Phytoremediation Using TreeWell® Technology: An Innovative Approach to Groundwater Remediation at CCR Sites

Herwig Goldemund¹ and Ron Gestler²

¹Geosyntec Consultants, Inc., 1255 Roberts Boulevard NW, Suite 200, Kennesaw, GA 30144; ²Geosyntec Consultants, Inc. 2700 Ygnacio Valley Road, Suite 130, Walnut Creek, CA 94598

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ABSTRACT

Some coal combustion residual (CCR) disposal units regulated by the Federal CCR Rule may require groundwater remedies based on statistically significant levels of constituents regulated in Appendix IV of the Rule. These inorganic constituents cannot be destroyed or degraded, but only captured/contained, rendered immobile, or allowed to migrate into the environment at concentrations deemed acceptable. This, in turn, affects (and also limits) the selection of potentially applicable groundwater remedial alternatives. One of these technologies involves the use of phytoremediation. Traditional phytoremediation methodologies, however, have often been limited in their effectiveness due to constraints including inaccessibility to deep groundwater, poor growing conditions and/or highly elevated (and potentially phytotoxic) levels of contaminants. More recently, an engineered approach to phytoremediation, the TreeWell® system, has been shown to overcome typical limitations of applying phytoremediation to groundwater cleanup. This phytoremediation system targets specific groundwater strata, at depths of 50 feet (15 meters) below ground surface (or more), and forces roots to use only water from a specific targeted zone. TreeWell technology has great potential for groundwater remediation applications at CCR sites, especially as an enhancement to source control measures. The TreeWell system can be used for both hydraulic control of contaminant plumes and for groundwater contaminant treatment via degradation (for organic constituents) or immobilization/containment mechanisms (for organic and inorganic constituents). This paper discusses mechanisms utilized in phytoremediation systems applied to address sites impacted by inorganic contaminants, including those typically encountered at CCR sites, and also presents case studies demonstrating the successful use of engineered phytoremediation systems.
INTRODUCTION

Some coal combustion residual (CCR) disposal units regulated by the Federal CCR Rule\(^1\) may require groundwater remedies based on statistically significant levels of constituents regulated in Appendix IV of the Rule. Groundwater below basins that have been used to store CCR materials may have concentrations of certain groundwater constituents in excess of applicable regulatory standards and/or background conditions. These include mostly inorganic constituents such as metal(loid)s (e.g., arsenic [As], selenium [Se], mercury [Hg], iron [Fe], manganese [Mn], and boron [B]) and anions (e.g., chloride [Cl], or sulfate [SO\(_4\)]). While some of these constituents may not require remediation under the Federal Rule, they may be regulated by individual states and require some form of remedial action.

Once released or mobilized, inorganics cannot be destroyed or degraded, but only captured/contained, rendered immobile or allowed to migrate into the environment at concentrations deemed acceptable. This, in turn, affects (and also limits) the selection of potentially applicable remedial alternatives. One of these technologies involves the use of phytoremediation.

PHYTOREMEDICATION

Phytoremediation is the use of plants to degrade or contain contaminants in soil, groundwater, surface water, and sediments. Over recent decades, phytoremediation has emerged as a feasible alternative to more active and costly environmental cleanup technologies, especially for large areas with relatively low levels of contamination in shallow soils or groundwater. In general, six main mechanisms are involved in the application of phytoremediation:\(^2\)

1) Phytosequestration (inorganic and organic contaminants) is the ability of plants to sequester contaminants in the rhizosphere (an area a few millimeters away from a root surface). This is a containment mechanism.
2) Rhizodegradation (organic contaminants) refers to the microbial breakdown of contaminants in soil through the bioactivity that exists in the rhizosphere (an area a few millimeters away from a root surface). This is remediation by destruction.
3) Phytohydraulics is the ability of plants to capture and evaporate water. This is hydraulic control of a groundwater plume through plant root uptake and is considered a containment mechanism.
4) Phytoextraction (mostly inorganic contaminants) is the process of contaminant uptake into the plant. This is remediation by removal.
5) Phytodegradation (organic contaminants) is the ability of plants to take up and break down of contaminants in the transpiration stream. This is remediation by destruction.
6) Phytovolatilization (mostly organic, but some inorganic contaminants) is the mechanism of plant uptake and translocation of contaminant into the leaves with subsequent transpiration of volatile contaminants. This is remediation by removal.
Typically, a combination of these mechanisms acts in concert to achieve successful applications of phytoremediation for site cleanup. For example, phytohydraulics may act in conjunction with phytoextraction for remediation of inorganic contaminant plumes, while phytohydraulics coupled with phytovolatilization can together achieve effective remediation of 1,4-dioxane plumes and can also address inorganic constituents such as selenium and mercury plumes.

