Phytoremediation Preliminary Final Design Report

for the Former Seaboard Chemical Corporation Facility and
City of High Point Landfill, Jamestown, North Carolina

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1.0 INTRODUCTION

1.1 Background

1.1.1 Site Description

The Seaboard Facility property (the Site) is located at 5899 Riverdale Drive, Jamestown, NC, as shown generally on Figure 1. The adjacent City of Highpoint Landfill, a closed municipal solid waste landfill upon which the full-scale 35-acre phytoremediation project is proposed, bounds the Site to the north and east. Plan sheets C-1 and C-2 (attached) illustrate the location and topographic characteristics of the proposed full-scale phytoremediation system. Presently, this area is typical of a closed, capped landfill with gently rolling topography and a dominance of native perennial non-woody weed species. The location of the 35-acre phytoremediation system has been chosen to take advantage of the most level parts of the closed Landfill exhibiting suitable soil characteristics.

1.2 Summary of Site Contaminants/Groundwater

Primary constituents of concern in the site groundwater include perchloroethene, 1,2-dichloroethane, 1,1,1-tricholoroethane, 1,1-dicholoroethane, 1,1-dicholoroethene, 1,2-dichloroethene, trichloroethene, vinyl chloride, chlorobenzene, methylene chloride and 1,4 dioxane. All of these compounds (with the exception of the 1,4 dioxane) are considered chlorinated Volatile Organic Compounds (cVOCs). These cVOCs are the primary compounds being targeted by the constructed treatment wetland system for treatment and destruction. *The persistent and recalcitrant compound 1,4 dioxane is the target compound for the upland phytoremediation system, with primary removal from the groundwater accomplished via phytovolatization.*

Remedial treatment objectives developed at the outset of considering a natural treatment system approach included the following:

1. Providing effective treatment and removal of cVOCs from the extracted groundwater [100% removal objective, constructed wetland].
2. Providing effective removal of the 1,4 dioxane from the extracted groundwater [100% removal objective, phytoremediation system].
3. Design objective of a zero discharge system; no treated effluent sent to POTW.

The natural treatment systems (constructed wetland cell and phytoremediation stand) are the proposed primary long-term remedies for the site designed to meet the three objectives listed above. Groundwater will be pumped from a series of extraction wells along the margins of the Deep River, downgradient of the Site. This extracted groundwater will be delivered to the constructed wetland cell in closed, below grade piping. The extracted groundwater will then be treated in the constructed

wetland, then the discharge (with all chlorinated VOCs removed) will be routed to the phytoremediation stand in a closed distribution piping system. This document provides a draft design level description of the phytoremediation component of the Site's proposed natural treatment system.

1.3 Summary of Proposed Phytoremediation Technical Approach

A 35-acre full-scale phytoremediation system is proposed to be sited on the closed City of Highpoint Landfill proposed for the removal of the 1,4 dioxane from extracted Site groundwater. The 1,4 dioxane is a particularly recalcitrant compound that does not respond well to most conventional treatment methods, including many biological treatment methods. In addition, it does not readily volatilize from water exposed to the atmosphere. While the 1,4 dioxane will be present in the extracted groundwater which passes through the constructed treatment wetland prior to introduction to the phytoremediation system, it is unlikely that the wetland will remove or degrade this compound by any significant measure. However earlier research conducted by others and the ENSR Team pilot studies have demonstrated that phytoremediation of 1,4 dioxane via *phytovolatilization* processes by trees would effectively remove the compound from water. This removal mechanism is the key to the proposed phytoremediation system.

This approach specifies the establishment of a 35-acre upland phytoremediation stand comprised of a deciduous and coniferous tree plantation and adjacent separate conifer plantation to remove 1,4 dioxane from the groundwater. The extracted groundwater that has initially been treated in the constructed wetland will be piped in a closed system to the phytoremediation stand, and the water will be irrigated to the trees at a proposed rate of 50 gallons per minute (gpm). All design-level components of the system are depicted on attached sheets C-1 to C-2, "Proposed Phytoremediation System," ENSR, 2005. Sizing of the respective components of the phytoremediation stand has been based on the specific tree species transpirational water use taking into account site-specific environmental factors (soil moisture capacity, etc). To ensure year-round use of the extracted groundwater and to avoid accumulation of naturally occurring carbonates and bicarbonates, the extracted groundwater will be routed to the deciduous stand during the growing season, and to the coniferous stand between December and March of each year. The design establishes an 8-acre deciduous stand and a 27-acre coniferous stand. Water use is much greater in deciduous trees, and in conjunction with higher daily growing season temperatures and a longer photoperiod, this stand is much smaller than the proposed conifer stand. Both stands, however, are designed to treat a 50 gpm rate when being irrigated.

Three years of site-specific laboratory and field pilot studies (see Section 2.4.2) have demonstrated that certain tree species can effectively remove the 1,4 dioxane from the groundwater via *phytovolatization* without cumulative toxic effects to the trees, and can also tolerate naturally occurring dissolved metals. Further, several of these trees have shown an affinity to take-up the 1,4 dioxane in the groundwater without any negative effects. *Phytovolatization* is the gaseous release of volatile compounds from the leaves of plants after being taken up by the plant roots. This gaseous efflux

occurs through leaf stomata during a tree's transpiration. The primary removal mechanism associated with eliminating the 1,4 dioxane from the extracted groundwater is phytovolatization.

2.0 PROPOSED PHYTOREMEDIATION SYSTEM TECHNICAL APPROACH

2.1 Phytoremediation Background

2.1.1 Phytovolatization

The term *phytovolatilization* has been used to describe the gaseous efflux of volatile compounds from the leaves of plants. In this process, chemicals having certain physiochemical properties can be taken up by plant roots, move with the transpirational stream from roots to shoots, and leave the plant via volatilization through stomatal pathways to the atmosphere (Trapp and McFarlane, 1995). An advantage the tree provides on this case is the ability to transpire the generally non-volatile 1,4 dioxane. The schematic below illustrates the treatment concepts included in the phytoremediation system design.

