1,4-DIOXANE AND THE APPLICATION OF PHYTOREMEDIATION AT NORTH CAROLINA HAZARDOUS WASTE GROUNDWATER CONTAMINATED SITES

By

Heather Sorensen

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Approved by advisory committee:

Committee Chairs
Dr. Elizabeth Nichols
Linda Taylor

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Abstract

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1,4-Dioxane is a manufactured chemical that is considered to be recalcitrant in nature due to its inability to be remediated through traditional groundwater remediation systems and its inability to degrade under ambient groundwater conditions. 1,4-Dioxane has been established as “likely to be carcinogenic to humans by all routes of exposure” by the United States Environmental Protection Agency. Through historical releases and improper disposal of industrial waste and accidental spills of 1,4-dioxane chemicals to the environment, groundwater has become contaminated with 1,4-dioxane. The goal of this paper is to identify Treatment Storage and Disposal Facilities in North Carolina with 1,4-dioxane contaminated groundwater and evaluate the potential application of phytoremediation as a viable remedial option for 1,4-dioxane. Through the investigation of 1,4-dioxane and phytoremediation, this paper explores why 1,4-dixoane is a constituent of concern and why phytoremediation should be considered as an remediation strategy for contaminated groundwater. Twelve 1,4-dioxane hazardous waste sites with 1,4-dioxane contaminated groundwater were provided by the North Carolina Department of Environment and Natural Resources, Division of Waste Management, Hazardous Waste Section. Six out of the twelve sites were assessed for phytoremediation applicability. This assessment demonstrates that phytoremediation should be considered as a viable remedial option for 1,4-dioxane, specifically at sites that have no current remediation strategy and that have access to space for a phytoremediation tree stand.

Biography

Heather Sorensen is an Environmental Senior Specialist with North Carolina Department of Environment and Natural Resources, Division of Waste Management, Hazardous Waste Section, Compliance Branch. She has worked in the environmental field since 2000 with focus in Hazardous Waste Compliance, Surface Water Protection, and Environmental Education. She received her Bachelors of Science degree from the University of North Carolina at Charlotte. Heather Sorensen currently resides in Charlotte, North Carolina.

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I extend all my love to my family and friends, which have provided unlimited support and encouragement.

This paper is for all graduate and undergraduate students that are the first in their families to push forward into higher education.

List of Acronyms

ADH	Active Dowtherm® Heaters
AOC	Areas of Concern
COC	Constituents of Concern
DCA	Dichloroethane
DCE	Dichloroethylene
DL	Detection Limit
DWM	Division of Waste Management
EPA	U.S. Environmental Protection Agency
FID	Flame Ionization Detector
FMB	Facility Management Branch
GC	Gas Chromatographic
GIS	Geographical Information System
HEAA	β-hydroxyethoxy Acetic Acid
HSWA	Hazardous and Solid Waste Amendment
HWS	Hazardous Waste Section
IHSB	Inactive Hazardous Sites Branch
K_H	Henry's Law Constant
K_{OC}	Soil Organic Carbon-Water Partition Coefficient
K_{OW}	Octanol-Water Partition Coefficient
MCL	Maximum Contaminant Level
MDL	Method Detection Limit
MS	Mass Spectrometer
NCAC	North Carolina Administration Code
NCDENR	North Carolina Department of Environment and Natural Resources
NPDES	National Pollutant Discharge Elimination System
PCE	Tetrachloroethene
PTRG	*Phytotechnology Technical and Regulatory Guidance and Decision Trees, Revised*
RCRA	Resource Conservation and Recovery Act
SWMU	Solid Waste Management Unit
TCA	Tetrachloroethane
TCE	Trichloroethylene
TSDF	Treatment, Storage, Disposal Facility

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INTRODUCTION

The State of North Carolina has been granted final authorization from the United States Environmental Protection Agency (EPA) under the Federal Resource Conservation and Recovery Act (RCRA) section 3006(b), 42 U.S.C. 6926(b) to “maintain a hazardous waste program that is equivalent to, consistent with, and no less stringent than the Federal program” (1). Final authorization to implement a hazardous waste program was initially granted on December 14, 1984 (1). It is under this program that the State of North Carolina has responsibility for permitting treatment, storage, and disposal facilities (TSDFs) and for carrying out the RCRA Federal program, including 40 CFR parts 124, 260 through 268, 270, 273, and 279 within its borders, excluding Indian Country (1). North Carolina incorporated by reference specific RCRA Federal program rules, as well as state specific additions and revisions, in the North Carolina Administrative Code, Title 15A, Chapter 13, SubChapter A, .0101 through .0119. The Facility Management Branch (FMB) of the North Carolina Department of Environment and Natural Resources (NCDENR), Division of Waste Management (DWM), Hazardous Waste Section (HWS), is responsible for issuing operating permits and Administrative Orders on Consent to TSDFs and providing oversight for facilities that must investigate and clean-up hazardous waste releases to the environment.

The goal of this paper is to identify TSDFs in North Carolina with 1,4-dioxane contaminated groundwater and evaluate the potential application of phytoremediation as a viable remedial option for 1,4-dioxane. 1,4-Dioxane is a toxicant of interest due to its chemical and physical properties that make it recalcitrant in nature and challenging to remediate (2). Its toxicological properties make it likely to be carcinogenic to humans (3).

1,4-Dioxane

Historic and Current Day Uses

1,4-Dioxane was first reportedly commercially produced in 1951 and has been used as a solvent, stabilizer and a byproduct of polyester manufacturing, among various other industrial applications (4; 5). 1,4-Dioxane was primarily used as a stabilizer for the solvent methyl chloroform, also known as 1,1,1-tetrachloroethane (TCA) (6). 1,4-Dioxane is also used in consumer products as a surfactant component that may end up discharged in industrial wastewater (5). 1,4-Dioxane may be found in trace amounts in cosmetics as a byproduct of certain cosmetic ingredient manufacturing processes, including detergents, foaming agents, and emulsifiers (7). Although the U.S. Food and Drug Administration has stated that the “FDA has not established or recommended a specific limit on the level of 1,4-dioxane in cosmetics”, they have provided guidance on “vacuum stripping” at the end of the polymerization process to aid in evaporation of 1,4-dioxane (7).

In 1995, the EPA reported that in 1985 approximately 90% of the US production of 1,4-dioxane was used as a stabilizer for chlorinated solvents, particularly TCA (6). Industrial application of trichloroethylene (TCE) as a stabilizer moved to TCA after TCE was identified as an animal carcinogen (6). Likewise, the use of CFC-113, a chlorofluorocarbon, as a solvent was replaced with TCA as a less potent ozone depleter (6). However, production of CFC-113 and TCA was banned in the United States in 1996 as part of the Montreal Protocol, along with a tax on both of these chemicals to deter their use (8). Production ban of TCA has moved industry to use TCE, methyl ethyl ketone, toluene, xylene, methyl isobutyl ketone, glycol ethers, and isopropyl alcohols as alternatives (8). Through historical or improper disposal of industrial wastes and accidental spills, groundwater has become contaminated with 1,4-dioxane (5). Thus, it can be surmised that most of the 1,4-dioxane groundwater contamination that is present in North Carolina is due to the historical releases and not from current day activities.

Chemical and Physical Properties

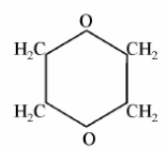

Figure 1: 2-Dimensional Structure of 1,4-Dioxane
Source: U.S. Environmental Protection Agency, 2006.

1,4-Dioxane is a manufactured chemical with a heterocyclic structure containing two symmetrically opposed ether linkages. 1,4-Dioxane has two oxygen atoms that make the molecule hydrophilic and completely miscible in water (5). Physical and chemical properties of 1,4-dioxane are listed in Table 1.

Table 1: Physical and Chemical Properties of 1,4-Dioxane (9; 10; 11; 12; 13; 14; 15)

Property	Value
CAS number	123-91-1
Molecular Formula	$C_4H_8O_2$
Physical State	Flammable liquid, faint pleasant odor
Aqueous Solubility	Miscible
Molecular Weight	88.10
Melting Point	11.80°C
Boiling Point	101.1°C at 760 mm Hg
Water Solubility	Soluble in water
Density	1.0329 g/mL at 20°C
Vapor Density (air = 1)	3.03
K_{OC}	1.23
Log K_{OW}	-0.27
Vapor Pressure	30 mm Hg at 20°C
Reactivity	Tends to form explosive peroxides especially when anhydrous
Flash Point	5-18°C

Property	Value
Henry's Law Constant	4.88 x 10^{-6} atm·m3/mol
Log Bioconcentration Factor	-0.44, calculated
Bioaccumulation Factor	0.2-0.7

Analytical Methods

Historically, analytical detection of 1,4-dioxane was limited due to technological constraints in obtaining a low detection limit. 1,4-Dioxane is fully miscible with water, which makes low detection levels difficult to achieve (5). In 1997, analytical technologies became available that allowed for the detection of 1,4-dioxane in the parts per billion range (16). This lower detection limit has made it possible to test for 1,4-dioxane at contaminated sites and to establish lower regulatory limits. The limitations presented by the available analytical technology also limited knowledge of 1,4-dioxane levels at historically contaminated sites. Thus, 1,4-dioxane can re-open closed contamination sites due to the presence of 1,4-dioxane at levels above regulatory limits. A few of the current analytical methods include gas chromatography (GC) methods with a flame ionization detector (FID) or mass spectrometer (MS) (5). Table 2 presents a comprehensive outline of available analytical methods.

Table 2: 1,4-Dioxane Analytical Methods

MATRIX	METHOD	INSTRUMENTATION	DETECTION LIMIT
Soil, Water	EPA SW 846 Method 8015	GC/FID	15 µg/L (MDL)
Soil, Water	EPA SW 846 Method 8240	GC/MS Purge and trap or direct injection	
Soil, Water	EPA SW 846 Method 8260	GC/MS	*
Soil, Water	EPA SW 846 Method 8260 SIM	GC/MS-SIM	0.5 - 10.0 µg/L (MDL)
Soil, Water, Tissue	EPA SW 846 Method 8261	VD/GC/MS	1.1 µg/L (MDL)
Soil, Water	EPA SW 846 Method 8270	GC/MS	0.23 - 1.0 µg/L (MDL)
Soil, Water	EPA SW 846 Method 8270 SIM	GC/MS-SIM	
Air	EPA Method TO-15	GC/MS	
Water	EPA Method 1624 (Note compound listed as a method analyte)	ID GC/MS	
Air	NIOSH 1602	GC/FID	
Water	EPA Method 522	SPE, GC/MS-SIM	0.020 -0.036 µg/L (DL)
Soil, Water	EPA Method 625 (Note: compound not listed as a method analyte)	GC/MS	

* When analyzed for with other chemicals of concern, a purge and trap extraction method is generally the default (SW 846 5030 or 5035) when direct injection is not performed. This extraction method is inappropriate for 1,4-dioxane and will yield a high detection limit. What is required is an extraction method for volatile, nonpurgeable, water-soluble compounds such as Azeotropic Distillation. Table Source: U.S. Environmental Protection Agency, 2013 (17), as adapted from Mohr, 2001 (6).

