2018 Thriving Earth Exchange

Community Science Fellow Remediation Report

Closed Colebrook Municipal Landfill
Skyline Drive
Colebrook, NH 03576

Prepared for:
The Town of Colebrook
17 Bridge Street
Colebrook, NH 03576
Phone Number (603) 237-4142
RP Contact Name: Mr. Greg Placy
RP Contact Title: Chairman of the Board of Selectmen
RP Contact Email: gplacy@colebrooknh.org

Prepared By:
Brad Geismar
176 Jackass Annie Rd
Minot, ME 04258
Phone Number: (207) 346-1962
Contact Email: bradley.geismar@gmail.com

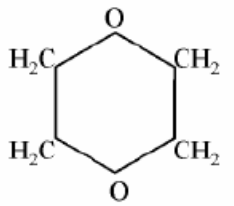
THRIVING EARTH EXCHANGE

Table of Contents

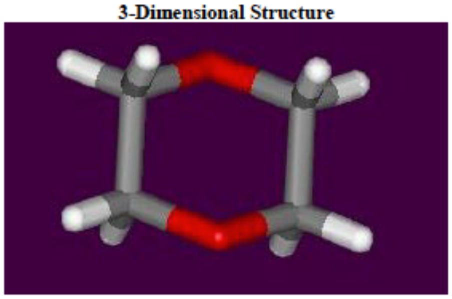
Table of Contents

Exhibit 3: Molecular Structure of Dioxane

2-Dimensional Structure



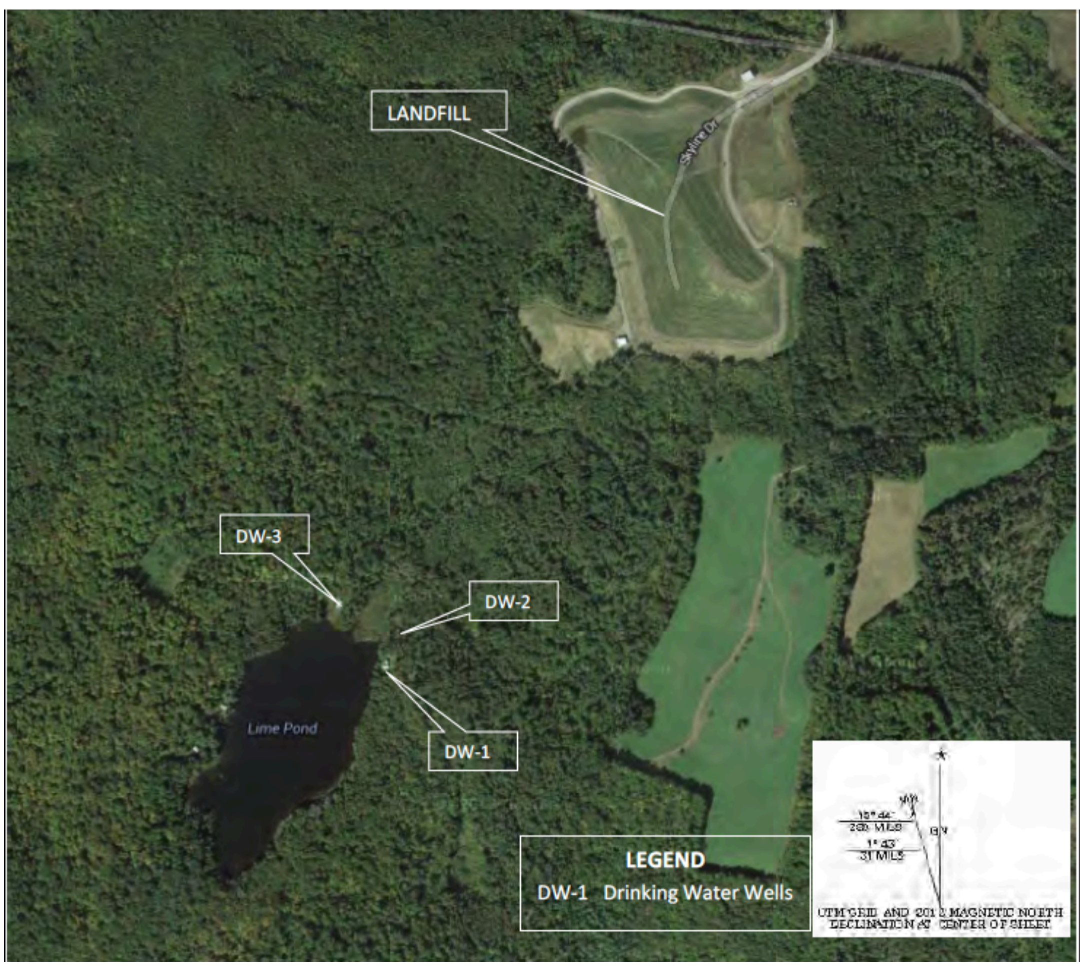
3-Dimensional Structure



Source: USDHHS 2003

Molecular Structure of 1,4-Dioxane.
Credit to (USEPA, 2006)

Satellite View of TOC Landfill
Credit to (Calex, Report, 2018)



TOC Landfill Remediation Summary

The Colebrook Municipal Landfill has been an active groundwater remediation site since 2005. Initial remedial operations at the site focused on both reducing concentrations of a range of Volatile Organic Compounds (VOCs) above New Hampshire's Ambient Groundwater Quality Standard(s) (AGQS) in a contaminant plume emanating from the landfill and preventing that plume from significantly increasing in size[1]. Though the remediation system made rapid progress towards achieving these original clean-up goals, in 2008 several Site monitoring wells recorded concentrations of an emergent contaminant 1,4-Dioxane (1,4-DX) above New Hampshire's (NH) AGQS of 3 micrograms/liter (ppb). The discovery of the newly identified contaminant, 1,4-DX, at the site prompted a revision of the initial remediation system's scope of work and a reassessment of the landfill remediation strategy. In 2009, Colebrook hired the environmental remediation firm Remediation & Environmental Management Services, Inc. (Remserv) to add an addendum to the town's initial landfill's remedial action plan (RAP). In 2010, the revised RAP was approved and since then the focus of remedial operations at the Colebrook Municipal Landfill have transitioned from reducing the concentration of a range of VOCs at the Colebrook site to just reducing concentrations of 1,4-D in both the contaminant plume and the site[2].