More recently, the term “phytotechnologies” has been introduced to more broadly describe a wide variety of plant-based environmental tools, including those used for site cleanup (i.e., phytoremediation). Phytotechnologies encompass a number of plant-based technologies and applications and includes any plantings that enhance the environmental goals for a given site. Conceptually, phytotechnologies include a variety of applications ranging from constructed wetlands to alternative landfill covers, from tree plantations for hydraulic control to the use of plants for slope stabilization, from planted (riparian) buffers for nutrient management and sediment control to the classical applications of contaminant uptake and degradation. However, this paper does not discuss the use of phytoremediation for cleanup of soils and/or its use in the larger variety of applications listed above but focuses instead on the use of this technology for groundwater applications. In particular, this paper focuses on the use of an innovative and proprietary phytoremediation technology and its feasibility for application to CCR sites.

THE TREEWELL SYSTEM

The effectiveness of groundwater remediation using traditional phytoremediation approaches may be limited by compacted soil conditions that impede root penetration, target groundwater that is too deep for root access, or phytotoxicity due to excessively high contaminant concentrations. More recently, an engineered approach to phytoremediation, the TreeWell system, has been shown to overcome these constraints by utilizing a specialized lined planting unit constructed with optimum planting media designed to promote downward root growth, encourage contaminant treatment, and focus groundwater extraction from a targeted depth interval. Developed and patented by Dr. Edward Gatliff of Applied Natural Sciences, Inc., the TreeWell system uses a proprietary design to focus groundwater extraction from a targeted depth interval; targeted groundwater is drawn upward through the planting unit and into the root zone, creating a hydraulic connection between impacted groundwater and the phytoremediation system. Advanced techniques have been developed to address groundwater typically too deep for root contact, at depths greater than 50 feet (15 meters) below ground surface, enabling TreeWell systems to target groundwater normally inaccessible to plant roots and therefore out of reach for effective phytoremediation. A schematic illustrating the typical construction of a TreeWell unit is presented on Figure 1.
The *TreeWell* system can be used for both hydraulic control of contaminant plumes and for groundwater contaminant treatment via degradation (for organic constituents) or immobilization/containment mechanisms (for organic and inorganic constituents). By contrast, in traditional hydraulic control/containment systems, such as a groundwater pump and treat (P&T) technology, extraction wells or trenches are used to capture groundwater, which may subsequently require above-ground treatment and discharge to a receiving stream, reinjection into the groundwater, or reuse at a given site. Groundwater P&T is often slow and costly as a means to restore groundwater quality but can be effective in providing hydraulic control to limit contaminant migration, while addressing a variety of inorganic constituents typically encountered at CCR sites.

Hydraulic control can also be achieved without the need for mechanical above-ground extraction and treatment of groundwater, however, through the use of an engineered phytoremediation technology such as the *TreeWell* system. This type of system installs a tree within a cased (i.e., sleeved) boring, which allows for groundwater to be extracted from a targeted zone which then enters the root system of the trees. This method forces the tree to use groundwater rather than meteoric/surface water to meet its water needs and encourages downward root growth to the saturated zone. By installing a cased “well” for tree planting using large diameter auger (LDA) technology, extraction of deeper groundwater zones (i.e., in excess of 50 feet [15 meters] below the ground surface) can be achieved, since the surface of the “well” is sealed and only groundwater...
from a targeted zone is allowed into the cased-off borehole. This type of system mirrors a traditional mechanical extraction system with the trees acting as solar-driven pumps. The advantage of the system includes no above-ground water management needs and minimal long-term operations and maintenance (O&M) requirements following the establishment of the tree system. Such systems have been observed to meet design hydraulic control parameters typically by the end of the third growing season, when properly designed and spaced. The layout for a TreeWell plantation is generally based on groundwater flow modeling, and typically assumes a design uptake rate of approximately 40 to 60 gallons per day per unit. Due to the relatively low concentrations of constituents in groundwater surrounding CCR units, contaminant uptake and accumulation within the aboveground biomass is generally not of concern but can be monitored if warranted under certain circumstances.

Typical installation of TreeWell units consists of drilling to target depth using an LDA. The boring from the LDA is then lined with a fabricated plastic liner and backfilled with imported agricultural-grade soils. Down-hole components, such as tubing and instrumentation for gas exchange, fertilizer injection and groundwater monitoring, are installed during the backfilling, and one or more selected trees are then planted at the top of the backfilled boring. The TreeWell unit is then completed at the ground surface per the TreeWell design and stabilized. Figure 2 presents a newly installed TreeWell system showing typical aboveground completion at a site in North Carolina. Figure 3 presents the same TreeWell system two years post-installation. The rapid growth and excellent health observed in trees at this site are typical of the results achieved at other sites using the TreeWell system, thanks to the optimized growing conditions created by this engineered phytoremediation system.

