed wetland are all key to a good location (Guiding Principles for Constructed Treatment Wetlands, 1999).

6.3 Hydraulics

A major component of wetland design involves the movement of water. Pumps may be required for a number of reasons. These include supplying water to the wetland for treatment, removing water from the wetland to downstream uses, and recycling water back to the inlet. Wetland inflow and outflow design are very important for controlling the flow through a wetland. It is best to have multiple inlets and outlets both for redundancy and to prevent short circuiting in the basin. When designing inlets, avoid high orifice velocities that could erode wetland soils or physically damage plants. In northern climates, freezing can be prevented by use of buried feeder mains followed by point discharge structures or submerged distribution headers. Wetland outlet design is important for maintaining flow distribution, for controlling water level, and for monitoring flow and water quality. Water level control is based on plant requirements, hydraulic residence time, and cell maintenance (Kadlec and Knight, 1996).

6.4 Soil Characteristics

Soil characteristics may influence the design of the constructed wetland. Soils that are highly permeable could lead to possible groundwater contamination and prevent the proper hydrological conditions from forming (i.e. the soil wetland may dry out). If these are possibilities, then the use of an impermeable barrier is required (Guiding Principles for Constructed Treatment Wetlands, 1999). Impermeable barriers may be made of synthetic materials such as polyvinylchloride or high-density polyethylene, or imported clays or clay bentonite mixtures. Another important consideration is the depth and composition of the overlying soils and gravel. These materials need to serve as protection for the liner from construction and root development damage (Kadlec and Knight, 1996). In some cases where a liner is not needed, dredged material from another project could be used to create a base substrate layer in the wetland.

6.5 Plant Selection

Selecting the right plants is critical to the success of the wetland. Design from a phytoremediation viewpoint is directly related to the selection of the plant species used. It is important to consider whether the wetland plants can remediate the contaminant to below action levels (usually water quality standards) and whether they can do so on a reasonable time frame. It is also important to consider how each species will respond to various water depths, contaminants, soil, and light conditions at the site. Plants that are hearty and can withstand fluctuations in flow and depth are recommended. It is also important that no foreign species be introduced to a region. Finally, it is suggested that the plants be obtained from a local nursery rather than transplanted from an existing wetland to a constructed wetland (Guiding Principles for Constructed Treatment Wetlands, 1999).

7.0 LAWS AND REGULATIONS

During construction, minimizing damage to the local communities by limiting the excavation and reducing the surface runoff are encouraged. A general construction storm water CWA Section 4.2 (NPDES) permit is required for projects greater than 5 acres (or 1 acre expected to begin in 2002). Obtaining this permit requires the development of a Storm Water Pollution Prevention Plan that calls for a plan to minimize pollutant loading during construction. Also, if the construction activities call for the disposal of dredged or fill material to waters of the U.S., then authorization to do so under the CWA is required (Guiding Principles for Constructed Treatment Wetlands, 1999).

Various permits are required for treating the water and for disposing of sediments. Regulations under the Clean Water Act (CWA) determine which discharge permit is required depending on where the wetland inflow and outflow are located with respect to waters of the U.S. If at least a part of the constructed wetland is considered a water of the U.S., it falls under the CWA and may be required to obtain specific permits as outlined by the CWA. If the constructed wetland is not a water of the U.S. but does discharge pollutants a water of the U.S., then it discharge is required to have a permit under the CWA, more specifically a National Pollutant Discharge Elimination System (NPDES) permit. If the constructed wetland is in a water of the U.S., then the pretreatment of the effluent is required to the water quality standards. For disposing of sediments that may be removed from the forebay of the wetland, an upland area can be used as a disposal site as long as it meets all legal requirements. Therefore toxic sediments may not be disposed of on the uplands. Co-ordination with authorities is suggested to ensure that a constructed wetland meets all legal requirements (Guiding Principles for Constructed Treatment Wetlands, 1999).