Carcinogenic Classification

1,4-Dioxane has been classified as "likely to be carcinogenic to humans by all routes of exposure" by the EPA (3). In the 1988 IRIS database, 1,4-dioxane was listed as a "Probable Human

Carcinogen" (3) that denotes "agents for which the weight of evidence of human carcinogenicity based on epidemiologic studies is "limited" and also includes agents for which the weight of evidence of carcinogenicity based on animal studies is 'sufficient'" (18). However, the USEPA 2005 report on *Guidelines for Carcinogen Risk Assessment* uses the standard hazard descriptor of "Likely to be Carcinogenic to Humans" to denote an agent when carcinogenesis in lab animals is dose dependent, but there is not critical information or evidence available to support a "causal association between human exposure and cancer" (19). 1,4-Dioxane follows the descriptor given in the USEPA 2005 guidelines (3) "an agent that has tested positive in animal experiments in more than one species, sex, strain, site or exposure route, with or without evidence of carcinogenicity in humans" (19). A mode of action, or "sequence of events and processes" that provides an explanation of how an agent causes carcinogenesis (19) has not been established for 1,4-dioxane (3). However, there is evidence that 1,4-dioxane acts as a tumor promoter (3). EPA has calculated an oral cancer slope factor of 0.1 mg/kg-day as based on the incidence of hepatocellular adenomas and carcinomas in female mice exposed to 1,4-dioxane in drinking water for two years as noted by Kane et al., 2009 (3). Eyes, skin, the respiratory system, liver, and kidneys are known target organs (20).

Toxicology

1,4-Dioxane is a water soluble chemical that is readily absorbed into the body through inhalation and ingestion, and is eliminated through urine (21). In humans, 1,4-Dioxane is metabolized into β-hydroxyethoxy acetic acid (HEAA) through a catalyzed reaction by mixed-function oxidase enzymes (21). HEAA can further be converted to another metabolite, 1,4-dioxane-2-one (22). During a human study conducted by The Dow Chemical Company researchers in 1977, four volunteers were exposed to 50 ppm of 1,4-dioxane vapor for six hours (23). The study found that 1,4-dioxane was readily absorbed into the body and oxidized to HEAA (23). Over the total amount of 1,4-dioxane and HEAA excreted from the body, 99% was eliminated as HEAA which was identified as the dominant route of elimination (23). The renal clearance rate of HEAA was 121 ml/min and 1,4-dioxane was 0.34 ml/min (23). The metabolic clearance of 1,4-dioxane was 75 ml/min (23). This indicates that 1,4-dioxane is "poorly eliminated by the kidneys" and metabolism to HEAA was the major route of elimination (23).

Fate and Transport

1,4-Dioxane is very mobile and persistent in aquatic environments (5). When released into the environment, 1,4-Dioxane is expected to sink into groundwater where it will then disperse throughout the water table. 1,4-Dioxane has a low Henry's law constant (K_H), low octanol-water partition coefficient (K_{OW}), and is miscible in water. With a soil organic carbon-water partition coefficient (K_{OC}) of 1.23, 1,4-dioxane is expected to very weakly sorb to soil particles. Thus, binding to soil is not expected to reduce the mobility of 1,4-dioxane in the environment. Vapor pressure and Henry's law constant govern the evaporation of a chemical from an aqueous solution. Due to the attractive strength of van der waal forces between dipoles of 1,4-dioxane and water molecules and with 1,4-dioxane's increased molecular size, vapor pressure is low. 1,4-Dioxane is expected to evaporate from dry soil. However, due to 1,4-dioxane's miscible properties and low K_{OC} it is not expected to volatilize from water or sorb to soil and sediment as natural attenuation mechanisms (5).

1,4-Dioxane is expected to have bioavailability since it is expected to bind very weakly to organic matter. M. Alexander (1973) as cited in Zenker et al., 2003, noted that 1,4-dioxane's heterocyclic structure and two ether linkages explains its resistant to abiotic and biotic degradation (5). Wolfe and Jeffers, 2000, listed functional groups that are susceptible to hydrolysis (21). 1,4-Dioxane lacks a functional group that would be susceptible to hydrolysis, thus attenuation by hydrolysis is not expected to occur (21). 1,4-Dioxane does not absorb light in the environmental spectrum and is not expected to undergo direct photolysis in aqueous media (21).

Naturally occurring biodegradation of 1,4-dioxane is also not expected to take place due to its lack of biological oxygen demand as demonstrated using the MITI test as documented by the Chemicals Inspection and Testing Institute, 1992 (24). However, numerous studies have evaluated the 1,4-dioxane degradation potential of bacteria with positive results. 1,4-Dioxane has a low bioaccumulation factor and is not expected to bioaccumulate in aquatic organisms.

Exposure Assessment

Potential routes of exposure of 1,4-dioxane for humans are inhalation, ingestion, and dermal contact (25). Although 1,4-dioxane is readily absorbed into the body through inhalation and ingestion, dermal absorption is poor (26). Outside of contaminated groundwater, the general public may be exposed to 1,4-dioxane through contact with residues contained in certain detergents, shampoos, surfactants, food additives, pharmaceuticals, adhesives, and antifreeze products (25). Occupational exposure by workers managing 1,4-dioxane is possible during its production or its use as a solvent in a wide range of organic products (26). Given 1,4-dioxane's physical and chemical attributes, groundwater is the primary media that is expected to be contaminated with 1,4-dioxane, which is due to industrial mismanagement. Current day non-occupational and non-consumer exposure to 1,4-dioxane is typically through contaminated groundwater that makes its way to tap water. This exposure may occur through (21). 1,4-Dioxane is expected to migrate through groundwater faster than related solvent plumes (6). Thus, it is likely that 1,4-dioxane will contaminate drinking water supply wells well before TCA or other co-contaminants are ever detected.

Environmental Regulation

Although no federal drinking water standards have been established, a maximum contaminant level (MCL) is not required to determine clean-up standards (25). Hazardous waste regulatory limits have been established. 40 CFR §268.48 outlines universal treatment standards for wastewater and non-wastewater treatment standards of hazardous waste, which may not be exceeded for compliance. 1,4-Dioxane is listed as an organic constituent with a universal treatment wastewater standard of 12.0 mg/L and a universal treatment non-wastewater standard of 170 mg/kg. 40 CFR §261.33 (f) classifies 1,4-dioxane as a toxic hazardous waste with hazardous waste code U108. A groundwater standard of 3 µg/L is established for 1,4-dioxane under Title 15A of the North Carolina Administration Code (NCAC) Subchapter 2L, Section .0202 (g)(66).

Remediation Options

1,4-Dioxane is a recalcitrant organic compound and a challenging chemical to remove from contaminated groundwater. Its chemical structure results in a highly aqueous compound that is resistant to most forms of biodegradation (5). Subsequently, 1,4-dioxane can be difficult to remove from water and wastewater using conventional processes (5). Advance oxidation processes such as UV/Oxidation techniques are proven technologies that work to degrade and remove 1,4-dioxane from contaminated water (5). These processes are typically energy and labor intensive to operate and maintain which results in an expensive treatment system.

Passive remediation, also known as natural attenuation is where natural processes are utilized to decrease concentrations of contaminants in soil and groundwater (27). Natural attenuation occurs through five natural processes: biodegradation, sorption, dilution, evaporation, and chemical reactions (27). Regular monitoring must occur to measure the contaminant to ensure it is attenuating at an acceptable rate and to track migration. This entire process is call monitored attenuation (27).

There have been many studies conducted to look at bacterial assisted biodegradation of 1,4-dioxane in soils as a viable means of remediation. Cultures of bacteria have been studied to see if 1,4-dioxane could serve a sole carbon and energy source and sustain culture growth through the biodegradation process (5). *Mycobacterium vaccae* was found to be successful at partially degrading 1,4-dioxane (5). *Rhodococcus* was unable to sustain its own growth on 1,4-dioxane (5). However, *Nocardioform actinomycete* strain CB1190 was found to be capable of sustained growth and mineralization of 1,4-dioxane (5). Thus, biodegradation is possible when assisted with certain cultured bacteria where enhanced conditions exist (6). However, no evidence has been presented to support that biodegradation occurs under ambient subsurface conditions (5). Sorption to soil particles, evaporation from soil or water, and chemical reactions in soil or groundwater are not expected to be viable remediation options for 1,4-dioxane. However, with 1,4-dioxane's miscible properties, 1,4-dioxane is expected to move from areas of high concentration to areas of low concentration, in an attempt to meet equilibrium in groundwater media. Groundwater flow also aids in the dispersion of 1,4-dioxane plume, which results in further dilution.

Phytoremediation

Phytoremediation is the use of plants to clean-up and remove contaminants from soils, sediments, and ground and surface waters (28). Thus, phytoremediation disrupts contamination pathways that lead from the environment to receptors, reducing exposure to hazardous substances (29). Phytoremediation was first used as a means for municipalities to treat chemicals in the ground that were used for plant nutrients, such as nitrogen (30). Phytoremediation has been shown to be effective at removing organic chemicals, lowering chlorinated benzenes and absorbing excess nutrients (28). Pulford and Watson, 2003, as described by Edwards et al. in 2011, noted that tree species of *Populus* (poplar) and *Salix* (willow) have been used for their effective phytoremediation properties (28). These durable trees have extensive root systems that enable them to take up large quantities of water (28). In 1996, Nyer and Gatliff described four ways that vegetation help to remediate contaminants. In 2002, Ouyang adapted these into five mechanisms: uptake of nutrients, uptake of non-essential metals and organics, creating an environment of diverse microbial population, water pumping action, and volatilization and stabilization (31). Volatilization and stabilization are important in the remediation of 1,4-dioxane as shown by Aitchison et al., 2000, in a nine day hydroponic and 15 day soil study where 76%-83% of 1,4-dioxane taken up by hybrid poplars was transpired from leaf surfaces to the atmosphere where it was readily dispersed and photodegraded (32). As noted by Howard, 1990, when 1,4-dioxane is released into the atmosphere it reacts with hydroxyl (OH) radicals and is broken down with a half-life of 6–10 hours (28). However, ATSDR, 2012, noted that, in the atmosphere, 1,4-dioxane is subject to photooxidation with an estimated half-life of 1-3 days (21). 2-Oxodioxane (c-C4H7O2), a reaction product from the photooxidation of the OH Radical, has a lifetime of 0.02 microseconds (21). Then, with the addition of O_2 a peroxy radical (c-C4H7O2)O2 is produced (21). The peroxy radical then reacts with NO to produce NO_2 and an alkoxy radical (c-C4H7O2)O (21).