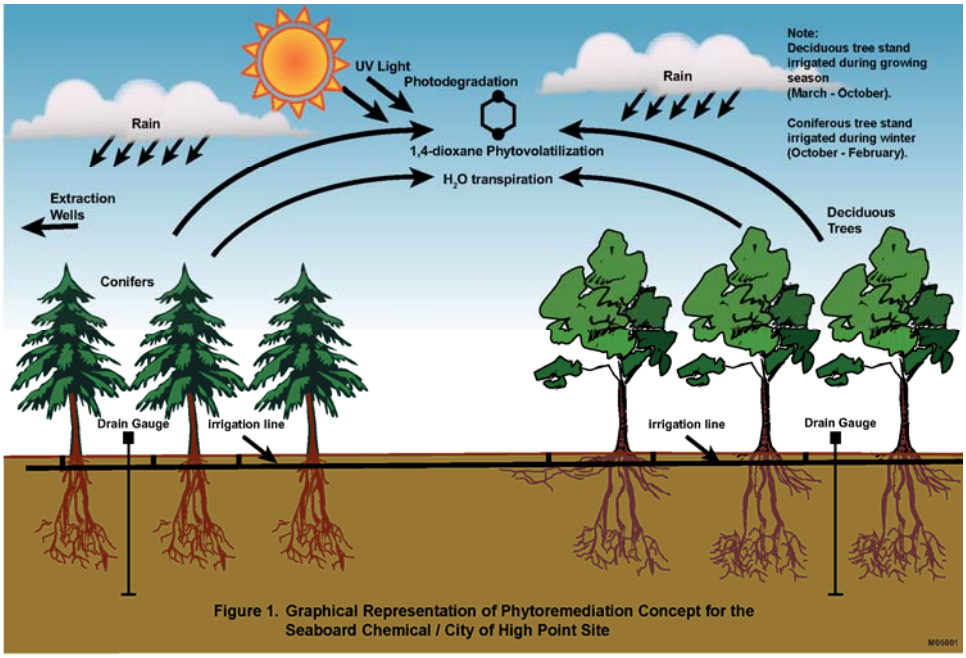


Figure 1. Graphical Representation of Phytoremediation Concept for the Seaboard Chemical / City of High Point Site

2.1.2 TSCF

When taking up water, plant roots can partially exclude or preferentially absorb compounds in solution. The efficiency of the movement of a compound from the soil solution into the shoot is expressed as the transpiration stream concentration factor (TSCF):

TSCF = chemical concentration in xylem sap /
chemical concentration in soil solution in contact with the roots

A TSCF of 1.0 indicates unrestricted passive uptake, meaning that the plant takes up water and the compound at the same rate. Constituents that are excluded to some extent by the plant have TSCF values < 1.0, while a TSCF > 1.0 represents active uptake (typical of N, P, and K). Values for TSCF have been measured for compounds with a wide range of log K_{OW} values (Trapp and McFarlane, 1995; Briggs *et al.* 1982; Burken and Schnoor, 1998). In hydroponic solution or in sandy soil, the highest values for TSCF (approaching 0.9) are generally obtained for compounds with log K_{OW} ~2.

2.1.3 Fate of 1,4 dioxane

The physiochemical characteristics of the 1,4-dioxane are such that many potential biological treatment processes are limited because 1,4-dioxane appears to biodegrade slowly. Also, 1,4-dioxane is considered difficult to remove in a treatment wetland system because it is highly soluble in water and does not sorb strongly to organic matter and thus passes unattenuated through a wetland. It is also very difficult and costly to treat with conventional treatment technologies.

According to the hypothesis upon which the proposed phytoremediation system is based, a number of phreatophytic tree species can take up dissolved 1,4-dioxane from soil water, translocate the compound to the shoots, and then phytovolatilize 1,4-dioxane. In the phytovolatilization process, 1,4-dioxane passes through the stomatal opening of the leaves (through the transpiration process) and into the atmosphere, where the compound is quickly degraded by UV light.

2.2 Phytoremediation Technical Approach

2.2.1 Deciduous and Coniferous Stands

Applying the sizing guidance below with projected water use and irrigation rates it has been established that an 8-acre deciduous stand and a 27-acre coniferous stand will be suitable to take up 100% of the irrigated extracted groundwater by Year 7 following system installation. As shown on sheet C-1, the coniferous and deciduous stands are located in separate adjacent stands; tree species composition within the stands represents a mixed species arrangement, as shown on sheet C-2.

2.2.2 Irrigation with Extracted Groundwater

Groundwater will be extracted from a series of extraction wells along the margins of the Deep River, and delivered to the constructed wetland cell in closed, below grade piping. The extracted groundwater will then be treated in the constructed wetland, then the discharge (with chlorinated VOCs removed) will be routed to the phytoremediation stand in a closed distribution piping system.

In the context of the Site, groundwater containing 1,4-dioxane would be pumped from extraction well PW-DR1, located near the Deep River, and will be used to irrigate the phytoremediation stand of trees on the Landfill. A conceptual irrigation has been designed allowing selective irrigation of the varied areas of the phytoremediation tree stands.

Effluent from the treatment wetland would be used to irrigate large stands of trees located on the western section of the landfill (the upland phytoremediation system). The trees would use the water via transpiration and remove the 1, 4 - dioxane via phytovolatilization. However, the phytoremediation system must operate year-round, and the recovered groundwater is moderately saline (due to carbonate salts). Therefore, a deciduous stand would be irrigated with recovered groundwater during the summer, and winter precipitation would leach accumulated carbonates from the root-zone of the trees. A conifer stand would be irrigated during winter months, and summer rains (or tap water irrigation) would be allowed to leach carbonates from the root-zone of the coniferous trees. The performance requirements for the upland phytoremediation system, specified by the City of High Point, are that there will be no increase in the rate of landfill leachate production (gallons per month) and that there will be no leaching of dioxane and below the root-zone of the trees.

2.3 Design Rationale

The design approach for the effective uptake and phytovolatization of the 1,4 dioxane by the phytoremediation system represents consideration of several factors. These include ensuring the unrestricted uptake of the groundwater containing the 1,4 dioxane; determining the comprehensive water balance for the system to account for climatological factors, which will then allows determination of the appropriate irrigation rate at which extracted groundwater can be applied, and iteratively, determining the size of entire phytoremediation system to successfully manage the 50 gpm design flow anticipated. This section provides a detailed accounting of the entire water budget for the proposed system, and projected water use by the trees. This water use then determines the irrigation rate which ultimately determines the size of the phytoremediation system.

