Engineered wetlands for on-site groundwater remediation

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ABSTRACT
Engineered wetlands incorporate a subsurface flow gravel bed lined with an impermeable liner and equipped with a Forced Bed Aeration™ system to enhance oxygen delivery to the aqueous phase for microbial oxidation. Design parameters include biodegradation rate coefficients, flowrate, hydraulic residence time, and influent and required effluent concentrations. These parameters were used to design a large-scale engineered wetland to remediate hydrocarbon-contaminated groundwater at a former BP Refinery in Casper, Wyoming. This engineered wetland is capable of treating 6,000 cubic meters per day of contaminated groundwater and has been operational since May 2003.

RESUME
Les filtres plantés avec ingénierie confinés par une géomembrane imperméable combinent les lits de graviers plantés à écoulements avec un système d'aération forcée (Forced Bed Aeration™). L'aération forcée augmente l'apport en oxygène qui favorise l'oxydation microbienne dans la phase aqueuse. Les paramètres de dimensionnement de ces systèmes sont les taux de biodégradation, le débit, le temps de séjour hydraulique, ainsi que les concentrations des effluents à l'entrée et celles visés à la sortie. Ces paramètres ont été appliqués à la conception d'un filtre plantés avec ingénierie de grande échelle pour traiter les eaux contaminées par des hydrocarbures de l'ancienne raffinerie pétrolière de BP Casper, Wyoming.

1 INTRODUCTION

Long-term operations and maintenance (O&M) costs associated with the long time scales of groundwater remediation represent a challenge to the engineering community. Engineered wetlands are a viable, sustainable technology for groundwater remediation at petroleum hydrocarbon-contaminated sites. Engineered wetlands incorporate subsurface flow gravel bed reactors in a horizontal or vertical flow configuration, lined with an impermeable liner and equipped with a Forced Bed Aeration™ system to enhance oxygen delivery to the aqueous phase for microbial oxidation. The British Petroleum (BP) former refinery in Casper, Wyoming, USA provides a case study of a site where long-term O&M costs have been reduced through the use of engineered wetland treatment technologies. The site is contaminated by light nonaqueous phase and dissolved phase petroleum hydrocarbons, not an uncommon occurrence at refineries that operated during the early and mid-20th century. The site is bordered on the north by the North Platte River, complicating remediation efforts because of the close proximity of an ecological receptor to the site. The proximity of the site to the river, combined with changes in river stage and water table elevation, has resulted in a smear zone containing residual hydrocarbons that extends from approximately 1.5 m above the water table to 3 m below the water table. Since 1981, over 36,718 m^3 of light nonaqueous phase liquids (LNAPL) have been removed from the subsurface. A 1998 Wyoming Department of Environmental Quality (WDEQ) Consent Decree established the framework for site remediation, whereby BP and the City of Casper agreed to convert the site into a golf course and office park with a river trail system.

Because of the long timeframe for remediation (50 to 100 years), BP was interested in pursuing long-term O&M cost savings through a sustainable biological treatment processes. An engineered wetland treatment system was identified as a low-maintenance system compatible with the intended golf course use of the property. The treatment system was required by WDEQ permit to achieve effluent benzene concentrations of less than 50 µg/L.

2 BTEX TREATMENT IN WETLANDS

Petroleum hydrocarbons are documented to naturally degrade in natural wetland environments (Wemple et al., 2000). The microbial community associated with the plant rhizosphere creates an environment conducive to degradation of many volatile organic compounds (Schnoor et al. 1995; Pardue et al. 2000). Both surface flow wetlands (open water bodies similar to natural marshes) and subsurface flow wetlands (a gravel bed planted with wetland vegetation) have been used to treat petroleum wastewaters (American Petroleum Institute 1998).

Surface flow constructed wetlands have been used in the United States to treat petroleum wastewaters since the early 1970's (Litchfield et al. 1989). However, due to the higher surface area present in a gravel bed, subsurface flow wetlands can achieve greater biological treatment in a given unit area (United States Environmental Protection Agency 1988). Initial work on the use of subsurface flow wetlands to treat industrial organic compounds was performed in the early 1960's in Germany (Seidel 1973).

A recent engineering development in subsurface flow wetland remediation systems involves adding aeration (Figure 1) to optimize in situ biodegradation (Wallace 2001a). Engineered wetlands are characterized by the addition of aeration systems and other engineered systems including reactive media.