Contaminant of Concern: 1,4-Dioxane (1,4-DX)

<u>History</u> – 1,4-DX is a synthetic industrial compound that is frequently used as a stabilizer for chlorinated solvents, such as trichloroacetic acid (TCA), as well as paint-strippers and lacquers. First synthesized in 1863, 1,4-DX saw its highest production and use in the US from 1986-1994[3]. Though 1,4-DX tends to be associated with industrial waste, regulatory agencies did not have a test sensitive enough to detect the chemical until 1997 and 1,4-DX is still considered an emergent contaminant of concern

---

[1] (GeoInsight, 2006)
[2] (GeoInsight, 2006) (Remserv, 2010) (Calex, Report, 2018)
[3] (Mohr, 2010)

(COC)[4]. While Colebrook's landfill lacks a categorical record of waste delivered to the site, 1,4-DX is thought to have been introduced to the site by any of several industrial companies who deposited waste at the site over the course of its lifespan[5].

Properties – As a chemical contaminant, 1,4-DX has been deemed recalcitrant towards remediation efforts. One of the properties that makes 1,4-DX particularly difficult to remediate is its low Henry's Law constant. The Henry's Law constant essentially indicates how easily a chemical transition between a vaporous state and an aqueous state. Molecules with a low Henry's Law constant have a fairly low potential to volatilize from the water surface, and it often takes a significant amount of energy to bring those molecules into a gaseous state[6]. 1,4-DX's low Henry's Law constant, combined with its low affinity for soils, its ability to resist biodegradation in most local soils, and its full miscibility in water, make it a highly mobile and long-lived contaminant[7]. Rather than sticking to soils and building up high, relatively static points of concentration in a groundwater system, 1,4-DX will remain in an aqueous state and diffuse throughout a groundwater system. As a result, 1,4-DX remediation systems tend to have to focus on treating a relatively widespread, potentially multi-zoned area instead of treating dense points of concentration. Additionally, since 1,4-DX is a stable chemical, remediation systems have to account for the fact that contaminant levels are unlikely to decrease as the result of natural attenuation through chemical or biological degradation over time[8].

Toxicology – Human volunteer studies demonstrate that acute exposure via inhalation to relatively high concentrations of 1,4-DX over a period of several minutes can cause irritation of the eyes, nose, and throat[9]. The negative effects of prolonged exposure to

---

4 (USEPA, 2017) (USEPA, 2006) (Mohr, 2010)
5 (GeoInsight, 2006) (Remserv, 2010)
6 (Mohr, 2010)
7 (USEPA, 2006) (USEPA, 2017) (Mohr, 2010)
8 (GeoInsight, 2006) (Mohr, 2010) (REMSERV 2010)
9 (Mohr, 2010)

1,4-DX in humans are well documented in oral and inhalation studies and primarily manifest in severe liver and kidney degeneration[10]. Even with these findings, studies investigating the impact of 1,4-DX exposure on human health remain fairly limited. Sufficient research exists to affirm 1,4-DX's carcinogenicity in experimental animals, however, since data for human exposure to 1,4-DX's is relatively limited, the EPA has listed 1,4-DX as a probable human carcinogen. EPA risk assessments for 1,4-DX indicate that the drinking water concentration representing a 1 in 1,000,000 cancer risk for humans is 0.35 ppb and 1,4-DX is on the EPA's drinking water contaminant candidate list[11].

Present Situation

Remediation Goals – In remediating the landfill site, the Town of Colebrook seeks to:

- Prevent the spread of 1,4-DX beyond the plume's current extent and contain 1,4-DX contamination within the boundaries of the Groundwater Management zone (GMZ).
- Bring 1,4-DX concentrations in the subsurface at the landfill Site and abutting properties into compliance with NHDES' current AGQS.
- Ensure the continued protection of potential 1,4-DX threat vectors, such as the drinking water resources and recreational water resources near Lime Pond.
- Minimize environmental disruption associated with remediation efforts.
- Reduce taxpayer burden by finding the most cost-effective ways to perform site-remediation.
- Look towards regulatory trends to ensure that remediation performed at the landfill Site keeps the Site in compliance with future regulatory standards.

Site Summary – Remediation operations have run more or less continuously at the landfill Site since 2005[12]. The remediation system currently operating at the landfill Site

---

[10] (Mohr, 2010)
[11] (USEPA, 2017)
[12] (Calex, Report, 2018)

is commonly known as a “pump and treat” or “pump and dump” system. The system uses a network of wells to monitor and manage concentrations of 1,4-DX at the Site by extracting 1,4-DX from 2 distinct layers of the subsurface, periodically analyzing samples of the water to determine COC levels, and subsequently sending the rest of the extracted water to Colebrook’s Waste Water Treatment Facility (WWTF) for treatment and disposal[13]. When the system was first constructed, an air stripper was installed at the site to provide on-site treatment for the water extracted from the ground so that a portion of the water could be circulated back into the groundwater site via an infiltration system installed at the site. The air stripper system proved effective at lowering the concentration of most VOCs at the site, however it had relatively little impact on the concentrations of 1,4-DX in water removed at the site. Because of the air stripper’s efficacy with VOC treatment but relative inefficacy with 1,4-DX treatment, shortly after 1,4-DX was discovered at the site in 2008, the re-infiltration system was taken off-line to prevent re-introduction of 1,4-DX contaminated water into the groundwater system. Ultimately, the air stripper system was decommissioned in 2011 once concentrations of nearly all VOCs except 1,4-DX were successfully lowered to beneath NH’s AGQS[14].

Following the decommissioning of the air stripper system, the remediation system installed at the landfill Site transitioned from an extract and treat to solely an extraction system. As a result, the main mechanism for both plume containment and the reduction of 1,4-DX concentrations at the landfill Site is the extraction of large volumes of groundwater. On average, the system removes some 330,000 gallons of water from the ground per month and anywhere from 2-4.5 million gallons of water from the site annually at a cost of roughly ~$80,000/yr[15]. Thus far, some 45 million gallons of groundwater have been extracted from the Colebrook site and trucked to the

[13] (Remserv, 2010)
[14] (NHDES, 2011)
[15] (Town of Colebrook, 2018)

Town's WWTF[16]. Tables providing gallons extracted per month from the site are included on pages 10 and 11 of this report.