Using these widely regarded design principles for phytoremediation system sizing, the ENSR Team came up with a 35-acre combined stand as the area required for the complete phytovolatization of the 1,4 dioxane given the irrigation rate. This area specified has been developed with a conservative contingency of approximately 20% (system is oversized). The system does have a maturation period, and the design team believes the deciduous stand could receive extracted groundwater during the second growing season following installation and the conifer stand could receive extracted groundwater closer to the third season following installation. We have projected that 100% of the extracted groundwater could be managed in the summer and winter months by Years 7 following installation (under the current planting specification). The specific design and sizing basis is described in detail below.

2.3.1 Sizing Design Equation and Water Use

The rate of transpirational water use for a stand of trees during a given time period can be estimated using the following equation (Ferro et al., 2003):

$V_T = ET * \theta * LAI * A$, where [Eq. 1]

V_T = transpirational water use by the stand,

ET_0 = reference evapotranspiration during the given time period,

θ = the water use multiplier for a tree within a stand, which is equivalent to the rate of water use per leaf as a percentage of ET_0,

LAI = leaf area index (the leaf area per unit area of ground surface),

A = the total area of the stand.

Monthly estimates for ET_0 for the City of High Point area are presented in Table 1. During the growing season (April through October), the average ET/precipitation ratio is 1.3. In the winter months the ratio is 0.63.

Values for θ and LAI are species-specific and depend on planting density and stand maturity. Rough estimates for θ and LAI for a stand of hybrid poplar trees planted on 7 ft centers (approximately 850 trees/acre) growing in the High Point area are shown in Table 2. Note that the LAI increases gradually and would probably reach a plateau (at canopy closure) during the third to fourth growing season, and at this time V_T reaches a maximal value. Mean values for transpirational water use by the stand during the growing season (V_T; gpm/acre) estimated using Equation 1 are shown in Table 2. *For a mature (3 to 4 year-old) stand of poplars, the average rate of water use in May through October is estimated to be 11.5 gpm/acre.*

Equation 1 can give reasonably accurate estimates of V_T, although another key factor in estimating transpiration is potential plant stresses. The equation assumes that the trees are freely transpiring, and any kind of stress – water, nutritional, toxic substances, etc. - can reduce photosynthesis and stomatal conductance. If the stomata close, the transpiration rate is reduced.

2.3.2 Estimates of Water Use for Fast Growing Deciduous Trees

The rate at which a stand of trees could be subirrigated with extracted groundwater without producing excess drainage is approximately equal to V_T minus the rate of soaking precipitation (*i.e*. the precipitation that infiltrates the soil). As the stand of trees matures and V_T increases, the rate that irrigation water could be added also increases. *The expected rate at which a mature 1-acre stand of poplar trees could be irrigated is approximately 9.4 gpm/acre (Table 3).*

Table 1 Climate Data for Highpoint/Jamestown Vicinity.

Month	Pan Evaporation (in.)	ET_0 (=Pan Evap*0.8)	Total Precip. (in.)	Interception (in.)	Corrected Precip. (in.)	ET_0/Precip
Jan	1.8	1.5	4.1	0.6	3.5	0.4
Feb	2.2	1.8	3.5	0.5	2.9	0.6
Mar	4.0	3.2	4.3	0.6	3.6	0.9
Apr	5.3	4.2	3.7	0.6	3.2	1.3
May	6.4	5.1	4.2	0.6	3.6	1.4
June	6.7	5.4	3.9	0.6	3.3	1.6
July	6.7	5.4	4.3	0.6	3.6	1.5
Aug	6.2	5.0	4.2	0.6	3.6	1.4
Sept	4.6	3.7	3.9	0.6	3.3	1.1
Oct	3.5	2.8	3.5	0.5	3.0	0.9
Nov	2.5	2.0	3.2	0.5	2.8	0.7
Dec	1.9	1.5	3.4	0.5	2.9	0.5
Total	51.7	41.4	46.2	6.9	39.3	
Growing season (May to Oct)		31.5	27.7	4.2	23.6	9.3
Winter (Nov to April)		9.9	18.5	2.8	15.7	3.1

Precipitation data is for the City of High Point (monthly averages from weather.com). ET_0 is calculated from the pan evaporation data for Greensboro, NC (the weather station nearest to High Point collecting pan data). Precipitation is corrected for interception by the trees. Daily precipitation less than 0.2 inches is assumed to be intercepted by the stand of trees and evaporated before it reaches the soil (calculated as 15% of precipitation). It is assumed that precipitation greater than 0.2 in/day infiltrates the soil (i.e. "soaking" precipitation referred to in the text).

Table 2 Estimation of average seasonal VT for a 1-acre stand

Year	ET_O (in)	θ	LAI	V_T (gal/min)
1	31.5	0.10	2	0.6
2	31.5	0.60	3.8	6.4
3	31.5	0.70	5.8	11.5
4	31.5	0.68	6.0	11.6
5	31.5	0.68	6.0	11.5
6	31.5	0.67	6.0	11.4
7	31.5	0.66	6.0	11.2

The growing season is May though October. Estimates are given for years 1 to 7.

2.3.3 Estimates of Water Use for Stands of Conifers

Equation 1 was used to estimate V_T for a 1-acre stand of conifers growing at High Point NC (Table 6). Values for V_T are estimated for a 1-acre stand at different stages of maturity both in summer (Table 6A) and winter when ET_0 is low (Table 6B). The values for θ and LAI for the conifer stand are different from those for the poplar stand (specifically θ is lower and LAI is higher) and the time required for the stand to reach maturity (canopy closure) is longer (7 years). *For a mature stand of conifers, it is estimated that the average rate of water use in the winter (November through April) is 4.8 gpm/acre. The rate at which a mature stand of conifers could be subirrigated without producing excess drainage (V_T minus soaking precipitation) is approximately 2.9 gpm/acre (Table 7*).

Table 3 VT and expected irrigation rates for a 1-acre stand of poplars.

Year	ET_o	V_T (gal/min/acre)	Corrected Precipitation (gal/min/acre)	Irrigation Rate (gal/min/acre)
1	31.5	0.5	2.1	-1.6
2	31.5	6.4	2.1	4.3
3	31.5	11.5	2.1	9.4
4	31.5	11.6	2.1	9.4
5	31.5	11.5	2.1	9.4
6	31.5	11.4	2.1	9.3
7	31.5	11.2	2.1	9.1

Estimates are for the growing season (May through October) for the first 7 years after planting.

Table 4 Estimation of average seasonal VT for a 1-acre stand of conifers at High Point NC.

A.