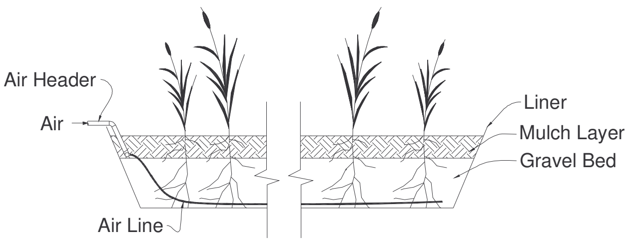

Figure 1. Aerated subsurface flow engineered wetland (Jacques Whitford NAWE, Inc.)

Removal of BTEX (benzene, toluene, ethylbenzene, xylene) compounds occurs through volatilization and aerobic biodegradation (Pruden et al. 2003). Aerated subsurface flow engineered wetlands have been demonstrated to be more effective than non-aerated systems in removing BTEX compounds from contaminated groundwater (Moore et al. 2000). An aerated engineered wetland system has been successfully operated by Williams Pipeline since 1998 (Figure 2).

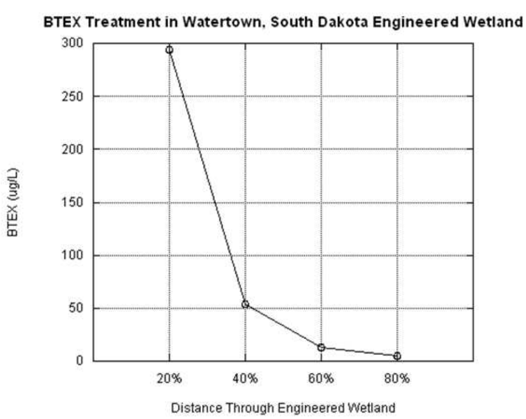

Figure 2. BTEX removal with distance in an engineered wetland treatment system (Wallace 2001a)

Engineered wetland bioremediation systems require much less operation and maintenance than conventional mechanical treatment systems. Their visual impact is minimal, allowing them to be easily integrated into site re-use opportunities such as brownfields redevelopment.

3 PILOT SYSTEM

For the Casper project, based on a review of the existing literature, Kadlec (2001) estimated a 3 tanks-in-series (3TIS) areal rate constant (k_A) of 115 m/yr for BTEX and benzene. For the initial design flow criteria of 7,949 m^3/day, this would have required 11 hectares of non-aerated subsurface flow wetlands (which was deemed excessive). The initial feasibility study also recognized the need for cascade aeration for iron oxidation, together with a settling basin for iron precipitate settling. A pilot system was constructed to assess aerated wetland performance (Wallace et al. 2005).

3.1 Pilot System Design

Four subsurface flow engineered wetland treatment cells (operating in parallel) were established. Each cell was 1.7 m wide by 7 m long by 1.1 m deep (Ferro et al. 2002). Cells were loaded at a nominal flow rate of 5.4 m^3/day, resulting in a nominal hydraulic retention time of one day.

In each pilot cell, influent was introduced across the bottom area of the wetland, flowed upward through the (lower) gravel and (upper) sand bed, and then across the upper portion of the sand bed to the outlet. This flow path was selected based on intellectual property constraints in the United States, although Kadlec (2001) noted that vertical upward flow presented a potentially unstable flow regime. Indeed, short-circuiting problems were observed in this vertical upward flow system.

Various species of wetland plants were transported from the University of Wyoming-Laramie greenhouse for planting in the pilot systems, including species of willows (*Salix*), reed (*Phragmites*), bulrush (*Schoenoplectus*), rush (*Juncus*), and dogwood (*Cornus*). Two of the four cells were vegetated using a 0.15 m thick mulch layer consisting of plant detritus interlocked with roots and rhizomes harvested from a nearby wetland which had a mature assemblage of wetland vegetation adapted to alkaline conditions (Ferro et al. 2002).

3.2 Pilot System Results

The pilot system was operated between August and December 2002, and was designed to test the relative effects of operating the cells with and without wetland mulch and with and without aeration. Some problems (non-uniform flow due the upward flow direction and non-uniform air distribution) were noted during pilot operation which led to subsequent changes in full-scale design. During the course of pilot system operation, all four pilot cells were operated with aeration for at least part of the study period. Data from each of the pilot cells was segregated into periods with and without aeration. The presence of wetland mulch and aeration both improved treatment performance. Although the water temperature decreased seasonally throughout the period of pilot operation, no impact on removal rates was observed. Mean areal rate constants based on assumed 3TIS flow were established for benzene, BTEX, TPH, and methyl *tert*-butyl ether (MTBE) as summarized below:

Table 1. Pilot system areal rate constants (k_A, m/yr, based on 3TIS).