<u>Current Remedial System Design</u> – The precise technical details of the remediation system operating at the landfill Site have been comprehensively described in several reports written about the site over the past few years[17]. In overview, the remediation system at the landfill Site has 26 wells that monitor contaminant levels and 9 wells that extract contaminated groundwater from two zones at the landfill Site: the source and plume zones[18]. Water extracted from the ground is stored in a 20,000 gallon tank prior to its transport to the town's WWTF for treatment and disposal. Water is transported from the Site to the WWTF anywhere from 5-10 times a day 5 days a week. Extraction rates at the site very from 12-34 gallons per minute (gpm) depending on groundwater conditions[19].

The source zone at the site is delineated by the fact that it is relatively close to the landfill and represents a store of contaminated groundwater which could migrate into the plume stretching away from the landfill Site. The plume zone delineates a body of groundwater that has actively migrated away from the landfill and it essentially reveals the direction high concentrations of 1,4-DX would migrate towards if left unchecked. The majority of source zone groundwater extraction is currently performed by 7 source extraction wells (SEWs) located at the southwestern toe of the landfill. Plume extraction is currently performed by 2 plume extraction wells (PEW-1 and CEW-1) that are designed to contain the additional spread of the contaminant plume into properties abutting the landfill site.

Each of the groundwater zones can be understood as being further delineated by two different subsurface layers: the overburden (soil) layer and fractured bedrock layer. The soil layer can be understood as an area where contaminated groundwater

---

[16] (Calex, Report, 2018)
[17] (GeoInsight, 2005) (Remserv, 2010) (Calex, Report, 2018)
[18] (NHDES, 2016)
[19] (Brooks, 2018)

can travel relatively quickly and is also relatively accessible for extraction. The bedrock layer can be understood as an area in which contaminated groundwater travels relatively slowly and, due to the depth and nature of the bedrock layer, is relatively more difficult to extract or treat. Both the source and plume groundwater zones at the landfill Site have wells that specifically extract contaminated groundwater from the overburden and bedrock layers. In each zone, each layer presents its own remediation trends and challenges[20].

[20] (GeoInsight, 2005) (Remserv, 2010)

Records of Gallons Extracted at the Landfill Site/Month: Jan-2011 until Oct-2014
Credit to (Calex, Report, 2018)

TABLE 5
PLUME/SOURCE CONTROL RECOVERY WELLS
MONTHLY DISCHARGE VOLUMES
CLOSED COLEBROOK MUNICIPAL LANDFILL
COLEBROOK, NH

Calex Environmental Consulting

Date	Source Leachate Gallons	Plume Leachate Gallons	Total Gallons	Source Leachate AVG Daily Gallons	Plume Leachate AVG Daily Gallons	Total AVG Daily Gallons
Jan-2011	155,200	172,522	327,722	5,006	5,565	10,572
Feb-2011	62,095	145,454	207,549	2,218	5,195	7,412
Mar-2011	0	109,133	109,133	0	3,520	3,520
Apr-2011	0	161,675	161,675	0	5,389	5,389
May-2011	214,653	206,145	420,798	6,924	6,650	13,574
Jun-2011	110,339	175,146	285,485	3,678	5,838	9,516
Jul-2011	25,730	159,278	185,008	830	5,138	5,968
Aug-2011	51,454	180,851	232,305	1,660	5,834	7,494
Sep-2011	40,347	139,654	180,001	1,345	4,655	6,000
Oct-2011	54,633	177,928	232,561	1,762	5,740	7,502
Nov-2011	119,010	128,895	247,905	3,967	4,297	8,264
Dec-2011	189,705	157,247	346,952	6,120	5,072	11,192
Jan-2012	148,221	135,435	283,656	4,781	4,369	9,150
Feb-2012	123,741	158,022	281,763	4,419	5,644	10,063
Mar-2012	162,875	90,666	253,541	5,254	2,925	8,179
Apr-2012	87,323	87,800	175,123	2,911	2,927	5,837
May-2012	0	0	0	0	0	0
Jun-2012	81,690	93,588	175,278	2,723	3,120	5,843
Jul-2012	20,824	197,928	218,752	672	6,385	7,057
Aug-2012	0	180,484	180,484	0	5,822	5,822
Sep-2012	0	176,882	176,882	0	5,896	5,896
Oct-2012	0	202,197	202,197	0	6,522	6,522
Nov-2012	159,681	168,091	327,772	5,323	5,603	10,926
Dec-2012	383,152	186,808	569,960	12,360	6,026	18,386
Jan-2013	203,290	148,093	351,383	6,558	4,777	11,335
Feb-2013	132,321	129,892	262,213	4,726	4,639	9,365
Mar-2013	398,908	143,512	542,420	12,868	4,629	17,497
Apr-2013	215,148	180,485	395,633	7,172	6,016	13,188
May-2013	451,771	137,329	589,100	14,573	4,430	19,003
Jun-2013	302,177	154,083	456,260	10,073	5,136	15,209
Jul-2013	447,192	69,028	516,220	14,426	2,227	16,652
Aug-2013	469,726	145,972	615,698	15,152	4,709	19,861
Sep-2013	419,950	143,924	563,874	13,998	4,797	18,796
Oct-2013	613,172	168,929	782,101	19,780	5,449	25,229
Nov-2013	533,619	166,595	700,214	17,787	5,553	23,340
Dec-2013	464,860	120,019	584,879	15,495	4,001	19,496
Jan-2014	281,893	109,534	391,427	9,396	3,651	13,048
Feb-2014	375,550	134,862	510,412	12,518	4,495	17,014
Mar-2014	211,432	81,379	292,811	7,048	2,713	9,760
Apr-2014	303,519	98,123	401,642	10,117	3,271	13,388
May-2014	404,950	121,735	526,685	13,498	4,058	17,556
Jun-2014	328,056	119,112	447,168	10,935	3,970	14,906
Jul-2014	249,499	108,544	358,043	8,317	3,618	11,935
Aug-2014	113,595	47,556	161,151	3,787	1,585	5,372
Sep-2014	188,903	75,044	263,947	6,297	2,501	8,798
Oct-2014	276,178	84,678	360,856	9,206	2,823	12,029

Records of Gallons Extracted at the Landfill Site/Month: Nov-2014 until Dec-2017
Credit to (Calex, Report, 2018)