SUMMER				
Year	ETo (in)	LAI	θ	V_T (gal/min)
1	31.5	0.1	0.1	0.03
2	31.5	1	0.15	0.4
3	31.5	2	0.2	1.3
4	31.5	4	0.25	2.8
5	31.5	7	0.3	6.0
6	31.5	9	0.35	8.9
7	31.5	10	0.4	11.3

B.

WINTER			
ETo (in)	LAI	θ	V_T (gal/min)
9.9	0.1	0.1	0.01
9.9	1	0.15	0.2
9.9	2	0.2	0.5
9.9	4	0.25	1.2
9.9	7	0.3	2.5
9.9	9	0.35	3.8
9.9	10	0.4	4.8

A, summer (May through October) B, winter (November to April).

Table 5 VT and expected irrigation rates for a 1-acre stand of conifers. .

Year	ET_o	V_T (gal/min/acre)	Soaking Precipitation (gal/min/acre)	Irrigation Rate (gal/min/acre)
1	9.9	0.01	1.9	-1.9
2	9.9	0.2	1.9	-1.7
3	9.9	0.5	1.9	-1.4
4	9.9	1.2	1.9	-0.7
5	9.9	2.5	1.9	0.6
6	9.9	3.8	1.9	1.9
7	9.9	4.8	1.9	2.9

Estimates are for the winter (November through April) for the first 7 years after planting

Using these calculations as the foundation for the proposed phytoremediation system, the ENSR Team has conducted greenhouse and a field-scale pilot program over the last two years to test these concepts and reinforce our support for the system with specific focus on tests for specific trees species ability to take-up and phytovolatilize the 1,4 dioxane, water use, growth, irrigation rate and other variables such as the ability of the landfill to support a large tree plantation. Applying the sizing guidance above with projected water use and irrigation rates we have established that an 8-acre deciduous stand and a 27-acre coniferous stand will be suitable for 100% of the irrigated extracted groundwater by Year 7 following installation. The proposed primary location of the full-scale

phytoremediation system is on the western and central lobe of the Landfill where there is sufficient land available to site a 35 acre tree stand. Research of the soil cap and soil characteristics in this area indicates that the soil will be conducive to establishing a large tree plantation without significant soil amendments. In addition as this is the older section of the landfill, most of the settling has already occurred. Therefore there are a number of very favorable factors supporting this location. The ENSR Team is currently conducting a long-term field-scale pilot program with four test plots established and scaled to mimic the full-scale system. We are collecting ongoing data from this program and this will program will serve as the basis for the final design of the full-scale system.

2.4 Summary of Greenhouse Studies and Field Piloting

2.4.1 Initial Greenhouse Study Objectives and Summary

An initial Greenhouse pilot study of the effectiveness of upland phytoremediation for treatment of recovered Site ground water was conducted over a six month period. The study was conducted over a six month period (October 2003 to March 2004) to test the hypothesis that phreatophytic poplar trees, and potentially other tree species, can take up dissolved 1,4-dioxane from soil moisture, translocate the compound to the shoots, and then phytovolatilize it. A supplemental greenhouse study was undertaken to expand the candidate tree species for the full scale system.

The Greenhouse Study evaluated five different species of trees (hybrid poplar saplings and four species of conifers) to determine the most effective variety for the specific Site conditions. Complete details of the study methodology are found in the *Work Plan for a Greenhouse Study to Test the Feasibility of the Conceptual Design for an Upland Phytoremediation System* (ENSR/Phytokinetics, 2003b). The results of that study indicated the following major points:

- In the 1,4-dioxane tolerance study, there was no decrease in plant biomass production for any of the species across the four concentrations of 1,4-dioxane tested, therefore it was determined that 1,4-dioxane is not phytotoxic at these concentrations.
- In the phytovolatilization study, the Transpiration Stream Concentration Factor value for the hybrid polar and Ponderosa pine saplings indicated that 1,4-dioxane is readily taken up by these species.
- The hybrid poplar saplings could phytovolatilize 1,4-dioxane at an 11-fold greater rate than the most promising conifer species, the Ponderosa pine.
- The hybrid poplar appeared to be tolerant of the Site's saline ground water and tended to exclude manganese, a potentially phytotoxic metal, which the Ponderosa pine accumulated (but did not show any deleterious effects within the short duration).

The results suggest that fast growing phreatophytic species including poplars and possibly willows (*Salix* spp.) will effectively take up the ground water at the Site without adverse effects from mineral salt accumulation, will not accumulate potentially phytotoxic metals, and will provide an efficient and cost-effective remedial treatment option for removing 1,4-dioxane from the recovered ground water via phytovolatilization.

2.4.2 Supplemental Greenhouse Study Objectives and Summary

Additional greenhouse studies were carried out in July and August 2005 to address the observation reported above that certain deciduous tree species (e.g. poplars and willows) developed chlorosis when irrigated with the Seaboard groundwater. The additional studies were carried out in the following two phases: *Phase 1* studies with hybrid poplar DN-34 to determine a) if the addition of chelated iron (Fe-EDDHA) could prevent the chlorotic symptoms; and b) the optimal concentration of Fe-EDDHA that would produce the desired effect. *Phase 2* studies were carried out with a variety of deciduous tree species. These species were irrigated with Seaboard groundwater plus/minus the optimal Fe-EDDHA concentration that was determined in Phase 1.

Phase 2 methodology included establishment of Individual saplings in pots containing a sandy loam soil. For each tree species investigated, triplicate sets of pots were surface irrigated either with tap water, with site groundwater (Table 1, 07/14/05 analysis), or with site groundwater containing various concentrations of Fe-EDDHA (Sequestrene 138 Fe; Becker Underwood, Inc.). In all cases, the irrigation water contained Peter's water soluble fertilizer (20-20-20 plus micronutrients) at a concentration of 360 mg/L. Chlorometer readings were obtained for three leaves per sapling at weekly intervals, and mean values calculated.

In Phase 1 of the greenhouse study, five different tree species were tested for tolerance to 1,4-dioxane dissolved in tap water. It was anticipated that 1,4-dioxane could be phytotoxic at sufficiently high concentrations. In this tolerance study, there was no decrease in plant biomass production for any of the species across the four concentrations of 1,4-dioxane tested (i.e., 0, 25, 50, and 75 mg/L). It was determined that 1,4-dioxane is not phytotoxic at these concentrations, therefore a concentration of 75 mg/L 1,4-dioxane was selected for the phytovolatilization study. Also, the hybrid poplar appeared to be tolerant of the Site's saline groundwater and tended to exclude manganese (Mn), a potentially phytotoxic metal, which the Ponderosa pine accumulated (but did not show any deleterious effects within the short duration).