8.0 OPERATION AND MAINTENANCE

A long term maintenance plan should identify which parties are responsible for maintaining the project along with the funding sources for the project to ensure that the wetland will not be neglected. Regular maintenance inspections of the treatment wetland should cover the weir settings, inlet and outlet structures, clearing of surfaces that may be blocked and inhibit flow, removing nuisance species, maintaining the appearance of the wetland, removing sediment accumulation in the forebays, and harvesting of plants that with high levels of accumulated contaminants. Monitoring the wetland such as sampling collection and wildlife counts can be made at the same time as the maintenance inspections. This may mean that sampling of the water, soil, or wildlife in addition to observations of the hydrology and temperature may be necessary to determine the efficiency of the constructed wetland. For remediation of hazardous wastes, toxicity testing may be necessary to ensure that the wildlife and vegetation are not being threatened. Training the operators in the operation and maintenance of constructed wetlands is also recommended if not required. Contingency plans should also be made jointly with project designers and operators that address problems such as unattainable discharge goals, design or operational errors, and unpredictable events as well as protocols to deal with nuisance conditions and possible toxicity (Guiding Principles for Constructed Treatment Wetlands, 1999).

9.0 COSTS

The use of construction wetlands will depend on whether that treatment option is more cost-effective than other available treatment technologies. Primary capital costs include design work, construction of basin and hydraulic features, and planting the wetland. If a liner is needed, it may also significantly add to the cost. Although estimating the initial capital cost of a project is routine, Kadlac and Knight point out two nuances peculiar to flow treatment wetlands. A treatment wetland has a longer life expectancy than concrete and steel equipment. As fully functional ecosystems, treatment wetlands may be expected to retain their character for as long as appropriate hydrology is maintained. In addition, the land used for a wetland project will probably have greater or equal value at the end of the project life as the beginning (1996).

Wetland systems have very low intrinsic operation and maintenance costs. The operating and maintenance costs for a surface flow facility include pumping energy, compliance monitoring, dike maintenance, maintenance of access roads and berms, and mechanical component repair. These operation costs are much lower than those for concrete and steel technologies. Nuisance control might also be a possible O&M cost, but not an expensive one. The cost of replanting and maintenance should be considered in part of project cost along with fertilizing the wetland. It is recommended to plan that at least 30 percent of the plants may need to be replanted by the second or third year of the project (Schnoor, 1997). Harvesting or maintenance of a particular vegetation species composition could be costly, as well as ancillary research costs, which occur at the directive of the regulatory agencies.

10.0 TEAM PLANNING

Planning a constructed treatment wetland should be done with a team consisting of a botanist and/or agricultural specialist, regulators, operators, and the public. Botanists will ensure that the proper plants will be chosen for the site that are native and can tolerate the growing conditions at the site. Regulators often appreciate being brought into the design of constructed wetlands. Public opinion of the project can lead to the project's success or failure.

11.0 CONCLUSIONS

As the field of wetland science continues to progress, better design equations and guidelines will be developed. Wetland plants have clearly been shown to enhance removal of contaminants in various studies, as well as other mechanisms such as biotic and abiotic chemical transformations in wetland soils. Future work will involve further identification of particular plant species capable of hyperaccumulating or transforming contaminants of interest and quantifying their respective rate constants. The kinetics and mechanisms of other chemical partitioning and transformations may also be modeled. While it is unlikely that all rate coefficients of wetland reactions will be identified due to the large number of possible pathways, it is probable that the more significant removal mechanisms

will be quantified. The current K-C* model may be expanded to include more parameters, or new models based on a hybrid of plug flow and continuous stirred tank reactor kinetics may be used.

The greatest potential use for constructed wetlands in the treatment of hazardous waste may involve their use in storm water management and urban runoff. Runoff contains small concentrations of a wide variety of different pollutants, such as oil and grease from parking lots and lawn pesticide residues. Many of these runoff components would be susceptible to removal or degradation in a wetland system. With the proper hydraulics, a wetland could serve as both a detention area to help control the conveyance of storm water and as a treatment facility to enhance water quality. New laws will eventually require treatment of storm water. Many treatment facilities are taking the initiative and incorporating wetlands into their facilities for storm water or tertiary treatment. Another major area of focus will include the collection and treatment of landfill leachate. Regulations for landfill management are becoming much more stringent. Leachate needs to be collected and managed, and wetlands may very well serve this niche.

Wetlands have the potential to be a cost effective and aesthetically pleasing alternative to conventional wastewater treatment and dilute hazardous waste treatment. Wetland treatment systems rely on different sources of energy than conventional treatment facilities. Although traditional wastewater treatment depends on naturally occurring biological transformations, these processes are controlled in concrete basins and are powered by forced aeration or mechanical mixing. A variety of chemicals are often added to enhance contaminant removal. While these conventional systems are advantageous in urban areas because they provide a compact method of pollution control, they require large amounts of fossil fuel energies to do so. Wetlands require the same amount of energy input for every gram of pollutant degraded, however, the energy source is different. Wetland systems rely to a greater extent on renewable energies. A wetland is a living system that harnesses radiation of the sun, kinetic energy of the wind and water, and potential energy in biomass and soils to remove water contaminants. Wetlands are land intensive, rather than energy intensive. In areas where land is readily available, carefully monitored wetlands can provide a cost effective and more environmentally friendly method of treatment for wastewater and dilute hazardous waste effluents.