Figure 2: Newly completed TreeWell units at North Carolina site.
Figure 3: *TreeWell* phytoremediation system two and a half years post-installation at North Carolina site.

**FEASIBILITY OF TREEWELL TECHNOLOGY FOR CCR SITES**

*TreeWell* technology has great potential for groundwater remediation applications at CCR sites, especially as an enhancement to source control measures. Observed groundwater impacts around CCR sites are generally limited and concentrations of groundwater contaminants are typically low. Typical constituents observed in groundwater underlying basins used to store CCR materials include metal(loid)s such as As, Se, Hg, Fe, Mn, B and anions such as Cl and SO$_4$. While concentrations of these contaminants may be in excess of applicable regulatory standards and/or background conditions, they may however be within the range that is suitable for phytoremediation with *TreeWell* technology. By directly targeting the impacted water-bearing zone of interest, the *TreeWell* system can achieve hydraulic control of contaminant plumes in as little as two growing seasons post-installation, and more typically within three to four years post-installation. In addition, the *TreeWell* system can concurrently address the mix of inorganic constituents found in groundwater associated with CCR sites through one or more of the key phytoremediation mechanisms described above. The exact mechanism(s) involved will be constituent-specific and may also be impacted by speciation or form of the metal(loid) or anion. Some examples include the following:

- Fortuitously, several of the typical groundwater constituents encountered at CCR sites are essential (micro-) nutrients for plants, such as Fe, Mn, B and SO$_4$. Thus, these constituents may be absorbed by plant roots and translocated throughout the plant (i.e., phytoextraction) to support its growth;

- Plants can effectively remove Se from impacted sites by uptake of selenate or selenite. Once absorbed by roots, plants have the capacity to (i) sequester the metal in plant tissue and/or (ii) phytovolatilize the Se as volatile and non-toxic dimethyl selenide. Further, both plants and their associated soil microbes
contribute to the biosynthesis and emission of volatile Se gases, e.g., dimethyl selenide.⁶

- Select amendments may be utilized when constructing the TreeWell units in order to immobilize or precipitate specific constituents. These amendments include sulfide- and zero-valent iron-based reactive treatment technologies, which can be emplaced as backfill in the TreeWell units during construction. For example, sulfide-based amendments can be used to promote the formation of stable and insoluble sulfide-metal complexes, effectively immobilizing metals such as iron and manganese in the TreeWell column;⁷ and

- Production of root exudates (labile organic compounds including sugars, polysaccharides, polypeptides and organic acids) can establish conditions favorable to the reduction of sulfate to sulfide.⁸ This sulfide may, in turn, lead to formation of stable and insoluble sulfide-metal complexes, thus effectively immobilizing both the sulfate and metal constituents of concern within the TreeWell column.

Specific metal(loid)s and/or anions may potentially pose adverse or phytotoxic risks to plants at higher concentrations, depending on speciation or form and the specific plant under consideration; as noted above, pre-treatment options may be necessary to sorb and immobilize some contaminants in the soil column of TreeWell units prior to potential root uptake. The exact type and amount of pre-treatment material would be dependent on constituents of concern and would take into consideration the planned lifespan of the phytoremediation system (typically 30 years or more).

Plant selection is often a critical design consideration when developing a phytoremediation system, including those using TreeWell technology. When designing a phytoremediation system for CCR sites, careful selection of plant species should be performed to tailor the plants used in the system to the constituents observed in groundwater. For example, at CCR sites where Cl concentrations are high relative to other groundwater constituents, the use of halotolerant or halophytic plant species may be warranted to mitigate against the potentially adverse accumulation of Cl in plant tissues. Likewise, at CCR sites where high B groundwater concentrations are observed, the use of plant species known for elevated tolerance to B should be considered, to mitigate against potential phytotoxicity from this constituent.

**SELECT TREEWELL PHYTOREMEDIATION CASE STUDIES**

**Case Study 1: Phytoremediation of Mercury-Impacted, High-Salinity, High-pH Groundwater at a Former Outfall Pond (Confidential Client)**