The preliminary series of experiments were performed to determine: a) if the addition of Fe-EDDHA could prevent the chlorotic symptoms; and b) the optimal Fe-EDDHA concentration. The results are shown in Figure 4. In Group A (saplings irrigated with tap water), the mean chlorometer readings were relatively constant throughout the duration of the five-week study. Groups B and C were irrigated with groundwater, and the decreasing chlorometer readings were a quantitative measure of the developing chlorotic condition. This result confirmed the previous observations (Section 3.7). Addition

of Fe-EDDHA to the groundwater irrigant prevented chlorosis: In sets D through G, the iron concentration was systematically increased. An Fe-EDDHA concentration of 1.2 mg Fe (the concentration used for Set F) was chosen for further experiments.

In Phase 2, tests were carried out for a variety of deciduous species to determine their tolerance to the Seaboard groundwater (as judged by the development of chlorosis) and the effects of amending the groundwater with chelated iron (1.2 mg Fe/L). The species tested were listed in Section 1.0. The species fell into the following categories:

1) Species that did not develop chlorosis and that transpired groundwater at the same rate (or at a higher rate) than tap water. Hackberry, Kentucky coffee tree, Russian mulberry and elm were in this category.
2) Species that developed chlorosis, but for which these symptoms could be prevented using chelated iron. Hybrid poplar DN-34, alder, sycamore, and black locust fell into this category.
3) Hackberry, Kentucky coffee tree, Russian mulberry and Chinese elm did not show symptoms of chlorosis (Figure 5), and appeared to thrive when irrigated with the groundwater. For these species, the transpiration rate was greater when groundwater was used as an irrigant than when tapwater was used as an irrigant (Figure 6). On the other hand, alder sycamore, and black locust tended to develop chlorosis (Figure 5). This effect was immediate for alder, but somewhat delayed for black locust. Addition of chelated iron prevented chlorotic symptoms and these species thrived on the amended groundwater (Figure 6).

As mentioned above, suitable candidate species must be tolerant of Seaboard groundwater, have a high TSCF for dioxane, and have a reasonable transpiration rate. The deciduous species Kentucky coffee tree, hackberry, Chinese elm, and Russian mulberry were tolerant of the groundwater, and the coffee tree also had a high TSCF for dioxane (Table 2). Note that hackberry, Russian mulberry, and Chinese elm were not tested in the greenhouse studies reported in Section 3.0.

Although hybrid poplar DN-34, sycamore, alder, and black locust were not tolerant of the unamended groundwater, these species thrived when Fe-EDDHA was added to the irrigant. Hybrid poplar DN-34 and sycamore also had a high TSCF for dioxane (Table 2). Alder and black locust were not tested in the previous greenhouse studies. The deciduous species that thrived when irrigated with the amended groundwater could be considered suitable candidates for the full-scale upland phytoremediation system. For example, the recovered groundwater irrigation system for the tree stands on the landfill could be divided into zones: Species requiring the addition of chelated iron to the water could be planted in zones equipped with a nutrient injector system.

2.4.2.1 Tree Species Selection for Full Scale System

The basis for selecting coniferous and deciduous tree species for the full–scale upland phytoremediation system was the performance of the species in the various phases of the greenhouse studies (2, 3). Principally, suitable candidate species must remain robust when irrigated with Seaboard groundwater, have a high TSCF for dioxane, and have a reasonable transpiration rate. The performance of the different species is summarized in Table 2. The conifers judged to be the best candidates, include the following: Western red cedar, slash pine, and loblolly pine. Japanese black pine is also a good candidate. The deciduous tree species considered to be best suited for the project was Kentucky coffee tree. Note that the Kentucky coffee tree, while an excellent candidate, is considered to have a moderate growth rate. Rapidly growing white willow, hybrid poplar DN-34, and Chinese elm are the other deciduous species selected.

The high TSCF for dioxane reportedly by Aitchison et al (2000) for hybrid poplar DN-34 is not unique to this specific hybrid. Other poplar hybrids (OP-367) and other deciduous species (Kentucky coffee tree and sycamore) also have the ability to efficiently take up dioxane. Moreover, surprisingly high TSCF values for dioxane were also obtained for a variety of conifers. We may tentatively conclude that the tendency for dioxane to be taken up by plants is a characteristic of the compound itself (e.g. its miscibility with water and relatively small molecular size), and not a characteristic that is specific to certain plants. Table 6 provides the proposed tree planting schedule for the full scale system.

In the relatively mild climate of North Carolina, the growing season for the candidate species is very long compared to other locations in the country that are well within the natural range of poplars. Specifically in Raleigh (Zone 7b), poplars may actively transpire from late March through November (8-9 months). Therefore, in North Carolina, fast-growing, water-loving tree species such as willows (*Salix* spp.), can be considered for a phytoremediation systems in which a positive water balance must be maintained year round.

2.4.2.2 Field Pilot Testing

A field scale pilot project, started in 2004, involves four small plots on the western section of the landfill. Two plots were planted with hybrid poplar, one plot was planted with Japanese black pine, and one plot (not planted with trees) has the original cover of weeds. The objective of this on-going pilot is to test the feasibility of irrigating the tree stands with recovered groundwater while maintaining the abovementioned performance requirements while testing to determine if surplus drainage results.

The small scale field pilot remained in a setup and establishment mode for 2005. Conifers were installed during the initial setup in November 2004 and poplars were installed in April 2005. The plots are plumbed to receive city tap water and/or extracted groundwater. The plots include complete measurement instrumentation, and ENSR has been collecting baseline information since December 2004 via remote telemetry. The current plan is to begin irrigating the poplars in April 2006 to begin

assessing water use, transpiration, irrigation rates, and the efficacy of the system in phytovolatilizing 1,4 dioxane.

3.0 PRELIMINARY FINAL DESIGN COMPONENTS OF CONFIGURATION

3.1 Preliminary Final Design

3.1.1 Location, Size, and Configuration of Tree Stands

Sheet C-1 illustrates the proposed location of the 35 acre upland phytoremediation system. Located on the western part of the Landfill, the irregularly-shaped stand is comprised of an 8 acre stand of deciduous tree species due east of a contiguous 27 acre stand of conifers. As shown on the attached plan sheets, the proposed system is installed in north-south oriented rows, with an existing mature stand of loblolly pine incorporated into the southern boundary of the system.