The transpiration stream is the overall process where a plant removes water from the soil through the roots and pumps the water through the plants vascular system, and then to the leaves (28). The water is then evaporated and transpired from the leaves into the atmosphere (28). This evaporative loss drives the pumping action that allows the tree to take up and pump large volumes of water from the roots and through the tree system (28). This pumping action along with sufficiently large root systems, as noted by Susarla et al., 2002, can effectively prevent the spread of contaminants beyond the root system (28). Phytovolatilization is the term used to describe the process where a plant takes up a contaminant, pumps or translocates the contaminant through the plant to the leaves, then transpires the volatile contaminant in the transpiration stream through the leaf stomata or plant stems (33).

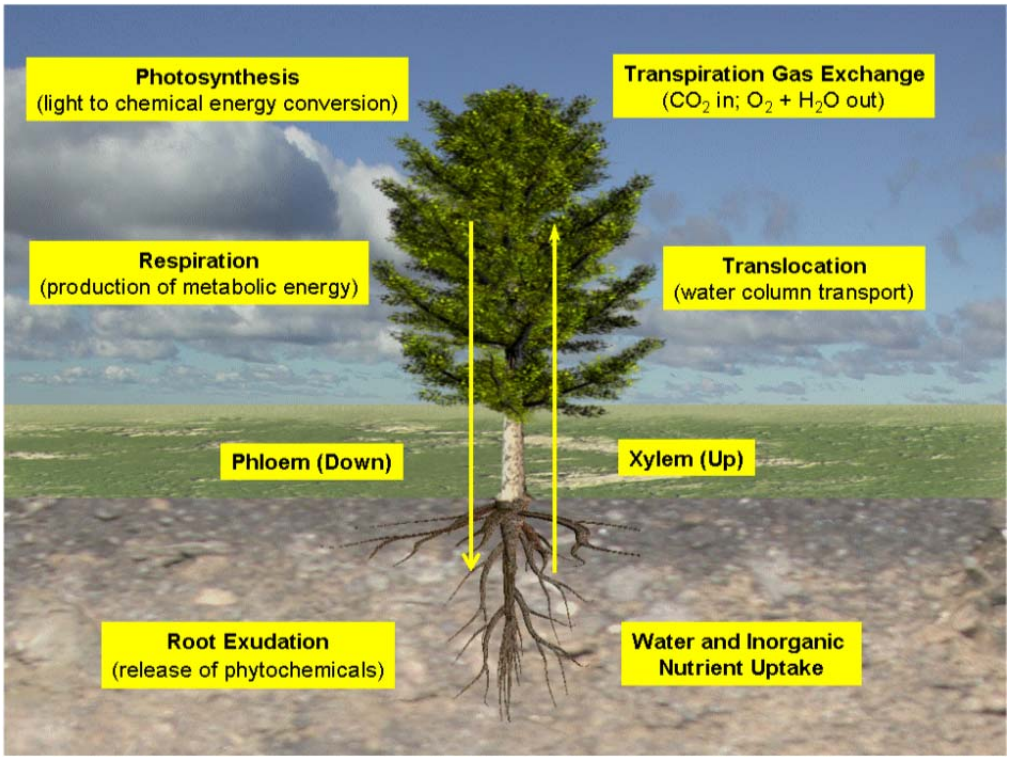

Figure 2: Plant Physiological Processes
Source: The Interstate Technology & Regulatory Council Phytotechnologies Team, 2009

Benefits of phytoremediation were described by The Interstate Technology & Regulatory Council Phytotechnologies Team in 2009 as the relative lower cost, labor requirements, and safer operations compared to the more intensive and invasive conventional techniques (33). Cost is a driving factor when project managers and stakeholders make decisions on which remediation strategy to implement at contaminated sites. In 2005, Linacre et al. noted that phytoremediation based optimism is driven by the beliefs that it is less expensive than engineering-intensive remediation solutions, including dig and dump, soil washing, and heat treatment. This optimism is also based on the belief that phytoremediation is more sustainable and environmentally friendly (34). However, Linacre et al. found that there are real criteria that stakeholders take into consideration: the likelihood of success (i.e. meeting regulatory criteria for contaminants), time taken to achieve success, and cost effectiveness of the solution (34). By incorporating Net Present Value into a simple management decision model that incorporates the effect of uncertainty on management decisions, they were able to demonstrate that uncertainty has a large impact on the decision to use phytoremediation (34). Linacre et al. found that obtaining realistic prices for remediation strategies was problematic due to the varying needs between projects and varying cost of landfill rates and hazardous waste disposal from state to state (34). The Federal Remediation Technology Roundtable presented estimated cost to apply phytoremediation technology at soil contaminated sites of varying size and complexity as shown in Table 3. This table compares four scenarios and estimates that the cost of a large site is less expensive per foot than the cost of a small site. Real estate prices, technology cost, clean-up levels, and time limits, among other parameters, can all influence stakeholders decision making (34).

Table 3: Estimated Cost Analysis of Phytoremediation
Source: Adapted from Federal Remediation Technologies Roundtable, 2013.

PARAMETERS	Scenario A	Scenario B	Scenario C	Scenario D
	Small Site		Large Site	
	Easy	Difficult	Easy	Difficult
COST PER SQUARE FOOT	$2	$7	$0.42	$1
COST PER CUBIC FOOT	$18	$66	$4	$14
COST PER CUBIC METER	$626	$2,322	$147	$483
COST PER CUBIC YARD	$479	$1,775	$112	$369

METHODS

The North Carolina Department of Environment and Natural Resources (NCDNER), Division of Waste Management (DWM), Hazardous Waste Section (HWS), Facility Management Branch (FMB) oversees the clean-up of hazardous waste contamination at facilities across the State of North Carolina. These facilities are managed as permitted TSDFs or under Administrative Orders as interim status facilities. 1,4-Dioxane is a constituents of concern (COC) found at several contamination sites across North Carolina. As discussed below, site specific treatment requirements for 1,4-dioxane may not exist. The groundwater standards for 1,4-dioxane that are applied to hazardous waste contaminated sites are listed at Title 15A of the North Carolina Administration Code (NCAC) Subchapter 2L, Section .0202 (g)(66), otherwise known as the NCAC 2L Standard. This standard establishes the total concentration "of any constituent in a dissolved, colloidal or particulate form which is mobile in groundwater." The NCAC 2L Standard for 1,4-dioxane is 3 µg/L.

In June, 2013 an inquiry was made to NCDENR's DWM HWS FMB for groundwater sites with known 1,4-dioxane contamination. A list of 12 facilities and their respective EPA identification numbers were provided. The list of facilities includes a range of sites located across the State of North Carolina including DAK Americas, LLC in Brunswick County; A.B. Carter, Incorporated in Gaston County; Former Ashland, Incorporated, Seaboard Chemical Corporation, and Wysong & Miles Company located in Guilford County; DuPont Kinston Site in Lenoir County; Former Heatcraft Remediation Site in New Hanover County; Former DuPont Brevard Facility in Transylvania County; Radiator Specialty Company in Union County; and Alcatel Lucent USA, Incorporated and Parker Hannifin Corporation (Pneumatics Division) in Wake County. The location of each site is shown in Attachment 1: North Carolina Hazardous Waste Sites with 1,4-Dioxane Groundwater Contamination.

A subsequent review of publically available documents for each of the facilities was conducted to obtain site specific information incorporated into this document. Facility names, EPA identification numbers, and addresses were verified using the EPA's Envirofacts Data Warehouse. Facility names that were active in the Envirofacts Data Warehouse for each EPA identification number were used for each respective facility. The name of the facility used in this paper does not necessarily represent the financially responsible party or the party that caused the contamination. Facility documents were retrieved using CARA[3] Portal, an internet based document management system that houses NCDENR's Waste Management documents. Cara[3] Portal can be accessed at: https://edm.nc.gov/DENR-Portal/. Property information for each location was obtained from county specific Geographical Information System hosted websites. GIS data obtained included property ownership, site acreage, natural environmental features, aerial views, and the location of industrial structures and residential areas. To assist in making decisions on which facilities would be good candidates for phytoremediation, decision trees from The Interstate Technology & Regulatory Council Phytotechnologies Team's guidance document, *Phytotechnology Technical and Regulatory Guidance and Decision Trees, Revised* (PTRG), were utilized. Decision trees utilized include the Remedy Selection Decision Tree which attempts to present phytoremediation options based on parameters such as impacted media the COC's behavior in the soil-plant-atmosphere continuum (33) and the Groundwater Decision Tree that provides direction on if a phytoremediation tree stand should be considered as a supplement to other remediation strategies, a standalone strategy, or not considered at all.

Initial Site Screening

Each facility was found to be at a different phase in the remediation process. It can take decades after the initial discovery of groundwater contamination before site specific active remediation strategies are implemented. Contamination sites that were being managed under the NCDNER's Superfund Section, Inactive Hazardous Sites Branch (IHSB) Order or working towards closure were not further considered for this project. Seaboard Chemical Corporation is overseen by the FMB and under an IHSB Order. This facility is also working towards implementing phytoremediation as part of a treatment system to remediate for 1,4-dioxane. This site may be used as a test case and model for other sites considering phytoremediation as a remedial option for 1,4-dioxane. Wysong and Miles was also found to be overseen by the FMB while under an IHSB Order. As outlined in Table 3, the Former DuPont Brevard Facility is under current conditions of "Current human exposure is under control" and the maximum level of 1,4-dioxane contamination is 9 µg/L. Schneider Electric is working to close their contamination site by using risk factors to justify current low levels. The maximum concentration of 1,4-dioxane at Schneider Electric is 8.3 µg/L. These four sites were not further considered as part of this project as summarized in Table 4.

To further narrow the list of sites, major limitations of phytoremediation were assessed. The PTRG outlines the major limitations of phytoremediation as depth, area, and time (33). With depth, the groundwater level can be too deep below the ground surface to have root penetration. In this situation, a pump and treat system is possible; thus, the groundwater depth below land surface was not considered a limiting factor for the purpose of this project. Trees take up a large amount of area when compared to traditional remediation systems, and can be a limiting factor when there is not enough available property to house a phytoremediation stand of trees. Area was considered as a limiting factor. Time is a limiting factor when there are future land use plans that do not accommodate for the long term needs of a phytoremediation system. However, for the purpose of this project, time was assumed not to be a limiting factor.

The next step was to consider the eight remaining sites and surrounding properties to determine which sites lacked sufficient open space to construct and manage a phytoremediation tree stand. The PTRG document recommends 75 square feet per tree that can be cleared of obstructions and support planting equipment (33). Phytoremediation was determined not to be a potential remedy for two contamination sites based on the limitation of space as listed in Table 4. Although Alcatel Lucent USA, Inc. has 23.12 acres of property, the entire property is built out and actively utilized as industrial space. The Former Ashland, Inc. site is located in 1.77 acres of built upon property that is actively utilized as an industrial facility. Ashland, Inc. owns an adjacent lot with 3.18 acres of wooded land. Nevertheless, this property is land locked between a railroad line and other industrial facilities in a position that prevents road access. Thus, this site was not considered further for this project.