Compound	Aeration Wetland Mulch (m/yr)	No Mulch (m/yr)	No Aeration Wetland Mulch (m/yr)	No Mulch (m/yr)
Benzene	518	456	317	256
BTEX	356	311	257	244
TPH	1,058	965	725	579
MTBE	64	60	35	22

4 FULL-SCALE SYSTEM

The full-scale system was designed to treat 6,000 m^3/day of contaminated groundwater. Because potential iron fouling of the subsurface flow (SSF) engineered wetland media was identified during the pilot operation, a cascade aeration system (for iron oxidation) and free water surface (FWS) wetland (for iron precipitation and settling) was added to the system upgradient from the subsurface flow engineered wetland (Figure 3).

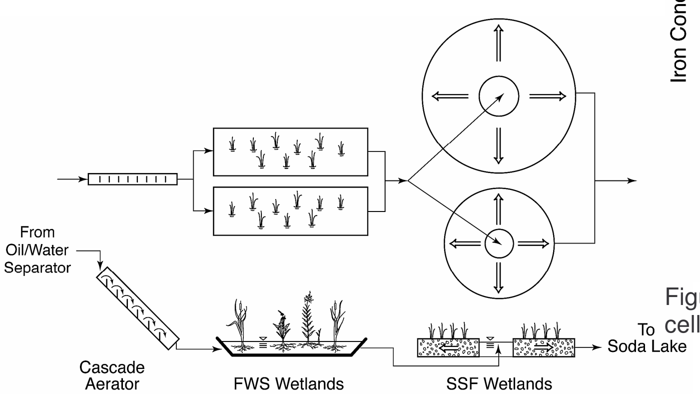

Figure 3. Plan view (upper) and cross-section (lower) schematics of full-scale engineered wetland treatment system at Casper, Wyoming. The FWS wetland cells have a combined area of 0.6 ha. The SSF wetland cells have a combined area of 1.3 ha with 0.9 m deep gravel beds

4.1 Cascade Aerator

U.S. regulations require that the benzene concentration of the water released to the wetland treatment system be less than 500 µg/L. An enclosed, ventilated cascade aerator was designed to reduce benzene concentration to this value in the oil/water separator effluent. Volatile organics stripped from the water column are routed to a soil-matrix biofilter for degradation. Average benzene reduction in the cascade aerator has been approximately 54 percent.

4.2 Free Water Surface Wetlands

The primary function of the FWS wetlands is to precipitate and remove iron to prevent fouling of the SSF wetland media. Reduced iron present in the groundwater is oxidized in the cascade aerator. Due to the pH of the water (~ 8.3), oxidized iron rapidly forms ferric oxyhydroxide precipitates and settles as the water moves downgradient through the FWS wetlands (Figure 4).

The FWS wetland is divided into two parallel treatment cells with a combined surface area of 0.6 ha. The water depth in each cell can be independently adjusted from 0 to 0.6 m, with a typical operating depth of 0.3 m. The FWS wetland cells were planted with hardstem bulrush (*Schoenoplectus acutus*), cattail (*Typha angustifolia*) and bur-reed (*Sparganium eurycarpum*). Transect data indicates the FWS wetlands are effective in removing iron.

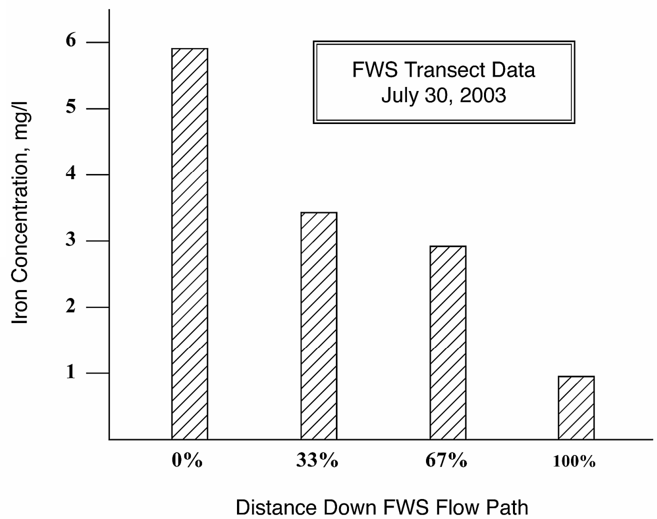

Figure 4. Iron precipitation and settling in FWS wetland cell

4.3 Subsurface Flow Engineered Wetland Cells

The thousand-fold scale-up from the pilot to full-scale treatment system presented a number of design challenges, first and foremost of which was flow distribution. In order to apply the rate constants developed from the pilot, the full-scale system had to be designed such that the degree of short-circuiting and dispersion was less than that observed in the pilot study. The vertical upward flow design was abandoned in favor of a center-feed, horizontal, radial flow configuration.