3.1.2 Proposed Tree Species

The following tree species are currently proposed for the full-scale upland phytoremediation system. Substitutions to this proposed list may be made based upon availability or preferable treatment capacity based upon whether iron supplements are included within the extracted groundwater used for irrigation.

Table 6 TREE PLANTING SCHEDULE SEABOARD PHYTOREMEDIATION SYSTEM				
Deciduous species				
	Species Name		Total Number	Average Size
	Hybrid poplar var. DN-34 (*Populus deltoides x nigra*)		605	2’-4’ bare root
	White willow (*Salix alba*)		605	2’-4’ bare root
	Chinese elm (*Ulmus parvifolia*)		605	2’-4’ bare root
	Kentucky coffee tree (*Gymnocladus dioica*)		605	2’-4’ bare root
	Coniferous species			
	Loblolly pine (*Pinus taeda*)		1890	1’-2’ bare root
	Japanese black pine (*Pinus thunbergii*)		1890	1’-2’ bare root
	Western red cedar (*Thuja plicata*)		1890	1’-2’ bare root
	Slash pine (*Pinus elliottii)*		1890	1’-2’ bare root

3.1.3 Landfill Surface Preparation for Establishing Trees

In order to prepare the landfill surface for the planting, it would only be necessary to mow the weeds and tall grass. All trees currently established on the landfill would be left undisturbed. These trees could be incorporated into the upland phytoremediation system.

3.1.4 Tree Installation

Planting stock would be primarily bare root saplings (1 to 2 ft for the conifers, 2 to 4 ft for the deciduous trees). Conifers of this size are generally 3 years old (2 years growth in seedbeds, 1 year in transplantation beds). Planting can be done in either late fall (late October, November) or early spring (late February, March). The best success rate would most likely be obtained with a late fall planting. Plant availability is one limiting factor for fall plantings, but if orders are placed early that same year, stock can usually be secured. A mechanized tree planter would be used, with which two workers can plant three trees per minutes. The machine cuts a trench 6 to 8 in wide and 8 in deep. Saplings are set in and pressure wheels close the trench around the tree while it is kept in an upright position. All trees would be planted on 12 ft centers. It is very important that spring planting be done early, as soon as the soil can be worked. Trees that can tolerate moist, poorly drained conditions (e.g. willow and loblolly pine) would be planted in the swales.

3.1.5 Groundwater Delivery and Irrigation Conceptual Approach

The total area of the upland phytoremediation stands will be 35 acres: 8 acres of deciduous trees and 27 acres of coniferous trees. All of the trees will be planted on 12 ft centers, and thus there will be approximately 300 trees per acre. The trees will be irrigated so that 50 gpm of recovered groundwater will be continuously routed to selected components of the stand. The conifers will be irrigated in winter (November through April) and the deciduous trees in summer (May through October). An aboveground storage tank will be incorporated to store water during extended frost periods or during heavy precipitation events.

The phytoremediation system will be divided into irrigation zones, as shown in Table 7. There will be deciduous zones (D-system) and coniferous zones (C-system). Further conceptual details are provided below:

- The design of the system will assure that there is sufficient time between irrigation cycles to allow water to percolate into the soil. It also helps prevent areas of the landfill with relatively poor percolation rates (or that tend to receive storm water run-off) from becoming overly wet.
- One plant species will be planted per zone, generally corresponding to individual rows within the system. The different tree species will have different growth rates, different rates of water use, and different soil moisture requirements. Therefore, the one species/zone approach will help with optimizing soil moisture for each species.
- The actual irrigation delivery system (e.g. large surface aerial sprayers (rain birds) or surface emitters) is being determined.
- The basis for the design of the irrigation system is that 50 gpm of recovered groundwater must be dispensed continuously year round. Therefore, the system is not designed like a

conventional irrigation system that dispenses water to the plants when the soil is sufficiently dry (i.e. when the plants need water). We expect that during some periods (e.g. during a rain storm in January) the system may irrigate planted soil that is already at field water holding capacity and the irrigation water will be held in the soil profile (i.e. in the "sponge") until rapid plant transpiration commences the next warm dry day. Moreover, the proposed irrigation system is not designed to simply irrigate the various zones on a timed schedule. Employing that type of conventional system some of the zones, such as those in low lying areas of the landfill or areas with low percolation rates, could allow excessive irrigation during cold, wet periods, resulting in standing water and potential runoff. Note that the design of the proposed system could be simplified, and a more conventional system could be used, if there were an adequate contingency for the storage of recovered groundwater (Section 3.1.8).

- *Water supply system*. Water main lines will be routed to a central location in each zone in 18" deep trenches, and terminate in a utility box containing a single valve and the system will be frost proof and incorporate above ground storage for extended frost periods or during heavy precipitation events.

Table 7 Irrigation zones for the upland phytoremediation system. The density of the coniferous and deciduous stands will be 300 trees/acre, and the stand will be comprised of 2420 deciduous trees and 7,560 coniferous trees (~10,000 trees total on 35 acres).

Irrigation Systems	Total Acres	Irrigation Zones	Per Zone	
			Acres	Trees
D-System	8	TBD	TBD	TBD
Deciduous				
C-System	27	TBD	TBD	TBD
Coniferous				
TOTALS	35			

3.1.6 Power Requirements and Instrumentation

The conceptual instrumentation requirements for the irrigation zones are outlined below.

- Two SM200 soil moisture content probes installed 50 ft apart at 8" bgs. These probes will be used by the Master Controller to select the driest zones for irrigation.
- Two conductivity probes (547-L20) installed at 8" bgs in the same areas (50 ft apart) as the SM200 probes. These probes will track the build-up and leaching of salts in the root-zone of the trees (see Section 3.1.9).

- Two soil moisture probes set at 1 ft bgs and 3 ft bgs. Data from these probes will be continuously monitored and the data used in conjunction with the data from the soil moisture release curves (Section 3.1.11) to estimate drainage.
- Two suction lysimeters would be installed in each zone: One would be installed at 8" bgs and one at 3 ft bgs. These instruments would be used to obtain samples of water from the vadose zone. Samples would be taken at regular intervals and analyzed for 1,4-dioxane.
- Data loggers, multiplexars, and the Master Controller network would require standard electrical power sources.