Table 4: 1,4-Dioxane Sites Under No Further Consideration for Phytoremediation

Facility Name	EPA ID#	Address	Maximum Analytical Result for 1,4-Dioxane	Reason for Exclusion from Assessment	Additional Comments
Alcatel Lucent USA, Inc.	NCD003185238	2912 Wake Forest Road, Raleigh, NC	760 µg/L October 2012 (35)	Insufficient space for phytoremediation.	23.12 acres of property is built out for industrial use (36). Treating 1,4-Dioxane with sodium persulfate using 82 treatment cells (35).
Former Ashland, Inc.	NCD024599011	2802 Patterson Street, Greensboro, NC	310 µg/L May 2012 (37)	Insufficient space for phytoremediation.	1.77 acres of property built out for industrial use. Ashland Inc. owns adjacent 3.18 acres of wooded land (38).
Former DuPont Brevard Facility	NCD003152329	701 DuPont Drive, Cedar Mountain, NC	9 µg/L September 2012 (39)	Phytoremediation not necessary for this location. Contamination range very low.	406.9 acres of open space and wooded property (40). Site under current conditions of "Current human exposure is under control" (41).
Schneider Electric (Formerly Square D Co.)	NCD067203752	8001 Knightdale Boulevard, Knightdale, NC	8.3 µg/L May 2012 (42)	Facility working to close contamination site by using a risk factor to justify current levels to achieve No Further Remediation determination (43).	59.16 acres of industrial property (36). Open spaces appear to be managed land units.

Facility Name	EPA ID#	Address	Maximum Analytical Result for 1,4-Dioxane	Reason for Exclusion from Assessment	Additional Comments
Seaboard Chemical Corp.	NCD071574164	5899 Riverdale Road, Jamestown, NC	4,310 µg/L November 2012 (44)	Managed under NDENER Superfund Section, IHSB. Currently planning to utilize phytoremediation as part of treatment train system to remediate for 1,4-dioxane. Treatment system not operational at this time (45).	101.78 and 10.32 acres of landfill and wooded property (38).
Wysong & Miles	NCD982156812	4820 Hwy 29 North, Greensboro, NC	65 µg/L August 2010 (46)	Managed under NCDENR Superfund Section, IHSB.	60.45acres of industrial and wooded property, including a pond (38).

Site Assessments

Six out the initial twelve groundwater contamination sites with elevated levels of 1,4-dioxane above the remedial objective were identified as potentially having enough space to manage a phytoremediation project. The remedial objective is set by the soil screening level, or NCAC 2L Standard, of 3 µg/L. Based on the PTRG document, a site assessment is conducted to define phytotechnology project objectives, such as control and containment, contaminant removal and destruction, or both (33). Each site was reviewed individually to determine the level of 1,4-dioxane contamination, current regulatory actions, existing or planned remediation strategies, groundwater table depth below land surface, and other relevant site specific information.

Table 5: 1,4-Dioxane Sites Under Further Consideration for Phytoremediation

Facility Name	EPA ID #	Address	Maximum Analytical 1,4-Dioxane
A.B. Carter, Inc.	NCD003154010	4801 York Highway, Gastonia, NC	35 µg/L (47)
DAK Americas, LLC	NCD047369046	3500 Daniels Road NE, Leland, NC	56,200 µg/L (48)
DuPont Kinston Site	NCD003190386	4693 Hwy 11 N, Kinston, NC	359 µg/L (49)
Former Heatcraft Remediation Site	NCD057451270	602 Sunnyvale Drive, Wilmington, NC	110 µg/L (50)
Parker Hannifin Corporation (Pneumatics Division)	NCD002591014	12415 Capital Boulevard, Wake Forest, NC	12 µg/L (51)
Radiator Specialty Company	NCD091245969	600 Radiator Road, Indian Trail, NC	>3000 µg/L (52)

The PTRG Remedy Selection Decision Tree was used to determine if phytoremediation should be considered as a viable remedial option. The Remedy Selection Decision Tree follows a series of questions that apply to each site as well as questions that are site specific as listed in Table 6. Based on the answer to the site specific questions, the tree specifies one or more of the following decision trees for consideration: Soil/Sediment, Riparian Zone, ITRC WTLND-1, and Groundwater. Soil/sediment, riparian zones, and surface water contamination are beyond the scope of this project. Only groundwater contamination will be considered as part of the assessment process. A discussion is then presented for each site that reflects consideration for information collected that includes general and site specific recommendations such as additional sampling needs and regulatory alterations.

Table 6: PTRG Remedy Selection Decision Tree Applicable Questions

Question*	Answer	General or Site Specific
Is the contaminant soluble?	Yes	General
Is the contaminant biodegradable?	No	General
Will the plant take up the contaminant or byproduct?	Yes	General
Will the contaminant or byproduct accumulate in the plant?	No	General
Will the contaminant or byproduct transpire from the plant?	Yes	General
Is the concentration in transpire gases acceptable?	Yes	General
Is the contamination in surface soils or sediments?	If yes, go to Soil/Sediment Decision Tree	General
Is the contamination from either runoff or a groundwater seep?	If yes, go to Riparian Zone Decision Tree	General
Is the contamination ALSO in surface water?	If yes, go to ITRC WTLND-1	Site Specific
Is the contamination ALSO in groundwater?	If yes, go to Groundwater Decision Tree.	Site Specific

*Questions from The Interstate Technology & Regulatory Council Phytotechnologies Team, 2009.

The Remedy Selection Decision Tree subsequently points the user to the Groundwater Decision Tree for further evaluation, as noted in Table 6. This decision trees requires information that is beyond the scope of this project, thus requiring assumptions to be made. To stay within the bounds of this project, specific groundwater geochemistry (pH, salinity, etc.) survival of selected phytoremediation plants was assumed. However, the toxicity of 1,4-dioxane on the phytoremediation tree must also be taken into consideration. Wichman, 1990, as described by Aitchison et al, 2000, found that 60 mg/L concentration of 1,4-dioxane, along with 60 mg/L each of benzene, carbon tetrachloride, m-dichlorobenzene, m-xylene, toluene, and TCE, did not exhibit visible toxic effects to hybrid poplars (32). Aitchison et al, 2000, conducted studies and noted that 23 mg/L of 1,4-dioxane did not cause visible toxic effects to hybrid poplars (32). Further research on the toxicity of 1,4-dioxane on hybrid poplars or other trees could not be found at the time of this research. Thus, more research is needed to understand at what concentrations trees demonstrate deleterious effects from 1,4-dioxane.

ASSESSMENTS

Site Reviews

A.B. Carter

The A.B. Carter facility is located at 4801 York Highway in Gastonia, North Carolina. Groundwater monitoring activities conducted August 20-21, 2012 resulted in 1,4-dioxane detected at levels above the NCAC 2L Standard of 3 µg/L in ten wells across the monitored area, ranging from 4.1 µg/L to 35 µg/L (47). Other COCs detected in the August 2012 groundwater monitoring samples include nickel, sulfate, 1,1-dichloroethylene (1,1-DCE), 1,2-dichloroethane (1,2-DCA), and tetrachloroethene (PCE) (47). Based on the hazardous waste contamination documented at the site, A.B. Carter is operating under a Hazardous Waste Management Permit that was issued on September 26, 2007 and modified on January 25, 2013 (53). The permit includes a list of hazardous constituents, excluding 1,4-dioxane, that will be part of a remedial action program, specifically monitored natural attenuation.

The facility has two Solid Waste Management Units (SWMUs), SWMU #1 the former Sludge Beds and SWMU #2 the former Storage Pond (47). The on-site remediation system focused on nickel, sulfate, PCE, and 1,1-DCE (47; 53). Remediation activities were initiated in 1989 and continued until NCDENR approved a request from A.B. Carter to shut down the remediation system in 2009 (47). Although 1,4-dioxane has been monitored for, it does not appear to be part of the site's remediation strategy.

The 1,4-dioxane contamination plume highest concentrations are found near the excavated sludge beds located east of the main building. The plume is reportedly migrating towards a stream that is located along the eastern side of the property and less than 200 feet from MW-23 that had a concentration level of 17µg/L of 1,4-dioxane. Groundwater depths were between 19.5 feet and 44.7 feet below land surface, as measured in monitoring wells during the August 2012 monitoring event (47). Groundwater flows in an east-southeastern direction as a result of site topography. Site groundwater has a horizontal hydraulic gradient of approximately 0.024 feet/foot and an average groundwater flow velocity of 124 feet per year (47).

Figure 3: Aerial of A.B. Carter (54).

DAK Americas, LLC

The DAK Americas, LLC facility is located at 3500 Daniels Road Northeast, Leland, North Carolina. In November 2012 and April 2013, groundwater samples were taken at the Active Dowtherm® Heaters (ADH) process area that resulted in 16 out of 20 monitoring wells with 1,4-dioxane at levels that exceeded the NCAC 2L Standard of 3 µg/L (48). The highest concentration, 56,200 µg/L, was observed in the Active Manufacturing Area of the property (48). 1,4-Dioxane was also identified in two other Active Manufacturing Areas, SWMU 37 and Areas of Concern (AOC) FMA, and in six areas of the Plant Support Area of the facility, including SWMU 5 & 6, 57, 58, and AOCs A, B, & C (55). This project will focus strictly on the ADH area of contamination. Other COCs at the ADH include chlorinated volatile organic compounds (PCE, TCE, cis-1,2-DCE, and vinyl chloride), diphenyl ether, 1,1-biphenyl, naphthalene, and arsenic (48).

DAK Americas, LLC was issued a Hazardous and Solid Waste Amendment (HSWA) Permit on October 27, 1989 (56). North Carolina was granted authority to administer the RCRA Corrective Action Program from the EPA in January 1995 (56). After closing a permitted hazardous waste storage area in 2004, the DAK Americas/DuPont Cape Fear Plant was issued a HSWA-only Permit on August 27, 2007 (49). Historically industrial waste generated at the facility was disposed in on-site pits, trenches, and landfills that have subsequently been identified as SWMUs under the RCRA Corrective Action Program, as required by the Permit (56). The most current permit lists eighty SWMUs and four AOCs (57). Based on a 2007 HSWA Permit, four SWMUs and four AOCs are still under investigation (58). The 2007 HSWA Permit list 1,4-dioxane as a constituent that exceeds applicable groundwater standards and will be addressed through a Corrective Measures Study and Corrective Measures Implementation (57). On May 2, 2005, NCDENR DWM HWS concurred with a DAK Monomers and DuPont-CRG report citing “current human exposures are under control” and the “migration of contaminated groundwater is under control” (56). A groundwater monitoring program is required through the facility’s HSWA Permit that directs groundwater sampling to monitor the COCs (56).

Groundwater depths ranges from two to ten feet below land surface (56). The water table slopes downwards towards the Cape Fear River to the north, south, and east (56). DuPont maintained ownership of adjacent parcels and placed a conservation easement on wetland acreage that is overseen by the North Carolina Costal Land Trust (56). The wetland conservation easement is located in areas with groundwater contamination between the Cape Fear River and the manufacturing area (56). This area is classified as deciduous, forest, and palustrine wetlands (56).