A TreeWell phytoremediation system was successfully applied at a confidential site in California to prevent flux of mercury-impacted groundwater to a sensitive waterbody. The site once housed a chloralkali unit consisting of multiple mercury cells used for production of chlorine and sodium hydroxide. The chloralkali unit ceased operations in the 1970’s, but a former outfall pond (FOP) associated with the unit had significant
mercury impacts to both soil and groundwater. Groundwater underlying the FOP had total mercury concentrations ranging from 245 ng/L to 540,000 ng/L, pH ranging from 7 to 12, and chloride and sodium concentrations ranging from 1.2 to 12.5 g/L and 0.9 to 10.0 g/L, respectively. A cap system (an impermeable geotextile and 12" of clean cover) was installed over the FOP in 2000 to prevent recharge to the underlying shallow aquifer. While the cap was successful in reducing recharge, the hydraulic gradient of the aquifer indicated that groundwater continued to flow towards the adjacent waterbody. Based on the results obtained from groundwater modeling, a TreeWell phytoremediation system was installed at the FOP in 2013, with its primary objectives being hydraulic control and contaminant sequestration (i.e., phytosequestration). These objectives were achieved through plant uptake and transpiration of target groundwater concomitant to metal sequestration in the root zone around each planting. The system was installed directly through the FOP cap to establish an inward hydraulic gradient, mitigating potential off-site migration of contaminants. The innovative phytoremediation design maintained the integrity of the FOP cap, minimizing recharge, while simultaneously promoting downward root development, targeting the impacted water-bearing zone. A total of 271 engineered TreeWell units were installed over a one-acre area of the FOP. Each unit contained two salt-tolerant plant species (Saltbush and Afghan Pine) previously identified as being well suited to groundwater conditions at the site.

The effects of the phytoremediation system on groundwater flow conditions were rapidly observed. An inward hydraulic gradient began to develop in the interior of the planting area by the end of the first growing season. The magnitude of the inward hydraulic gradient continued to increase with each growing season as the system’s plants matured and transpired larger volumes of water, leading to the desired goal of hydraulic control of impacted groundwater. Sequestration of mercury in the root zone was indirectly confirmed by semi-annual sampling of groundwater concentrations and through plant tissue analysis (to confirm that no mercury accumulation was occurring in above-ground plant tissues). The green and sustainable remediation approach used at this site was not only successful in meeting the remediation objectives but was also very cost-effective versus more conventional technologies initially considered for the site (e.g., P&T).

Case Study 2: Phytoremediation of Groundwater Impacted by Arsenic, Chlorinated Volatile Organic Compounds and 1,4-Dioxane at a Former Manufacturing Facility (Confidential Client)

The groundwater at this former manufacturing facility in Florida contained elevated levels of arsenic, chlorinated volatile organic compounds (CVOCs) and 1,4-dioxane (constituents of concern [COCs]) resulting from historical facility activities. Conditions at the site were complex and included residual source areas and multiple plumes both on- and off-site. Key remedial goals for the site were (i) reduce contaminant concentrations within the plume to levels that would be acceptable to the regulatory agency for a risk-based conditional closure, and (ii) provide hydraulic control to prevent the COC plumes
from migrating off-site, and to allow shut-down of the existing P&T system within a reasonable time frame.

Initially, a P&T system was installed and operated for 12 years at the site. However, due to aquifer properties, the system was only able to extract and treat at a very low rate (10 gallons per minute [gpm]) and was not effectively reducing concentrations within the groundwater plume. A minimum of 25 years of additional costly operations and maintenance were anticipated to obtain site closure. Therefore, alternative remediation technologies were evaluated to determine if a more cost-effective and sustainable strategy could be implemented to obtain site closure more quickly. Vertical geologic and groundwater profiling, pump testing, and groundwater flow modeling were completed to refine the conceptual site model and develop a final remedy for the site that included an engineered TreeWell phytoremediation system comprised of 150 units designed to reduce COC concentrations and capture the flow of affected groundwater.

As part of the phytoremediation approach, a distressed wetland area was reclaimed by removing solid waste and invasive species and installing TreeWell units employing native species. Within the second growing season, monitoring of the TreeWell system demonstrated complete capture of the affected groundwater flow and decrease in groundwater COC concentrations by up to two orders of magnitude. Based on these results, it was recommended to shut down and remove the existing P&T system, which was approved by the Florida Department of Environmental Protection (FDEP). By the end of the fourth growing season, contaminant concentrations in the source area and downgradient plume had been reduced to slightly above the State Cleanup Target Levels, and a conditional No Further Action proposal was submitted and approved.

CONCLUSIONS

While phytoremediation is often applied to address organic contaminants, it can also be an appropriate remedial strategy for the metal(loids) and anions typically observed in groundwater at CCR sites. Plant-based remediation technologies can be effective as either a hydraulic control strategy or a sequestration/containment strategy for metal(loids) and other inorganics from groundwater.

While traditional phytoremediation methodologies have often been limited in their effectiveness due to constraints including inaccessibility to deep groundwater, poor growing conditions and/or highly elevated (and potentially phytotoxic) levels of contaminants, the TreeWell system has been shown to overcome typical limitations of applying phytoremediation to groundwater cleanup. TreeWell technology has great potential for groundwater remediation applications at CCR sites, especially as an enhancement to source control measures. The TreeWell system can be used for both hydraulic control of contaminant plumes and for immobilization/containment of inorganic constituents. Remediation practitioners should consider keeping these versatile technologies in their toolbox.
REFERENCES