TABLE 5
PLUME/SOURCE CONTROL RECOVERY WELLS
MONTHLY DISCHARGE VOLUMES
CLOSED COLEBROOK MUNICIPAL LANDFILL
COLEBROOK, NH

Calex Environmental Consulting

Date	Source Leachate Gallons	Plume Leachate Gallons	Total Gallons	Source Leachate AVG Daily Gallons	Plume Leachate AVG Daily Gallons	Total AVG Daily Gallons
Nov-2014	251,127	62,796	313,923	8,371	2,093	10,464
Dec-2014	256,846	71,862	328,708	8,562	2,395	10,957
Jan-2015	23,268	9,618	32,886	751	310	1,061
Feb-2015	242,669	66,954	309,623	8,667	2,391	11,058
Mar-2015	132,597	110,405	243,002	4,277	3,561	7,839
Apr-2015	47,182	20,011	67,193	1,573	667	2,240
May-2015	92,185	46,889	139,074	2,974	1,513	4,486
Jun-2015	213,867	115,573	329,440	7,129	3,852	10,981
Jul-2015	300,397	112,451	412,848	9,690	3,627	13,318
Aug-2015	163,440	98,411	261,851	5,272	3,175	8,447
Sep-2015	207,221	85,187	292,408	6,907	2,840	9,747
Oct-2015	164,970	85,917	250,887	5,322	2,772	8,093
Nov-2015	205,923	68,340	274,263	6,643	2,205	8,847
Dec-2015	263,763	100,185	363,948	8,508	3,232	11,740
Jan-2016	263,117	103,041	366,158	8,488	3,324	11,812
Feb-2016	229,763	76,328	306,091	7,923	2,632	10,555
Mar-2016	94,510	58,124	152,634	3,049	1,875	4,924
Apr-2016	133,095	98,900	231,995	4,437	3,297	7,733
May-2016	198,363	166,090	364,453	6,399	5,358	11,757
Jun-2016	179,763	199,228	378,991	5,992	6,641	12,633
Jul-2016	173,606	180,211	353,817	5,600	5,813	11,413
Aug-2016	196,143	203,425	399,568	6,327	6,562	12,889
Sep-2016	164,820	177,403	342,223	5,494	5,913	11,407
Oct-2016	147,451	174,380	321,831	4,756	5,625	10,382
Nov-2016	186,589	185,003	371,592	6,220	6,167	12,386
Dec-2016	77,245	99,166	176,411	2,492	3,199	5,691
Jan-2017	131,688	185,199	316,887	4,248	5,974	10,222
Feb-2017	93,274	147,867	241,141	3,331	5,281	8,612
Mar-2017	125,534	206,817	332,351	4,049	6,672	10,721
Apr-2017	155,026	141,655	296,681	5,168	4,722	9,889
May-2017	174,569	165,360	339,929	5,631	5,334	10,965
Jun-2017	178,731	231,338	410,069	5,958	7,711	13,669
Jul-2017	149,936	228,284	378,220	4,837	7,364	12,201
Aug-2017	225,025	225,761	450,786	7,259	7,283	14,541
Sep-2017	138,631	173,102	311,733	4,621	5,770	10,391
Oct-2017	162,641	201,488	364,129	5,246	6,500	11,746
Nov-2017	151,705	164,166	315,871	5,057	5,472	10,529
Dec-2017	137,717	142,722	280,439	4,442	4,604	9,046

<u>1,4-Dioxane Trends</u> – The 2017 Annual Groundwater Monitoring Report produced by Calex Environmental Consulting, LLC for the town of Colebrook provides an excellent, comprehensive analysis of 1,4-DX trends at the landfill Site over the course of its remediation history. In brief overview of the report, since monitoring began in 2008 concentrations of 1,4-DX throughout the landfill site have generally experienced a gradual decrease. In 2010, concentrations of 1,4-DX greater than 30 ppb were measured at some of the bedrock monitoring wells whereas in 2017, the highest average concentration of 1,4-DX, also measured at a bedrock site, was less than 14 ppb. Overburden layers have also experienced a more consistent decline in 1,4-DX levels over the past few years[21].

According to the most recent round of sampling performed in 2017, all monitoring wells have recorded concentrations of 1,4-DX below their historic highs. Still, concentrations of 1,4-DX above NH AGQS persist in both the source and plume zones at the landfill Site. 8 of the monitoring wells at the Site register concentrations of 1,4-D above AGQS. Additionally, and of particular concern, 2 monitoring wells – MW-18 and MW-18B – situated beyond the Site's permitted GMZ have shown some slight increases in 1,4-DX contamination in both overburden and bedrock layers of the contaminant plume during the last year[22]. The general decrease in 1,4-DX concentrations throughout the Site at both the source and plume extraction zones carries several implications. One implication is that the current remediation system is continuing to successfully remove 1,4-DX from the groundwater system[23]. Another is that the cap over the landfill has, to an extent, prevented rainfall from adding additional high quantities of contaminant to the groundwater system through recharge. A third implication could be that the original source of 1,4-DX contaminant has significantly depleted itself. This third implication would depend upon the state in which the original source of 1,4-DX contaminants was originally introduced to the groundwater system beneath the landfill. If the contaminant was introduced to the system in an unconfined

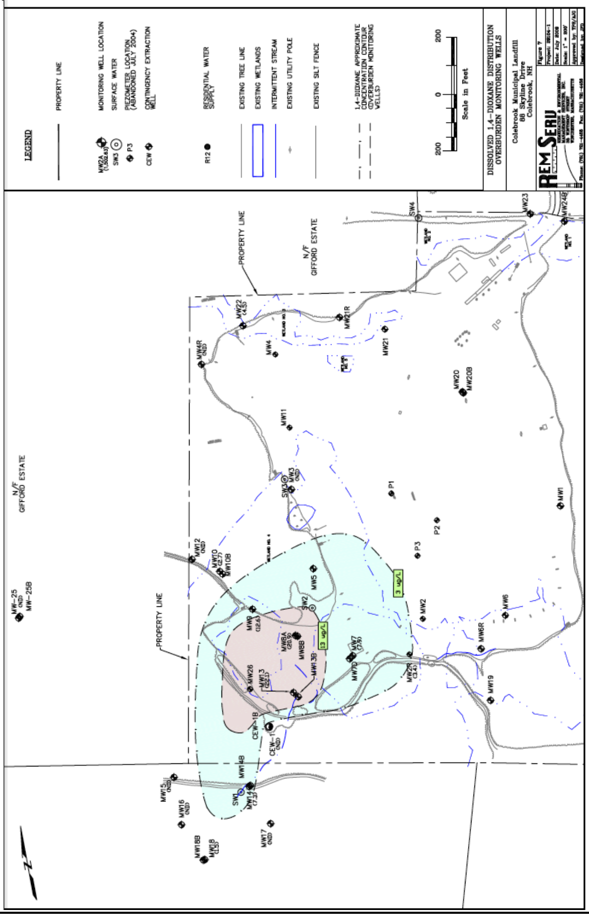
[21] (Calex, Report, 2018)
[22] (Calex, Report, 2018)
[23] (Calex, Report, 2018)

aqueous state (e.g. in a solution dumped onto the ground), then it is more likely that, given 1,4-DX's affinity for water, the majority of 1,4-DX could have already entered the groundwater system. If the original 1,4-DX contaminant were introduced due to the failure of some sort of now-buried containment system however, then it is possible that a source for future 1,4-DX contamination could remain within the landfill. Even assuming the latter condition, the general trend in 1,4-DX concentrations at the site suggest that additional significant concentrations of 1,4-DX are not entering the system for the time being.