E. I. DuPont de Nemours owns 1401 acres of undeveloped, adjacent property. The Cape Fear River travels along the northern and eastern boundaries of the property. This portion of the property is a riverine swamp forest (59) under a wetland conservation easement (56). The remaining portions of the property are drained riverine swamp forest, cutover pine flat, managed pineland, and other wooded areas (59). The main manufacturing property, owned by DAK Americas, LLC, totals 615 acres (59). The majority of this property is managed as manufacturing, with approximately 115 acres of managed pineland and wooded space.

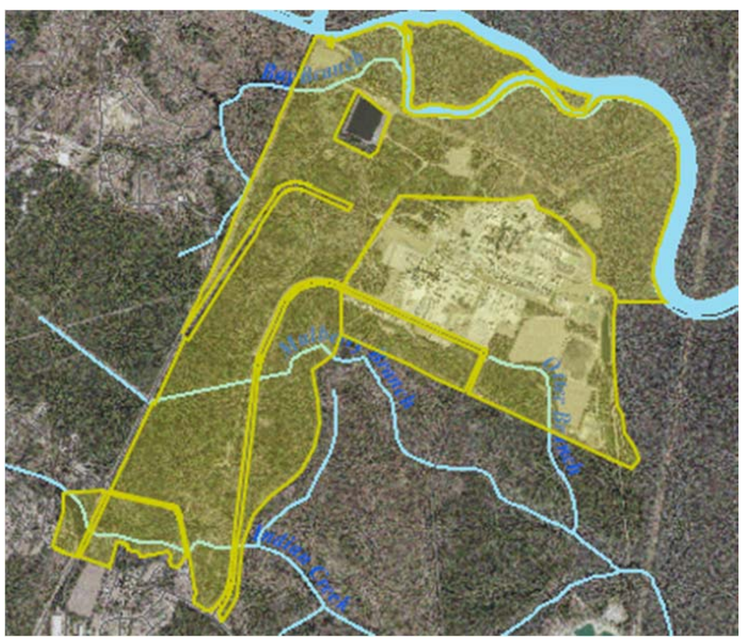

Figure 4: Aerial of DAK Americas, LLC (59).

DuPont Kinston Site

The DuPont Kinston Site is located at 4693 Highway 11 North, Kinston, North Carolina. In July 2012, 1,4-dioxane was detected in all three water samples that were taken from Channel 7 (SWMU 12) ranging from 13.5 µg/L to 392 µg/L (49). In addition, samples taken in April 2012 from 17 monitoring wells had detection of 1,4-dioxane at levels that exceeded the NCAC 2L Standard of 3 µg/L, ranging from 4.39 µg/L to 359 µg/L (49). Other COCs with concentrations that exceed applicable groundwater standards include TCE, cis-1,2-DCE, vinyl chloride, acetone, benzene, chloroform, 1,4-dioxane, methyl ethyl ketone, methyl isobutyl ketone, methylene chloride, tetrahydrofuran, 2-methylphenol, 4-methylphenol, phenol, ethylene glycol, diethylene glycol, triethylene glycol, arsenic, barium, cadmium, chromium, iron, lead, manganese, nickel, phosphorus, silver, and vanadium (60).

E. I. DuPont de Nemours and Co. was issued a Hazardous Waste Management Permit on July 21, 2010 (61). The DuPont Kinston Site is currently working under a RCRA Corrective Action Program. This facility has seventy-seven SWMUs and seven AOCs (60). As noted in the facility's July 21, 2010 Hazardous Waste Management Permit, constituents with groundwater standard exceedances, as listed above and including 1,4-dioxane, are to be addressed through a Corrective Measures Study and Corrective Measures Implementation. AOC-86 has an engineered remediation system for TCE that was released in that area of the facility (61). The facility started TCE groundwater treatment on May 24, 1995, where groundwater is pumped to an activated carbon treatment system (62). The water is then discharged to the site wastewater treatment plant (62).

National Pollutant Discharge Elimination System (NPDES) Permit for wastewater discharge, NC0003760, was originally issued on December 29, 1978 (63). E. I. DuPont de Nemours Kinston was issued the most current NPDES Permit which expired on January 31, 2013 (63). The NPDES Permit provides 82 parameters that the facility is allowed to discharge from point sources. 1,4-Dioxane is not included as part of the NPDES Permit list. Effluent sampling requirements could not be found. Per 40 CFR 261.4(a)(2), industrial wastewater discharges that are point source discharges subject to regulation under section 402 of the Clean Water Act, as amended, are not considered solid waste, and thus cannot be a hazardous waste.

In 1999, a permeable reactive barrier wall was installed to treat contaminated groundwater and the pump and treat remediation system was shut down in August 2001 with the "contingent verifiable effectiveness" of the zero valent iron treatment system (62). 1,4-Dioxane has not been analyzed for in this area of TCE contamination (62). The facility ceased generating 1,4-dioxane as part of its waste stream in 2008 when it switched to producing a bio-based polymer (49). Parson's 2012 Combined Annual Groundwater Monitoring Report noted that the switch to producing a bio-based polymer coincided with a significant decrease in 1,4-dioxane levels at MW-22 (49).

Groundwater flows towards the southeastern property boundary, which runs along the Neuse River (49). Depth of the groundwater table below land surface was between 3.6 feet to 11.8 feet in April 2012 (49). A forested buffer exists between the Neuse River and the industrial areas of the facility (64). A portion of this buffer is included Lenoir's National Wetlands Inventory (64).

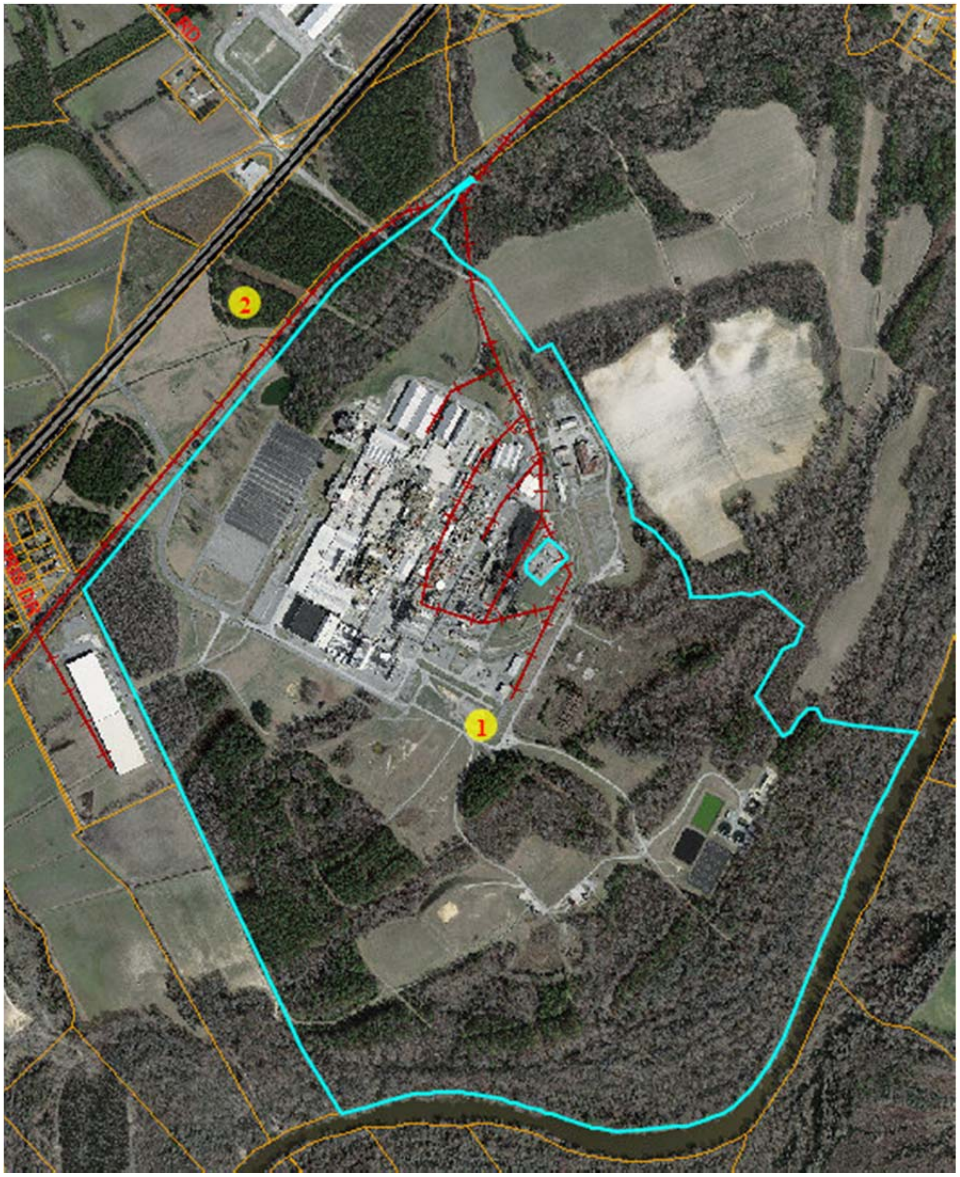

Figure 5: Aerial of DuPont Kinston Site (64).

Former HeatCraft Remediation Site

The Former HeatCraft Remediation Site is located at 602 Sunnyvale Drive, Wilmington, North Carolina. Groundwater monitoring activities conducted March 25 - 29, 2013 resulted in 1,4-dioxane detected at levels above the NCAC 2L Standard of 3 µg/L in five out of five sampled groundwater wells at levels ranging from 28 µg/L to 110 µg/L (50). Other COCs include 1,1,1-TCA, 1,1-DCA, 1,1-DCE, trans-1,2-DCE, cis-1,2 DCE, TCE, and vinyl chloride (50).

AAF-McQuay Inc., the entity responsible for continued monitoring and mitigation of site contamination, was issued an Administrative Order in Lieu of Post-Closure Permit on June 1, 2012 by NCDNER DWM HWS. This order covers the implementation of Post-Closure Care and Corrective Action activities to address soil and groundwater contamination at the facility (65). In a January 2005 report, 16 SWMUs and one AOC were identified (65). "No further action" has been recommended for 15 of the SWMUs (65). Remediation activities include natural attenuation of chlorinated solvents, pulse air sparging system, and a groundwater recovery and treatment system (50). A pulse air sparging system is utilized to help enhance shallow aquifer natural attenuation remediation efforts of a vinyl chloride plume (50). The groundwater recovery and treatment system is not designed to treat for 1,4-dioxane. This system treats for VOCs via an air stripping system and then discharges to an unnamed tributary of Bernards Creek (50). This surface water discharge is regulated by NPDES Permit NC0083658, which limits TCE concentration in the effluent at 30 ppb (50). 1,4-Dioxane is not included as a limited effluent characteristic parameter by the NPDES Permit. Other VOC constituent effluent concentrations are compared to Class C surface water quality standards (50). NCDENR DWM HWS requires quarterly effluent testing for 1,4-dioxane, the results of which are also submitted to the NCDENR Division of Water Quality, now N.C. Division of Water Resources, Central Files and the Environmental Science Branch (50). 1,4-Dioxane levels in the effluent discharge were 26.4 µg/L in August 2012 and 14.5 µg/L in February 2013 (50). As of May 29, 2013, there had been no correspondence from Division of Water Quality concerning 1,4-dioxane concentration levels present in the groundwater treatment system effluent (50).