3.1.7 Contingency Groundwater Storage

A capability to store recovered groundwater during cold wet periods (for example during a storm in January) would make it possible to simplify the design of the groundwater delivery and irrigation technical approach described in Section 3.1.6. We have proposed a location near the constructed treatment wetland for storage (this location can accommodate a 1.0 million gallon storage tank or basin).

3.1.8 Seasonal Irrigation Technical Approach

Seaboard groundwater would be continuously pumped year-round by the recovery wells at a rate of 50 gpm. The groundwater would be routed to the treatment wetlands, and effluent from the wetlands would be used to irrigate the upland phytoremediation system. The recovered groundwater is moderately saline due to carbonate salts (2000 µmhos/cm; TDS = 1200 mg/L; HCO_3 ~ 980 mg/L). If a single tree stand was continuously irrigated with the groundwater, salts would gradually accumulate in the soil and could eventually reach toxic levels. Therefore, two different tree stands will be irrigated with the groundwater: A deciduous stand in the summer (May through October) when ET is high, and a coniferous stand in winter (November through April) when ET is low. Irrigation of the stands will be seasonally altered to prevent carbonate accumulation. Summer rains (or tap water irrigation) will leach salts from the conifer stand, and winter rains will leach salts from the dormant deciduous stand. The conifer stand must be relatively large because of low transpiration rates in winter months.

One key aspect to managing the upland phytoremediation system on the landfill is the "sponge and pump" concept. Each fall, prior to the start of the irrigation cycle for the conifers, it is important that the soils of the conifer stand be as dry as possible so that they can act as a sponge. The water that is put to the system in winter (precipitation and irrigation) either can be used via transpiration or, if that rate of water use is exceeded on cold days, it can be held in storage by the "sponge" (i.e. the dry soil as it is brought up to field capacity). Thus, it is not necessary to use the entire 50 gpm of irrigation water every day during the winter. On some cold days, excess water can be added to the "sponge", and this water can be removed via transpiration on warm winter days. As a corollary to this management approach, the salts that accumulate in the soil of the conifer stand during the winter irrigation cycle

must be leached out early in the summer, so that the soil has time to dry out prior to the start of the irrigation cycle the following fall. Depending on rain fall and the data from the salinity probes, it may be necessary to irrigate the conifer zones with plenty of tap water starting in May.

No special management would be needed for the deciduous stand. By November, it would be dormant and precipitation (through the following April) would likely be adequate to leach the salts that accumulated during the previous summer's irrigation cycle. Note that because the footprint of the deciduous stand is smaller than that of the conifer stand (8 acres vs. 27 acres), and both stands are irrigated with the same total volume of recovered groundwater (13 million gallons per 6 months); the soil of the deciduous stand would accumulate more salt (primarily in the form of bicarbonate salts of Ca, Mg, and Na) than that of the conifer stand. Preliminary calculations indicate that after 6 months of irrigation with the groundwater, 4.3 g/Kg dissolved solids would accumulate in the top 1 ft of soil in the deciduous stand. The salt accumulation would increase the salinity of the soil from 0.2 mmhos/cm to approximately 8 mmhos/cm by the end of the irrigation cycle. This amount of salt accumulation may have some effects on the most sensitive species (see Section 3.1.12 for a management plan), and if the salinization was allowed to continue unchecked for several years, toxic effects predictably would be observed.

3.1.9 Fencing and Security

A six foot fence, with several double gates for maintenance equipment, will be constructed around the upland phytoremediation system to keep out potential tree predators such as deer and beaver. Fencing will be especially important during the first few years of stand development.

3.1.10 Sampling and Analysis Plan

Prior to the installation of trees, the site will be marked out into the irrigation zones. The soils in each of these zones will be characterized in regard to the water holding capacity at 0.2, 0.33, and 1 Bar of soil suction. These types of data are already available for some locations in the western portion of the landfill, and additional data will be collected during proposed 2006 characterization studies. However, there may be additional locations in which soil samples will be taken (0 to 3 ft bgs cores samples) and three point soil moisture release curves obtained for the composite sample. These data are necessary in order to estimate the extent of drainage in the various irrigation zones. As mentioned in Section 3.1.7, soil moisture probes will be installed in representative irrigation zones at 1 ft bgs and 3 ft bgs. The combined data from these probes (percent soil moisture) and the moisture release curves (percent soil moisture vs. Bars of soil suction) would be sufficient to determine whether or not drainage was occurring. For example, if the probe at 3 ft bgs indicated a percent soil moisture less than the field capacity (the percent soil moisture at 0.33 Bars soil suction) it could be concluded that no drainage was occurring. Conversely, a percent soil moisture corresponded to a valve indicating between 0.2 and 0.33 Bars would indicate that drainage was occurring. However, the exacts rates of drainage could not be determined from these data.

The pairs of conductivity probes installed at 8" bgs in the irrigation zones would track the accumulation and leaching of salts in the root zone of the trees. This tracking would be done automatically using a data logger. The salts (total dissolved solids from the groundwater irrigant, primarily bicarbonate salts) could accumulate in the soil, especially in the deciduous stands.

Suction lysimeters would be installed at two different depths in a representative irrigation zone; one would be installed at 8" bgs, and one at 3 ft bgs. Samples of vadose zone water would be collected at regular intervals and analyzed for 1, 4-dioxane. Comparisons of the dioxane concentrations at these two depths would indicate the effectiveness of dioxane phytovolatilization. The dioxane concentration of the soil water at 8 in bgs would presumably be the same as that in the irrigation water; the concentration a 3 ft bgs would be the concentration in the drainage water below the root zone of the trees. For the deciduous stand, samples would be analyzed in the middle and end of the irrigation period (July and October); for the coniferous stand, samples would be analyzed in January and April.

3.1.11 Operation, Monitoring, and Maintenance

As the deciduous and coniferous tree stands mature, their transpiration rates gradually will increase. Maximum rates of water use for the stands will be attained at the time of canopy closure (3 to 4 years for the deciduous stands, and approximately 7 years for the conifers). Starting from the first growing season, recovered groundwater can be used to irrigate the stands. The rate of ground water irrigation (in winter for the conifers; in summer for the deciduous stand) would be scaled appropriately to the stage of stand maturity.