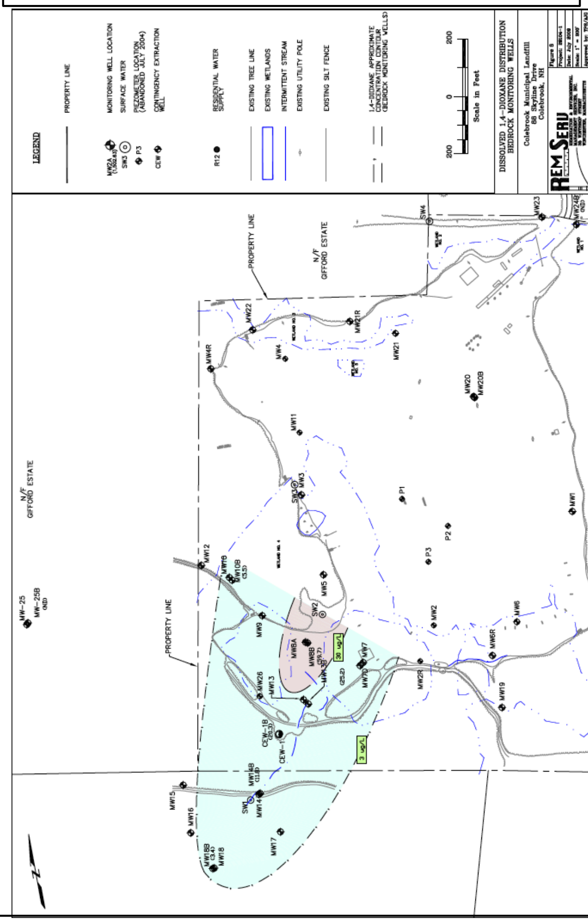
The majority of sampling data collected for off-site monitoring wells MW-18 and MW-18B appears to suggest a stable, if not decreasing, trend in 1,4-DX concentrations. Insufficient data exists to indicate whether the slight increase in 1,4-DX concentrations recorded at the wells during the last round of sampling could be the precursor for a new increasing trend of 1,4-DX concentrations at the wells. The slight increase in 1,4-DX concentrations at the wells in 2017 may be consistent with prior historical fluctuations in 1,4-DX in response to fluctuations in the groundwater system, or it may also indicate the presence of part of the original contaminant plume that may have evaded capture when the plume recovery system initially began its operation or during periods of shutdown[24]. In either case, it is likely that concentrations of 1,4-DX at the wells should decrease over time as continued operation of the plume recovery wells prevents any higher concentrations of 1,4-DX from migrating beyond the GMZ. So long as the wells prevent further 1,4-DX migration, the 1,4-DX beyond the GMZ should passively diffuse to lower levels in the groundwater system throughout the area surrounding the wells[25].

[24] (Calex, Report, 2018)
[25] (Mohr, 2010)

2009 Overburden Map of 1,4-DX Concentration
Credit to (Remserv, 2010)



2009 Bedrock Map of 1,4-Dioxane Concentration
Credit to (Remserv, 2010)



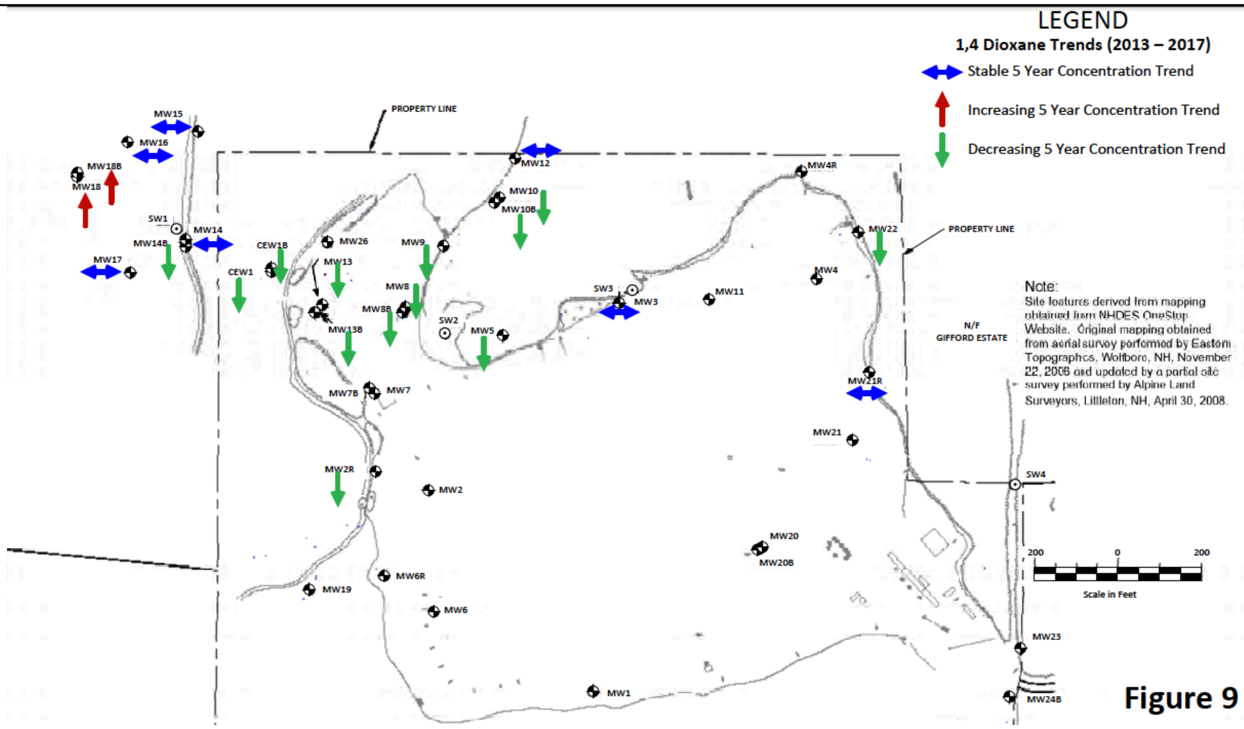
2009 Concentration Maps

The maps presented above show the modeled extents of groundwater contamination at the landfill Site. These maps have been included in this report to provide a picture of the original size of the dioxane plume when it was initially discovered in the groundwater in both overburden and bedrock layers at the landfill Site. As the maps show, concentrations of 1,4-DX tend to be higher in the bedrock, likely due to its low groundwater transportation rate.