Water table depth at the Former Heatcraft Remediation Site is between four and ten feet below land surface (50). Site groundwater discharges to North Creek, which acts as a discharge boundary for the water table aquifer (50). Groundwater flows to the southwest towards the creek on the eastern side of North Creek (50). There are two groundwater systems present: a surficial aquifer that flows towards the southeast towards an unnamed tributary and a deep Peedee Aquifer that flows to the south-southwest towards the Cape Fear River (65). 1,4-Dioxane contamination has been identified in both aquifer systems (65).

Figure 6: Aerial of Former Heatcraft Remediation Site (66).

Parker Hannifin Corporation (Pneumatics Division)

Parker Hannifin Corporation (Pneumatics Division) is located at 12415 Capital Boulevard, Wake Forest, North Carolina. Groundwater monitoring activities conducted on February 19 and 20, 2013 resulted in 1,4-dioxane detected at levels above the NCAC 2L Standard of 3 μg/L, in three out of 29 sampled wells (51). Detected 1,4-dioxane concentrations above the NCAC 2L Standards were between 5 μg/L and 12 μg/L (51). Except for two anomalies of 530 μg/L and 540 μg/L that were detected during a September 2010 sampling event, the highest historical detected level of 1,4-dioxane was 39 μg/L. This detection level was detected during the first sampling event for the analyte in July 2005 (51). Other contaminants of concern are TCE, cis-1,2-DCA, PCE, chromium, and mercury (51).

Parker Hannifin Corporation was originally issued a Permit in August 1991 by NCDNER and was later issued a 10 year renewal Part B Permit on June 1, 2006 (51). This permit requires the monitoring of 1,4-Dioxane, VOC's, and metals in 20 wells (51). The permit establishes a regulated limit for 1,4-dioxane of 3.0 μg/L (51). There are 13 corrective action system effectiveness wells, four Point of Compliance (POC) wells, and three groundwater extraction wells that pump water up to a groundwater treatment system that was brought online in May 1992 (51). NCAC 2L Standard exceedances documented during the February 2013 sampling event were from two monitoring wells, MW-33 & MW-34, and one POC well, POC-1B (51). MW-33 and MW-34 were sampled in addition to twenty Part B Permit required wells. Three groundwater extraction/recovery wells, RW-4, RW-6, and RW-19, pump contaminated groundwater to the groundwater treatment system (51). These three extraction wells are sampled for 1,4-dioxane, which was not detected above the laboratory reporting limit of 3.0 μg/L for the February 19 and 20, 2013 sampling event. Historically, recovery well RW-4 has had detection at levels of 1,4-dioxane up to 18.4 µg/L (51). Samples of influent and effluent from the groundwater treatment system has been conducted; however, the 1,4-dioxane is not included as part of the analytical suite (51). TCE is the main COC that is treated for by the remediation system (51).

The facility has three unnamed tributaries located on the Parker Hannifin Corporation property that drains into the adjacent Horse Creek (51). Five surface water samples were taken from these tributaries during the February 2013 sampling event (51). Although no constituents were found to be above RCRA Part B Permit limits, 1,4-Dioxane was not included in the surface water samples (51).

The groundwater table depth across the monitored area varies between 5.4 feet below land surface and 41.0 feet below land surface (51). Groundwater flows towards the three extraction wells and north-northwest towards surface water (51). Water table depth in the wells with detected 1,4-dioxane is between 37.8 and 41.8 feet below land surface.

Figure 7: Aerial of Parker Hannifin Corporation (36).

Radiator Specialty Company

The Radiator Specialty Company site is located at 600 Radiator Road, Indian Trail, North Carolina. Groundwater monitoring activities conducted October 29, 2012 – November 7, 2012 resulted in 1,4-dioxane detected at levels above the NCAC 2L Standard of 3 µg/L in twelve sampled wells. The detected levels were between 6.6 µg/L and greater than 3,000 µg/L (52). Other COCs are chlorinated solvents and petroleum constituents, including acetone, benzene, carbon disulfide, chloroethane, 2-chlorotoluene, 4-chlorotoluene, cis-1,2-DCE, 1,1-DCA, 1,1-DCE, 1,2-DCA, methylene chloride, 4-methyl-2-pentanone, PCE, 1,1,1-TCE, 1,1,2-TCA, TCE, trans-1,2-DCE, and vinyl chloride (67). Semi-volatile organic compounds include pentachlorophenol, bis(2-ethylhexyl) phthalate, 2,4-dimethylphenol, 2-methyl-4,6-dinitrophenol, 2-methylphenol, and 4-methylphenol (67). Metals present include arsenic, cadmium, chromium, and lead (67).

Radiator Specialty Company was issued a Hazardous Waste Management Permit on July 7, 2010 (68). Under this permit, the facility is required to monitor and treat groundwater, and implement post-closure care and corrective actions of the closed Charlotte Impoundment (SWMU-5) and Monroe Impoundment (SWMU-6) (68). Per Condition IV.G(2) of the permit, the facility is required to conduct corrective actions for regulated SWMUs and to treat in place hazardous constituents, including 1,4-dioxane as listed in Condition IV.B of the permit, in groundwater at the facility, and remove or treat in place these constituents located beyond the facility boundary (68). The facility's 2009 Post-Closure Permit Renewal Application listed ten SWMUs that have been identified on-site. Two SWMUs are regulated under the current RCRA Permit four of the SWMUs are under remediation using an existing groundwater remediation system, and four other SWUMs have been successfully assessed and closed (67). The facility's groundwater treatment system includes two vapor extraction systems and an air stripping tower for treating VOCs, which exit through an air stream from the top of the unit (67). Groundwater is pumped from four recovery wells, R-1, RW-2, RW-3, and RW-4, into a 6,000-gallon equalization tank and then to the air stripping tower for treatment (67). During the October 30, 2012 sampling event, 1,4-dioxane was detected at 4.4 µg/L in RW-4. R-1, RW-2, and RW-3 did not appear to be sampled.

Vapor extraction system pretreated groundwater was discharged to the Union County publicly owned treatment works (POTW) until December 2009 (67). Starting in January 2010, the facility began discharging pretreated groundwater to the South Fork Crooked Creek based on a request from Union County Public Works to cease discharges to the POTW (67). The facility was subsequently issued NPDES Permit NC0088838 for the wastewater discharge to South Fork Crooked Creek. 1,4-Dioxane is not included as an effluent characteristic that is monitored for as part of the NPDES Permit requirements.

Groundwater table levels located on-site were measured between 8.5 feet and 77.0 feet below land surface (52). Surface water generated on the southwest side of the facility discharges through intermittent streams to Price Mill Creek while surface water generated on the northeast side of the facility discharges into intermittent streams draining to the South Fork Crooked Creek (67). Likewise, there is a groundwater divide in the area of the RCRA regulated units, where the groundwater flows to the northwest (67).

Figure 8: Aerial of Radiator Specialty Co. (69).

RESULTS

To determine if phytoremediation should be considered the PTRG Remedy Selection Decision Tree was resourced. Starting with the site specific question listed in Table 6, including “Is the contamination also in surface water?” and “Is the contamination also in groundwater?” each site was assessed. If 1,4-dioxane is found to be in surface water, the Remedy Selection Decision Tree recommends considering a constructed treatment wetland and a phytoremediation tree stand. The document referred to for wetland information is titled *Technical and Regulatory Guidance Document for Constructed Treatment Wetlands, 2003,* and is beyond the scope of this project. Although the PTRG decision tree recommends considering a constructed treatment wetland for surface water contamination, only groundwater remediation will be discussed. If 1,4-dioxane is determined to be in groundwater, then the PTRG Remedy Selection Decision Tree points to the Groundwater Decision Tree for further assessment. Site specific answers for the Groundwater Decision tree are listed in Table 7.

A.B. Carter, Inc.

Based on the lack of surface water analysis, it is unclear if 1,4-dioxane has migrated into surface water. 1,4-Dioxane was detected in groundwater during the August 2012 sampling event at levels up to 35 µg/L. Based on site specific answers for this decision tree, as noted in Table 7, this site can proceed to design a phytoremediation tree stand.

DAK Americas, LLC.

Based on the determination that the "migration of contaminated groundwater is under control", it appears that 1,4-dioxane has not migrated into surface water above the standard NCAC 2L Standard. Thus, the Remedy Selection Decision Tree points to the Groundwater Decision Tree. Based on site specific answers for this decision tree, as noted in Table 7, this site can proceed to design a phytoremediation tree stand.

DuPont Kinston Site

Starting with the site specific question listed in Table 6, 1,4-dioxane has migrated into surface water and has exceeded surface water screening criteria (60). 1,4-Dioxane was also found in groundwater in April 2012 up to concentration levels of 359 µg/L. Based on site specific answers for the Groundwater Decision Tree, as noted in Table 7, this site can proceed to design a phytoremediation tree stand. The vertical extent of 1,4-dioxane contamination was not available based available documents.

Former Heatcraft Remediation Site

Starting with the site specific question listed in Table 6, based on levels of 1,4-dioxane detected in the groundwater recovery and treatment system effluent on August 2012 and February 2013 of 26.4 µg/L and 14.5 µg/L respectively, it appears that 1,4-dioxane has made its way into surface water. In March 2013, 1,4-dioxane was detected in groundwater at concentrations up to 110 µg/L. Thus, the Remedy Selection Decision Tree points to the Groundwater Decision Tree. Based on site specific answers for this decision tree, as noted in Table 7, this site can proceed to design a phytoremediation tree stand.

Parker Hannifin Corporation (Pneumatics Division)

Due to the lack of data to support the presence or absence of 1,4-dioxane in surface waters, the status of 1,4-dioxane in surface water is unknown. 1,4-Dioxane was detected in groundwater sampled on February 19 and 20, 2013 at concentrations up to 12 µg/L. Thus, the Remedy Selection Decision Tree points to the Groundwater Decision Tree. Based on site specific answers for this decision tree, as noted in Table 7, this site can proceed to design a phytoremediation tree stand.

Radiator Specialty Company

Due to the lack of data to support the presence or absence of 1,4-dioxane in surface waters, the status of 1,4-dioxane in surface water is unknown. During the October and November 2012 sampling event 1,4-dioxane was detected in groundwater at concentrations up to greater than 3,000 µg/L. Thus, the Remedy Selection Decision Tree points to the Groundwater Decision Tree. Based on site specific answers for this decision tree, as noted in Table 7, this site can proceed to design a phytoremediation tree stand.