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Table 1. Plant Species Shown to be Good Accumulators

Contaminants	Plant	Scientific Name	BCF = mg cont./ kg plant mg cont./L	Location of majority of contaminant
As(V)	water lettuce	<i>Nettlia</i> sp.	all shown to be greater than 1000	
	water gentian	<i>Nymphoides indica</i> L.		
	bladderwort	<i>Utricularia</i> sp.		
	hydrilla	<i>Hydrilla verticillata</i> L.		
	muskgrass	<i>Chara</i> sp.		
	water spinach	<i>Ipomoea aquatica</i>		
Cd(II)	duckweed	<i>Lemna minor</i> L.	1300	roots roots
	water hyacinth	<i>Eichhornia crassipes</i>	2150	
	parrot's feather	<i>Myriophyllum brasiliense</i> Camb.	1426	
	inflated duckweed	<i>Lemna gibba</i>	5953	
	ivy duckweed	<i>Lemna trisulca</i>	3594	
	coontail		A	
	giant duckweed		A	
	bacopa		A	
	wild rice		A	
	channel grass		A	
	alligator weed		A	
	algae	<i>Hydrodictyon reticulatum</i>	A	
	algae	<i>Chara corallina</i>	A	
	smart weed	<i>Polygonum hydropiperoides</i> Michx. <i>Lemna trisulca</i>	1300 3594	
Cr(VI)	smartweed	<i>Polygonum hydropiperoides</i> L.	2980	roots
	parrot's feather	<i>Myriophyllum brasiliense</i> Camb.	1767	roots
	fuzzy water clover	<i>Marsilea drummondii</i>	1300	roots
	duckweed	<i>Lemna minor</i> L.	2870	
	water hyacinth	<i>Eichhornia crassipes</i>	1823, 3951	roots
Cu(II)	duckweed	<i>Lemna minor</i> L.	300-15000	roots
	water hyacinth	<i>Eichhornia crassipes</i>	6000-7000	
	water lettuce	<i>Nettlia</i> sp.	1038	
	bacopa		2500-3000	
Ni(II)	parrot's feather	<i>Myriophyllum brasiliense</i> Camb.	1077	roots
	smartweed	<i>Polygonum hydropiperoides</i> L.	953	roots
	waterfern	<i>Azolla filiculoides</i> Lam.	9000	
		<i>Salvinia natans</i> L.	6295	
	duckweed	<i>Lemna minor</i> L.	2000-5500	
Se(VI)	cattail		1000	roots
	duckweed	<i>Lemna minor</i> L.	850	
Pb	duckweed	<i>Lemna minor</i> L.	11500	
	water hyacinth	<i>Eichhornia crassipes</i>	3225	
	giant duckweed	<i>Lemna polyrhiza</i> L.	1000	
	water velvet		1200	
	smartweed	<i>Polygonum hydropiperoides</i> L.	1882	roots
	umbrella plants	<i>Cyperus alternifolius</i> L.	B	roots
	fuzzy water clover	<i>Marsilea drummondii</i>	B	roots
	parrot's feather	<i>Myriophyllum brasiliense</i> Camb.	B	roots
Mn	Bur-reed	<i>Sparganium americanum</i>	578	shoots
	bladderwort	<i>Utricularia</i> sp.	1330	shoots
	liverwort	<i>Scapania undulata</i> L.	188	shoots
	striped rush	<i>Baumia rubiginosa</i>	1683	roots
Hg	water lettuce	<i>Nettlia</i> sp.	1217	roots
	water lettuce	<i>Nettlia</i> sp.	7276	roots
	fuzzy water clover	<i>Marsilea drummondii</i>	1127	roots
TCE	baldcypress	<i>Taxodium distichum</i> (L) Rich		
hydrocarbons	cattails	<i>Typha</i> spp.		
	bulrushes	<i>Schoenoplectus</i> spp.		

A: all between 2125 - 29000

B: all between 1000 - 1200