Credit to (Remserv, 2010).

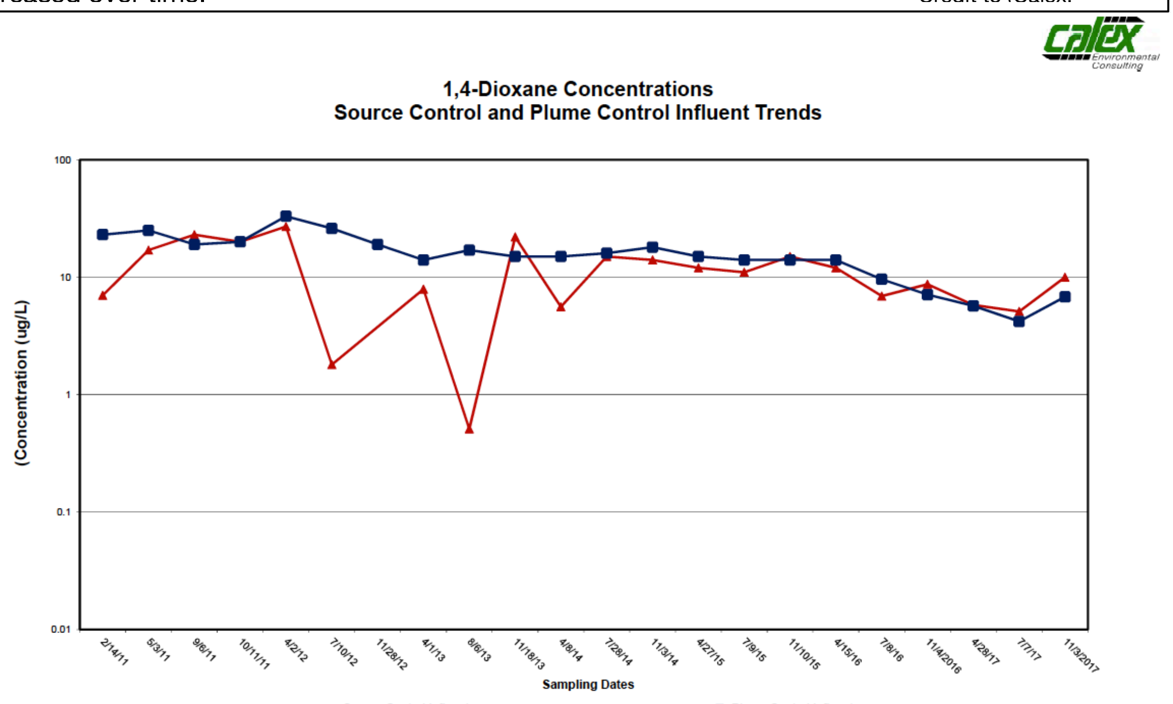
2013 - 2017 1,4-DX Trend Map

The 5-year 1,4-DX trend map presented below provides an visual depiction of the trend of 1,4-DX concentrations throughout the landfill over time. As discussed in the “1,4-DX Trends” section of this report, concentrations of 1,4-DX generally appear to be decreasing with the exception of two southwestern wells which have shown slight increases in the last year. Credit to (Calex,



2011 - 2017 1,4-DX Trend Lines

The Trend lines presented below demonstrate how, for the most part, 1,4-DX concentrations have decreased over time. Credit to (Calex.



Assessment of Alternative Technologies

The extract and transport remediation system currently in place at the landfill Site has proven that it is capable of reducing 1,4-DX concentrations in the groundwater at the Site. Nevertheless, after 10 years of operation, 9 of 26 active monitoring wells at the site still indicate 1,4-DX concentrations above the current AGQS of 3ppb[26]. Given that the current remediation system has to remove high-volumes of water from the subsurface to achieve modest reductions in groundwater 1,4-DX concentrations, it is likely that the system will require a fair amount of time to continue reducing the increasingly low concentrations of 1,4-DX to below NH AGQS. Furthermore, even though most wells at the site have either trended towards or achieved compliance with New Hampshire's AGQS for 1,4-D of 3 ppb, NHDES is currently considering reducing AGQS for 1,4-D to 0.32 ppb[27]. If such a change is realized, at least 12 of the landfill's monitoring wells would likely measure concentrations of 1,4-D above AGQS[28].

Using current annual landfill monitoring costs, it has been estimated that monitoring the landfill for another 10-years would cost roughly $255,000 and running the extraction system for another 10-years would cost approximately $375,000[29]. In response to the knowledge that AGQS standards may grow stricter and that the current remediation system will likely require a fair amount of time to continue treatment, a number of alternatives remediation technologies have been assessed to determine whether remediation operations at the landfill Site can be expedited in a cost-effective fashion. These treatment technologies fall into the categories of **In-Situ** – in the system – and **Ex-Situ** – outside the system – designs. The following section provides an overview of different remediation technologies, considerations of their applicability, and brief discussions of their associated costs.

---

[26] (Calex, *Comments,* 2018)
[27] (Calex, *Report,* 2018)
[28] (Calex, Report, 2018) (Remserv, 2010)
[29] (Calex, *Comments,* 2018)

In-Situ – In-situ remediation systems are designed to treat contaminated water within the subsurface. Such treatment options are attractive because they allow groundwater to be kept in the ground and, at least in theory, directly treat contamination within the system or even at the contaminant's source. As the name suggests, in-situ treatment technologies interact directly with the subsurface environment and the effects of their interactions with the sub-surface must be taken into account.