Table 7: PTRG Groundwater Decision Tree

Questions*	Site Specific Answers					
	A.B. Carter, Inc.	DAK Americas, LLC	DuPont Kinston Site	Former Heatcraft Remediation Site	Parker Hannifin Corporation	Radiator Specialty Company
Is the target groundwater within 15 feet of surface?	No	Yes	Yes	Yes	No	No
Is the target groundwater between 15 and 25 feet of surface?	No	-	-	-	No	No
Can the target groundwater be pumped and used as irrigation?	Yes	-	-	-	Yes	Yes
Is there sufficient area to plant that can be cleared of obstruction and support planting equipment?	Yes	Yes	Yes	Yes	Yes	Yes
Based on screening, can the plant survive the groundwater geochemistry (pH, salinity, etc.)?	Assumed Yes	Assumed Yes	Assumed Yes	Assumed Yes	Assumed Yes	Assumed Yes
Is the target groundwater impacted	Yes	Yes	Yes	Yes	Yes	Yes
Based on screening, can the plant survive the highest concentration of contaminant or byproduct?	Assumed Yes	Assumed Yes	Assumed Yes	Assumed Yes	Assumed Yes	Assumed Yes
If unacceptable levels of contaminant or byproduct accumulate, can harvesting be conducted as needed throughout the life of the tree stand?	Not applicable					
Is the thickness of impacted groundwater greater than five feet? (If No: Consider ONLY as a supplement to another alternative. If Yes: Continue to next question.)	Data Not Available	Data Not Available	Data Not Available	Data Not Available	Data Not Available	No (Less than 485 feet) (67)
Will the tree stand use groundwater after accounting for infiltration (minimized through engineering) and irrigation?	Proceed to Design a Phytoremediation Tree Stand.					

*Questions from The Interstate Technology & Regulatory Council Phytotechnologies Team, 2009.

DISCUSSION

A.B. Carter, Inc.

1,4-Dioxane was detected at levels up to 35 µg/L during the August 2012 groundwater monitoring event. It is recommended that 1,4-dioxane be added to A.B. Carter's Hazardous Waste Management Permit and included as part of the site's remedial action. Based on the August 2012 sampling results the extent of the 1,4-dioxane contamination plume does not appear to be clearly defined. It is recommended that the extent of the 1,4-dioxane contamination plume be evaluated. Potential groundwater and surface water interaction should be determined, as well as upstream and downstream testing to determine if 1,4-dioxane has migrated to surface water and then mobilized downstream.

A.B. Carter, Inc. includes three adjacent properties, with a total of 82.21 acres (54). Approximately 19 acres appear to be utilized as managed parking, building space, groundwater monitoring and treatment, SWMUs, or manicured lawn. The remaining properties are wooded with coniferous and deciduous tree stands. Thus, based on GIS data, it appears that there is sufficient space to house a phytoremediation tree stand on site. The existing tree stand should be evaluated for phytoremediation potential. If the existing trees would not be supportive of phytoremediation, selective harvesting for a phytoremediation tree stand should be considered. For the A.B. Carter site, 1,4-dioxane groundwater can be pumped up to the surface and out to a phytoremediation tree stand via an irrigation system as the final stage of a treatment train.

DAK Americas, LLC

1,4-Dioxane was detected at levels up to 56,200 µg/L during the April 2013 groundwater monitoring event. It is recommended that the NCAC 2L Standard for 1,4-dioxane be added to DAK Americas' HSWA Permit and included as part of the site's remedial action. Although the groundwater is located within two and ten feet below land surface, the ADH contamination area is located beneath an area that is built upon with impervious industrial structures. Currently, developing a phytoremediation tree stand in this area is not practical, and a groundwater pump and irrigation system should be considered. However, future plans for the facility should be taken into account for potential remedial opportunities. On May 7, 2013, O'Brien & Gere submitted a letter to NCDENR DWM that outlined plans considered by DAK to deactivate and demolish the Cape Fear Manufacturing Facility (70). If the industrial structures were removed and the soils were amended to support tree growth, a phytoremediation tree stand could be installed directly above the 1,4-dioxane contamination plume in the ADH area to facilitate direct tree root interaction with contaminated groundwater. However, the toxic effects of 56,200 µg/L of 1,4-dioxane on trees is not well understood. Controlled irrigation of treated groundwater to a phytoremediation tree stand should be considered.

A survey should be conducted to see if the existing stand of trees can function as a natural phytoremediation stands for 1,4-dioxane. If it determined that the current fauna would not support 1,4-dioxane phytoremediation strategies, then selective harvesting of an area that could support a phytoremediation stand should be investigated. Selective tree removal and replanting in a selected area could be carried out in a manner to minimize disturbing the soil or native fauna. Given that other COCs are present in the contaminated groundwater, phytoremediation should be incorporated as the final stage of treatment train.

DuPont Kinston Site

The DuPont Kinston Site monitors for 1,4-dioxane without an active remediation strategy. The facility should ensure that 1,4-dioxane is included in the facility's remedial action. The facility discharges treated groundwater to surface water under a NPDES Permit. The amount of 1,4-dioxane that is discharged to surface waters is unknown. E. I. DuPont de Nemours Co. Inc. owns the DuPont Kinston Site that totals 637 acres of land (64). A railroad right-of-way bisects the property along the road front side of the property (64). An estimated 165 acres of land are utilized for parking, building, and industrial process. The remaining acreage appears to be managed SWMUs, grassy lawn, and wooded areas. 1,4-dioxane contaminated groundwater is widespread throughout the southern portion of the property and groundwater table depth appears to be less than 12 feet below land surface. Existing tree stands are currently located in the area of groundwater contamination. These trees should be evaluated for their phytoremediation capabilities. The vertical extent of 1,4-dioxane contamination in the groundwater should be determined to assess whether phytoremediation trees can be planted directly in the area of the contamination plume. A groundwater irrigation system should be considered as the final stage of a treatment train.

On June 12, 2013, DuPont Engineering commented to NCDENR DWM "Sampling events have only been conducted at a limited number of wells, making it difficult to assess the current conditions at a limited number of wells, making it difficult to assess the current conditions across the entire site… … it is difficult to assess potential migration and or degradation of constituents of potential concern in groundwater at the site" (71). Thus, it is recommended that the 1,4-dioxane plume extent be evaluated.

Ethylene glycol was listed as one of the COCs and is a common co-contaminant of 1,4-Dioxane. The November 20, 2009 RCRA Permit Renewal Application for Corrective Action listed thirteen SWMUs that have 1,4-dioxane contamination detected in monitoring well samples, three of which also contained ethylene glycol (72). Ethylene glycol can complicate the phytoremediation process by causing deleterious effects on tree viability (28). Ethylene glycol acts as a plant stressor and can cause growth reduction and complete inhibition of germination (28). In 2011, Edwards et al. found that, under hydroponic conditions, 60 g/L ethylene glycol inhibited the phytovolatilization of 1,4-dioxane by more than 80% (28). Thus, emphasis should be made to ensure phytoremediation tree exposure to ethylene glycol is limited and prevented, if possible.

Former Heatcraft Remediation Site

Given that the groundwater table located at the Former Heatcraft Remediation Site is less than ten feet below level surface, direct contact of a phytoremediation tree roots with the contaminated groundwater is possible. In lieu of discharging treated groundwater to surface waters, irrigating the 1,4-dioxane contaminated effluent to a phytoremediation tree stand should be considered. In addition, the facility should conduct surface water samples to document the extent of potential 1,4-dioxane releases to surface water.

The property located at 602 Sunnyvale Drive is primarily built upon with industrial structures with the remaining wooded area surrounded by residential property. Port City Distribution, LLC, which owns 602 Sunnyvale Drive, also owns the adjacent property located at 314 Sunnyvale Drive (66). This 1.68 acre property is an undeveloped wooded lot that is zoned residential and is adjacent to other residential properties (66). It is important to ensure stakeholders, including the surrounding land owners and residents are included as part of the phytoremediation decision process. Utilizing these areas as phytoremediation tree stands without the input and inclusion of stakeholders involvement may lead to resistance by stakeholders.

The site may create access to open land by considering the purchase of additional property. Located adjacent and south of the Former HeatCraft Remediation Site property there is an upland pine barren consisting of pine and live oak (50). This property consists of 42.80 acres undeveloped land that is owned by Cameron Company, Ltd. (50). The facility should consider purchasing the Cameron Company, Ltd. property and assessing the existing tree stand for potential phytoremediation utilization. If the existing stand is determined not to be sufficient, then the facility should consider planting phytoremediation specific species.

Parker Hannifin Corporation (Pneumatics Division)

Although the Parker Hannifin Corporation property is located on two vacant parcels totaling 30.51 acres, which could potentially provide plenty of space for a phytoremediation tree stand, this property has other circumstances that must be considered. Brownfield project, No. 07029-03-92, was signed with the NCDENR DWM on June 1, 2006, totaling 33 acres (73) and four parcels, that include the Parker Hannifin Corporation parcels, totaling 64.21 acres were deeded to a new owner on 6/29/2012 (36). The properties are also located adjacent to residential properties (36). Current environmental exposures must also be taken into account. On March 28, 2012, the NCDENR DWM HWS conducted an environmental indicator evaluation and determined that current human exposures were not under control and that the migration of contaminated groundwater was under control (74). Exposure pathways for COCs were determined to be between groundwater, surface soil, and subsurface soil media with potential human receptors specified as construction workers and trespassers (74). 1,4-Dioxane was listed as a COC for groundwater and not for the other media pathways in NCDENR's environmental indicator evaluation (74). The greatest potential for exposure to contaminated groundwater for construction workers and trespassers is where the limits of the contamination plume approaches surface water and the groundwater is shallow (74).

If a phytoremediation tree stand were to be considered for this site, an evaluation of space for such a project would have to be incorporated into the brownfield plan. The local community stakeholders should be involved in plans from the beginning, and the phytoremediation tree stand should be built in a location where 1,4-dioxane that is transpired from trees would not pose an air quality risk to the local residents. In addition, the level of 1,4-dioxane was last detected at a maximum of 12 µg/L. The facility may consider monitored natural attenuation of 1,4-dioxane until the site can use risk factors to justify current levels of 1,4-dioxane.

Radiator Specialty Company

Radiator Specialty Company has a groundwater remediation system consisting of an air stripper. It has been demonstrated that air stripping is ineffective at treating for 1,4-dioxane in water due to 1,4-dioxane's low Henry's Law Constant (16). Thus, any 1,4-dioxane that is sent through the air stripper would pass through the system and discharge as treated wastewater to surface water. The effluent samples presented in the facility's March 20, 2013 groundwater monitoring report does not list 1,4-dioxane in the effluent monitored constituents. Thus, the amount of 1,4-dioxane that is discharged to surface waters is unknown. It is recommended that the facility start monitoring for 1,4-dioxane in surface waters as well as in the effluent of the air stripping treatment system. It is also recommended that 1,4-dioxane is added to the facility's NPDES Permit.