The monitoring of the accumulation and leaching of salts was outlined in Section 3.1.9, and the approach for monitoring the effectiveness of dioxane phytovolatilization discussed in Section 3.1.11. The management objective for the irrigation system is to maintain the percent soil moisture at 3 ft bgs at or less than field capacity in all of the irrigation zones. An adequate contingency groundwater storage capacity (Section 3.1.8) would help in meeting this management objective. For example, during storms in January, recovered groundwater could be stored for use during warmer dry winter days. In the event that salt effects are suspected in late summer for deciduous species in certain irrigation zones, one option would be to route the irrigation water from those zones to an appropriate number of conifer zones in the C-system.

A check list would be developed to accomodate routine maintenance of the Master Controller system, the drip irrigation system, as well as for the other instruments listed in Section 3.1.7.

3.1.12 Tree Stand Maintenance

The area between the trees will be kept mowed to prevent competition from weeds and to prevent the accumulation of thatch, a breeding ground for rodents. The trees will be side dressed with slow release fertilizer including micronutrients each spring, and will be appropriately pruned. Dead or dying

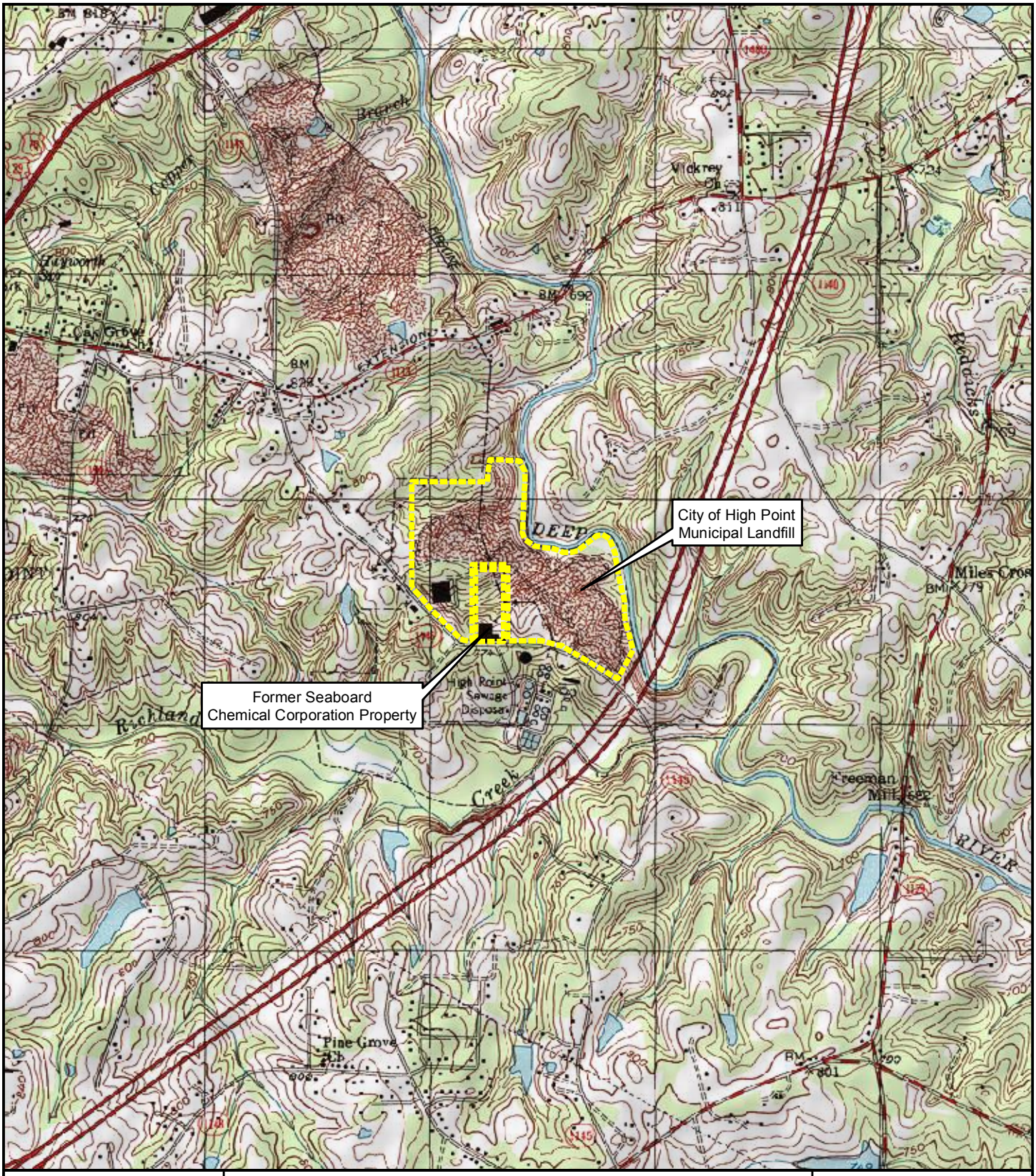
trees will be replaced. The stands will be regularly inspected for evidence of excessively wet soil conditions, salt effects (Section 3.1.12), browsing animals (deer, beaver), rodents, insects, and pathogens, and appropriate measures taken to address these issues. Such measures include, for example, adjusting the regulation of the irrigation system, repairing the fences, setting out repellents, traps, baits, and spraying. Cankerous trees will be removed from the site and replaced if necessary with trees of another variety. Leaves will be examined for signs of nutrient deficiency, and if found a soil sample will be analyzed to determine a fertilization regimen.

4.0 ONGOING PILOTING AND FUTURE WORK

The ENSR Team is still collecting data from ongoing field piloting activities that will shape the final design. These programs will continue in 2006 in order to develop the final configuration and specifications for the final phytoremediation system design.

LIST OF FIGURES

Figure 1 Site Location Map



Map Location

Site Location Map

Former Seaboard Chemical Corp. and City of High Point Landfill

Jamestown, North Carolina

N

Projection: UTM Zone 17N, North American Datum 83, Meters.
Source: USGS Topographic Quadrangle, High Point East, NC (1993).
Scale: 1:24,000

0 500 1,000 2,000 3,000 4,000 5,000 6,000 Feet

0 100 200 400 600 800 1,000 1,200 1,400 1,600 Meters

ENSR INTERNATIONAL

Figure 1

April 2005

Project #: 08734-679-615

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Appendix A

Phytoremediation System Preliminary Design Plans (Sheet C-1 and C-2)