Oxidation – In principle, in-situ oxidation remediation systems work by introducing chemicals, such as hydrogen peroxide, to the groundwater system that will react with contaminants within the water, degrade them, and produce a non-toxic byproduct that can remain within the groundwater. Oxidation is an attractive option because, when introduced to the groundwater system, it can directly reduce subsurface contaminant concentrations. However, as a chemical-reaction based remediation option, in-situ oxidation requires a few important considerations. First and foremost, the subsurface environment must be favorable for oxidative reactions (e.g. temperatures cannot be too low and ph values must be monitored). Additionally, since oxidative chemicals have a fairly short life-span, they would need to be introduced throughout the system, potentially over multiple doses, to effectively reduce 1,4-DX concentrations. Finally, oxidative chemicals are not, by design, contaminant-specific and will interact with any molecules, such as iron or other trace metals, that they have an affinity for which they come across within the system. As a result, the soils and waters of the groundwater system can become a natural sink which soaks up the oxidative chemicals before they have a chance to interact with all of the contaminated water in the groundwater system and potentially produces new, undesired compounds within the system. Any in-situ oxidation systems would require favorable conditions and infrastructure capable of delivering oxidative chemicals throughout the entire system over multiple rounds of chemicals over the period of remediation. Additionally, in-situ oxidation systems use strong oxidative chemicals which would have be handled and stored on site, thus creating another potential threat-vector[30].

Biodegradation – In-Situ bio-degradation remediation systems reduce contaminant concentrations by introducing bacteria and other organisms that use a particular contaminant in their metabolic pathway to the groundwater system. Ideally, the seed organisms introduced to the system will consume the contaminant, produce a harmless byproduct, reproduce, and spread throughout the system as they search for more food. While this technique represents some promise as a self-sustaining biological remedial alternative that would not necessarily need site-wide delivery, any organisms introduced to the area would need to be able to thrive in the subsurface environment without being encouraged to spread beyond the management zone[31].

Containment – Containment refers to a fairly broad spectrum of in-situ remediation options. In-situ containment systems could be designed around either installing impermeable barriers which alter flow regimes and actively reshape the subsurface groundwater system, installing trenches that alter flow regimes, or installing more passive structures, such as chemical or biological filtration walls, within the subsurface that remove contaminant from the groundwater as it moves through the system. In either case, containment systems operate as longer-term remediation options. Either option also necessitates a significant amount engineering and disruption to the surface and subsurface environments since groundwater systems tend to run fairly deep and occupy layers of earth with different properties. Passive filtration systems in particular would need to have established access points maintained over time for filter replacement. Any in-situ containment option will have to take into

[30] (GeoInsight, 2005) (Remserv, 2010) (Mohr, 2010)
[31] (Mohr, 2010)

account not only engineering/materials and potential maintenance costs, but also policies regulating environmental impact[32].

Attenuation – As a remedial option monitored natural attenuation (MNA) relies upon time and natural processes to reduce contamination levels. To present as a viable candidate for MNA, a contaminant must meet the criteria of being unlikely to rapidly spread throughout the groundwater system in high concentrations. Additionally, the candidate contaminant must be able to be broken down by local organisms or natural degradation processes in a timely fashion. As remedial option, MNA is attractive because it provides a non-invasive remediation option that requires relatively little in the way of capital or operations and maintenance (O&M) costs. MNA's applicability is largely based upon the mobility and stability of the remedial contaminant in a given environment[33].

Ex-Situ – Ex-situ remediation systems are designed to treat water after it has been extracted from the groundwater system. Compared to in-situ treatment technologies, ex-situ treatment systems allow for a greater degree of control over the quality of water entering the treatment systems. Ex-situ treatment options also help minimize the risk of unintended reactions occurring in the subsurface as a byproduct of remediation attempts. The efficacy of ex-situ treatment systems is largely determined by the ability of the system to access contaminated waters or soils throughout the management site.

Pump and Dump – The current system operating at the Colebrook landfill Site is a pump and dump system. Pump and dump remediation systems use wells to arrest a groundwater contaminant plume growth and remove contaminated groundwater from the subsurface eventual off-site disposal. With these systems, contaminant concentration reduction is performed by removing contaminated

[32] (GeoInsight, 2005) (Remserv, 2010)
[33] (GeoInsight, 2005) (Remserv, 2010) (Mohr, 2010)

water from the groundwater system to reduce the total mass of contaminant left in the system. In most pump and dump systems, groundwater will continue recharging the system and can potentially help reduce contaminant concentrations by increasing the total volume of water within the system. Pump and dump systems operate more or less continuously to ensure that contaminated water does not spread beyond the GMZ. The rate at which a pump and treat system reduces contaminant concentrations is dictated by the system's ability to access zones of high contaminant concentration and its ability of the pumps to extract water from a wide range of distinct layers. Since pump and treat systems need to operate continuously, operations and maintenance can be an important consideration over the long term.

Adsorption (Filtration) – Adsorption refers to a method of remediation in which water extracted from the subsurface is run through a granular activated carbon (GAC)- or resin-based filter that lets water pass through but is designed to capture contaminants. The efficacy of an adsorption system is largely determined by the filter's ability to bond to and sequester various contaminants. GAC filters have traditionally been used in adsorption-driven remediation systems, however GAC filters have proven somewhat ineffective at treating 1,4-DX. Recent technological advances have, however, led to the development of a resin-based filtration system that has been shown to effectively sequester 1,4-DX[34]. By design, adsorption-base systems produce concentrated amounts of captured contaminant as they operate. As a result, concentrated contaminant management and periodic disposal are important considerations with any adsorption system[35].

Advanced Oxidation Processes (AOP) – As a form of remediation, ex-situ AOP uses the same basic principles as in-situ oxidation. Strong oxidative chemicals

[34] (USEPA, 2006) (Mohr, 2010) (ECT2, 2011)
[35] (Mohr, 2010)

are introduced to extracted groundwater to degrade contaminants within the water. In contrast to in-situ oxidation, however, AOP benefits from the fact that it is much easier to control the conditions under which oxidation reactions occur. Above the subsurface, favorable environmental conditions can be ensured and water can be pre-treated or filtered to ensure that oxidative chemicals introduced to the water are not used up before they can react with contaminants within the water. Furthermore, rather than relying on delivering oxidative chemicals to the subsurface, surface AOP systems can produce oxidative chemicals within a reaction chamber that contaminated water passes through, thus abolishing any need to store strong oxidative chemicals on site[36]. AOP process have a well-documented history of successfully reducing 1,4-DX concentrations in extracted groundwater and they can often be readily integrated into existing extraction-based systems[37].