Historical data on the levels of 1,4-dioxane in all four recovery wells could not be found in available documents. In addition, a site map illustrating the location of monitoring wells and contamination plumes could not be found. Therefore, recommendation will be made in the absence of this information. Two POC monitoring wells had levels of 1,4-dioxane above the facility's permit limit of 3 µg/L: ETE-2A = 31 µg/L, MW-2B = 680 µg/L. Per the July 7, 2010 Hazardous Waste Management Permit, the facility is directed to conduct corrective actions for 1,4-dioxane. Based on the facility's 2009 Post-Closure Permit Renewal Application, no other remediation systems or alternative active treatment plans have been developed. Monitored natural attenuation appears to be the current method of treatment for 1,4-dioxane. In lieu of discharging treated groundwater to surface waters, the facility should consider re-routing the wastewater discharge as irrigation water to a phytoremediation tree stand for treatment.

Adequate space for a phytoremediation tree stand appears to be available. The Radiator Specialty Company manufacturing facility occupies approximately 23 acres of the 133-acre tract (67). However, the property is split by a railroad right-of-way which may limit the availability of open space to approximately 40 acres of wooded property that is adjoining the manufacturing area. A survey should be conducted to see if the existing stand of trees can function as a natural phytoremediation stand for 1,4-dioxane. If it determined that the current fauna would not support 1,4-dioxane phytoremediation strategies, then an area should be investigated that could support a phytoremediation stand. Selective tree removal and replanting in a selected area could be carried out to minimize disturbing the soil or native fauna. Part of this wooded space is adjacent to residential property that will need to be considered.

CONCLUSION

The goal of this paper was to identify Treatment Storage and Disposal Facilities in North Carolina with 1,4-dioxane contaminated groundwater and evaluate the potential application of phytoremediation as a viable remedial option for 1,4-dioxane. This assessment demonstrates that phytoremediation should be considered as a viable remedial option for 1,4-dioxane, specifically at sites that have no current remediation strategy and that have access to space for a phytoremediation tree stand. It is recommended that 1,4-dioxane contaminated groundwater be irrigated to a phytoremediation tree stand as the effluent of an active remediation system that treats for other COCs.

It is important that site groundwater investigations and active remediation designs be inclusive of 1,4-dioxane. At a minimal, groundwater treatment system influent and effluent should be monitored for 1,4-dioxane. This assessment revealed that for sites where active remediation options were implemented, 1,4-dioxane was not considered as part of remediation strategies. Active remediation systems that were identified during the review of the facilities, such as pules air sparging, air stripping system, and vapor extraction system, are treatment options that are ineffective at remediating 1,4-dioxane. The inability of 1,4-dioxane to be remediated through traditional groundwater remediation systems and 1,4-dioxane's inability to degrade under ambient groundwater conditions contributes to the recalcitrance of 1,4-dioxane in the environment and the importance of having a viable remediation alternative.

Table 8 summarizes the concentration ranges of 1,4-dioxane detected in groundwater as well as the depth of groundwater tables below land surface. The toxic implications of direct tree root interaction with 1,4-dioxane contaminated groundwater at concentrations greater than 60 mg/L needs to be studied. The highest concentration of 1,4-dixoxane detected was 56,000 μg/L. Thus, the level at which 1,4-dioxane will cause deleterious effects to the trees needs to be determined. Table 8 also summarizes the co-contaminants of 1,4-dioxane identified at each site. The potential toxic implications of 1,4-dioxane and other COCs on phytoremediation tree stands should be incorporated in remediation strategies. It is recommended that groundwater first be treated by an active remediation system, and then irrigated to a phytoremediation tree stand. This will allow for the treatment of constituents that are toxic to tree viability, such as ethylene glycol, as well as the controlled irrigation of 1,4-dioxane concentrations.

Additional site investigations will be required to determine the viability of managing phytoremediation tree stands with site specific conditions and evaluating potential soil conditioning measures to increase the survivability of selected species. Tree stands will need to be designed in a manner that accounts for infiltration rates of rain and irrigation. When considering phytoremediation as a remedial option, a cost benefit, cost comparison should be conducted to compare with other options. The cost of implementation and long term maintenance/management will also need to be considered.

The results presented in this paper demonstrate that phytoremediation should be considered as a remediation option for 1,4-dioxane at the six sites that were fully addressed. Phytoremediation does not represent the only remediation option, yet one option that should be considered as an important alternative to current remediation strategies.

Table 8: Site Specific Summary of Key Features

	A.B. Carter, Inc.	DAK Americas, LLC	DuPont Kinston Site	Former Heatcraft Remediation Site	Parker Hannifin Corporation	Radiator Specialty Company
1,4-Dioxane range in groundwater above the NCAC 2L Standard of 3 µg/L (µg/L)	4.1 to 35 (47)	56,200 (48)	4.39 to 359 (49)	28 to 110 (50)	5 to 12 (51)	6.6 to >3,000 (52)
Depth of Groundwater Below Land Surface (feet)	19.5 to 44.7 (47)	2 to 10 (56)	3.6 to 11.8 (49)	4 to 10 (50)	5.4 to 41 (51)	8.5 to 77.0 (52)

	A.B. Carter, Inc.	DAK Americas, LLC	DuPont Kinston Site	Former Heatcraft Remediation Site	Parker Hannifin Corporation	Radiator Specialty Company
Other Constituents of Concern	nickel, sulfate, 1,1-DCE, 1,2-DCA, PCE (47)	PCE, TCE, cis-1,2-DCE, vinyl chloride, diphenyl ether, 1,1-biphenyl, naphthalene, arsenic (48)	TCE, cis-1,2-DCE, vinyl chloride, acetone, benzene, chloroform, 1,4-dioxane, methyl ethyl ketone, methyl isobutyl ketone, methylene chloride, tetrahydrofuran, 2-methylphenol, 4-methylphenol, phenol, ethylene glycol, diethylene glycol, triethylene glycol, arsenic, barium, cadmium, chromium, iron, lead, manganese, nickel, phosphorus, silver, vanadium (60)	include 1,1,1-TCA, 1,1-DCA, 1,1-DCE, trans-1,2-DCE, cis-1,2 DCE, TCE, vinyl chloride (50)	TCE, cis-1,2-DCA, PCE, chromium, mercury (51)	acetone, benzene, carbon disulfide, chloroethane, 2-chlorotoluene, 4-chlorotoluene, cis-1,2-DCE, 1,1-DCA, 1,1-DCE, 1,2-DCA, methylene chloride, 4-methyl-2-pentanone, PCE, 1,1,1-TCE, 1,1,2-TCA, TCE, trans-1,2-DCE, vinyl chloride, pentachlorophenol, bis(2-ethylhexyl) phthalate, 2,4-dimethylphenol, 2-methyl-4,6-dinitrophenol, 2-methylphenol, 4-methylphenol, arsenic, cadmium, chromium, lead (67)

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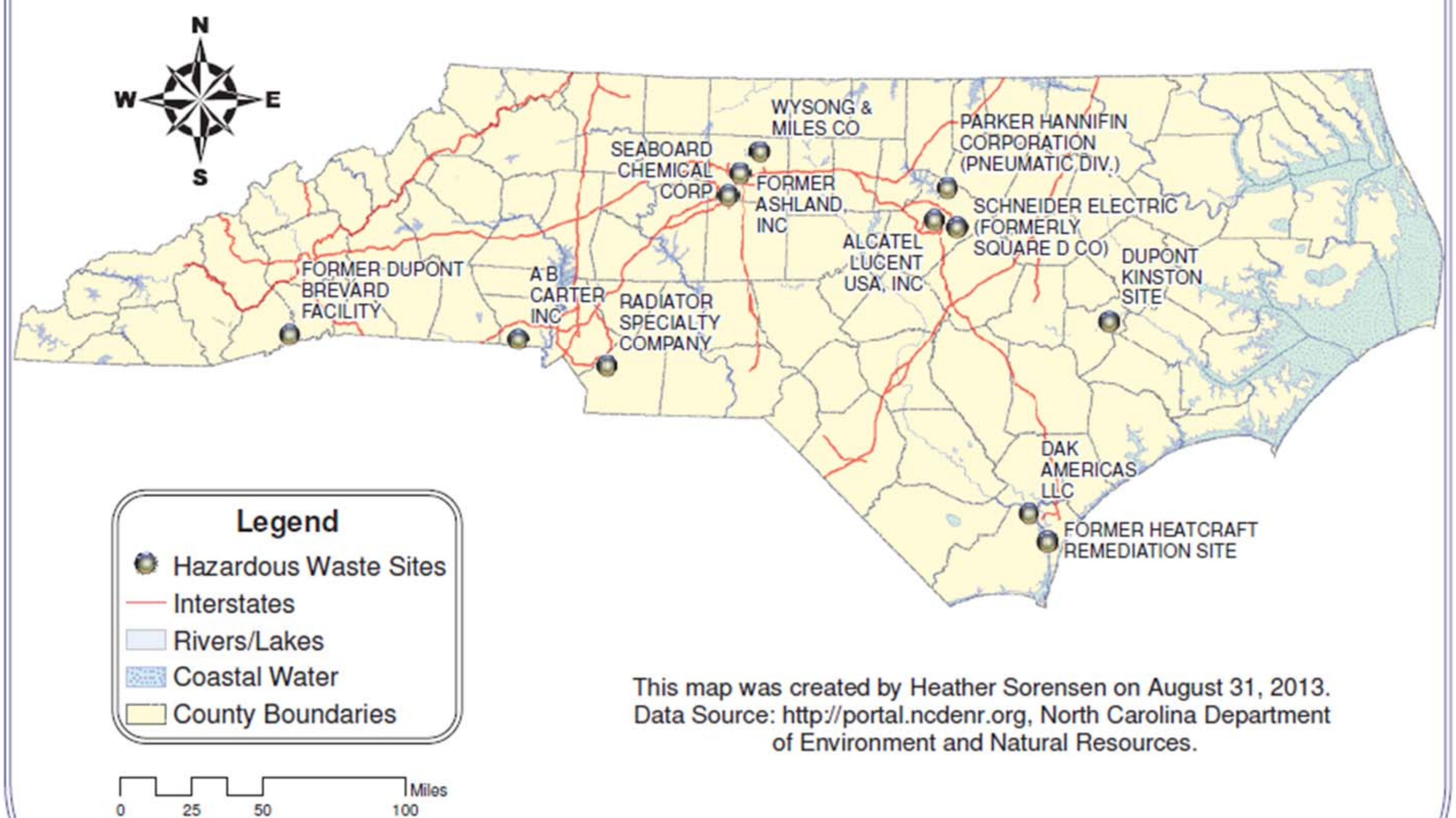
Attachment 1: North Carolina Hazardous Waste Sites with 1,4-Dioxane Groundwater Contamination



This map was created by Heather Sorensen on August 31, 2013.
Data Source: http://portal.ncdenr.org, North Carolina Department of Environment and Natural Resources.