In order to operate ice-free in the severe Wyoming winter, a 0.15 m thick insulating mulch layer was installed on top of the SSF wetland cells. The insulation layer was designed using energy balance methods described elsewhere (Wallace et al. 2001). The SSF wetland cells were constructed with an aeration system (Wallace 2001b) capable of uniformly distributing air throughout the wetland basins. Air blowers distribute air to the wetland bottom via aeration tubing on 0.6 m spacing. Thirty-seven kilowatts of blower capacity are employed. However, since the aeration system uses variable-frequency drives, actual power consumption is usually much less.

The full-scale system began operation in May 2003. The system was hydraulically loaded at approximately 2,700 m^3/day (45% of design) through March 2004. System performance during this initial full-scale operation period for benzene, BTEX, and gasoline-range organics (GRO) is summarized below:

Table 2. Mean influent and effluent concentrations for the full-scale wetland treatment system, May 2003 – March 2004.

Compound	Wetland Influent (μg/L)	Wetland Effluent (μg/L)
Benzene	170	Non-detect (≤10)
BTEX	470	Non-detect (≤10)
GRO	2,002	Non-detect (≤5)

Although the wetland treatment system was achieving non-detect levels of petroleum hydrocarbons, the current BTEX mass load was at the time only about 15% of the design mass load. The low mass loading resulted in lower observed removal rate constants (Table 3).

Table 3. Mean areal 3TIS rate constants for the full-scale treatment system, through March 2004.

Compound	k_A, m/yr
Benzene	~ 240
BTEX	~ 350
GRO	~ 325

Rate constants summarized in Table 3 are approximate in nature. Due to the location of sampling points, this represents the combined removal in the FWS and SSF wetland cells. Flow has steadily increased since 2003, with the design flowrate being reached in late 2005 (Figure 5).

Influent benzene concentrations have ranged from approximately 100 to 760 μg/L since 2004 (Figure 6). However, benzene concentrations in effluent from the wetland treatment system have remained at non-detect levels (with detection levels ranging from 0.5 to 10 μg/L).

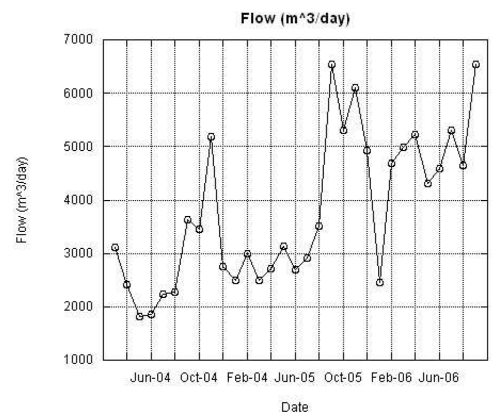

Figure 5. Flowrate through system (m^3/day)

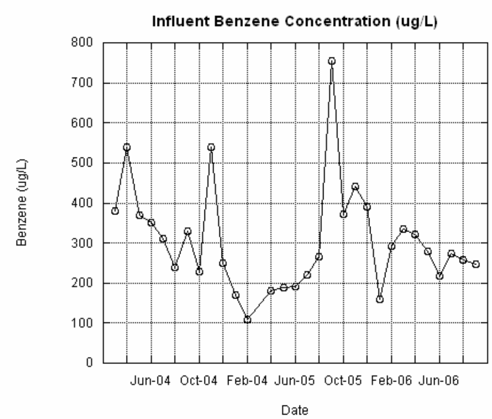

Figure 6. Influent benzene concentrations (μg/L)

5 CONCLUSIONS

This project demonstrated through the application of both pilot-scale and full-scale wetland treatment systems that removal rates for petroleum hydrocarbons in aerated subsurface flow wetlands are considerably greater than in non-aerated wetlands. Areal rate constants (3TIS k_A values) for BTEX degradation were measured in the pilot system at 244 m/yr for cells operating without aeration and mulch, and at 356 m/yr for cells with aeration and mulch. The full scale system, which uses aeration and mulch, has a 3TIS k_A value of 350 m/yr. Based on data from the pilot and the full-scale system, there appears to be little if any temperature effect on petroleum hydrocarbon degradation rate constants. The treatment system is now operating at design flow, reducing influent benzene concentrations from an average of approximately 300 μg/L to non-detect concentrations. The wetland treatment system has been incorporated into a large-scale redevelopment of the property, including a Robert Trent Jones-designed golf course, whitewater rafting park, and commercial office and light industrial park space. In 2005 the project won the U.S.

Environmental Protection Agency Region VIII Phoenix Award, which recognizes outstanding brownfield redevelopment projects.

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