Biodegradation – Ex-situ biodegradation remediation systems, such as batch reactors, are designed to use bacteria or other microorganisms to break down contaminants in extracted groundwater that is being held in some form of storage systems. Ex-situ biodegradation systems provide an attractive option because they do not require the on-site storage and handling of strong chemicals for contaminant treatment. In contrast to AOP or adsorption based systems, biodegradation systems generally require that extracted groundwater be stored for a relatively long period of time (1+ days) before 1,4-DX concentrations have been reduced to levels where they can be discharged[38]. The efficacy of biodegradation systems are largely determined by the ability of the microorganisms utilized in the system to utilize a particular contaminant in their metabolic pathway at a range of concentrations in the environment[39].

---

[36] (KPWT, 2018)
[37] (Mohr, 2010) (USEPA, 2006) (USEPA, 2017) (KPWT, 2018)
[38] (Mohr, 2010)
[39] (USEPA, 2017)

Alternatives Assessment

<u>Screening</u> – The aforementioned in-situ and ex-situ remediation technologies have been evaluated based upon their history of successful applications, their viability at the landfill Site, their ability to meet TOC's remediation goals, their cost, their anticipated environmental impacts, and their integrational compatibility with the remedial system currently operating at the landfill Site.

<u>In-situ</u> – Based on the screening criteria, all in-situ treatment technologies were ruled out as viable or cost-effective options for the Colebrook landfill Site. This judgement is consistent with the 2005 and 2010 remedial action plans produced by GeoInsight and REMSERV as the factors influencing their screening decisions largely have not changed in the past 8 years[40]. **Oxidation** was ruled out because installing the necessary infrastructure would be costly and there is insufficient evidence to prove that in-situ oxidation has developed enough to be a viable treatment technology[41]. **Biodegradation** was ruled out as a viable option because in-situ bioremediation systems have not advanced beyond pilot stages[42]. Additionally, many of the bacteria that have been shown to degrade 1,4-DX either need other contaminants to encourage 1,4-DX breakdown or else they are inhibited by the presence of chlorinated solvents that are often associated with 1,4-DX[43]. **Containment** was ruled out because past reports found that structures such as barrier walls or interceptor trenches would be too expensive and environmentally destructive to be cost-effective[44]. Finally,

---

[40] (GeoInsight, 2005) (Remserv, 2010)
[41] (SERDP, 2014) (USEPA, 2017)
[42] (SERDP, 2015) (EPA, 2018)
[43] (Mohr, 2010) (USEPA, 2017)
[44] (GeoInsight, 2005) (Remserv, 2010)

attenuation was ruled out due to 1,4-DX's stability, ability to rapidly migrate throughout a system if left unchecked, and because the Colebrook environment likely lacks a robust population of local microorganisms that will rapidly reduce 1,4-DX concentrations[45].

<u>Ex-situ</u> – Based on the screening criteria, **ex-situ biodegradation** was screened out as a viable alternative remediation option due to the high capital cost of most bioreactor systems and the relatively slow treatment time of such a system when compared to alternative ex-situ options[46]. Given that Colebrook's current extraction-based remediation system needs to run more or less continuously to effectively halt plume growth and reduce 1,4-DX concentrations throughout the site, any system that requires extracted water to be stored and treated for more than a few hours reduces the efficacy of the overall remediation system and potentially causes further spread of the contaminant plume.

<u>Recommendations</u> – Research of emergent 1,4-DX treatment technologies indicates that in-situ technologies are largely in their infancy and currently show little promise as viable remediation alternatives. As a result, ex-situ treatment technologies currently show the most promise as 1,4-DX treatment options. These findings suggest that consideration should be given to ex-situ technologies that can either cost-effectively replace the current remediation system operating at the landfill Site or can be integrated with the current remediation system to expedite treatment and ensure future compliance with NHDES regulatory standards. All ex-situ remediation systems incorporate extraction in their design. Given that Colebrook already has an operational extraction system that contains plume-growth and appears to be gradually reducing 1,4-DX concentrations in the Site's groundwater, there seems to be no need fully replace the current extraction system with a new extraction system. Furthermore, significantly modifying the current extraction system would be environmentally invasive

---

[45] (GeoInsight, 2005) (Remserv, 2010) (Mohr, 2010)
[46] (GeoInsight, 2005) (Mohr, 2010) (USEPA, 2017)

and would likely not prove cost effective in the long run; particularly if the remediation system remains solely a pump and treat system[47]. Bearing these considerations in mind, the most viable alternative treatment technologies for the landfill Site appear to be **on-site treatment technologies** that can be integrated into the operating extraction system. Of the on-site treatment abilities, AOP-based systems appear to be the most cost-effective with regards to the fact that scaled up versions of the systems are cheaper and do not produce a byproduct that requires additional treatment/disposal.

It is important to note that integrated on-site treatment technologies will not cause the reduction of 1,4-DX groundwater concentrations beyond rate of reduction that results from simple groundwater extraction. On-site treatment technologies do, however, have several promising features. On-site treatment technologies can reduce 1,4-DX concentrations to levels lower than NH's current AGQS of 3ppb and even the proposed standard of 0.32 ppb. Reducing 1,4-DX concentrations to levels that low would help ensure the town would not need to worry about creating a new contaminated site by disposing of the water. Furthermore, treating the water on-site opens up the possibility of re-infiltrating treated water on-site and thus reduces, or even totally abolishes, the present need to transport 1,4-DX contaminated water to the town's WWTF. Reducing or removing the need to transport groundwater to the town's WWTF could reduce current water transportation + treatment costs associated with the landfill Site. Additionally, since the landfill Site has limited on-site storage capacity, an on-site treatment + re-infiltration system could allow extraction occur more continuously throughout the day, thus increasing the rate of 1,4-DX concentration reduction in the subsurface.

Vendors

The most promising on-site treatment technologies appear to be **Advanced Oxidation Process (AOP)** based technologies and **adsorption-based** technologies. As a result

[47] (GeoInsight, 2005)

of market research, the following vendors were identified as having case-study proven success with their treatment technologies and were contacted for systems price quotes.

Keystone Pure Water Tech, Inc. (KPWT)

KPWT provides an AOP remediation system that is chemical free, low profile, and has a low energy-demand. The AOP system destroys 1,4-DX on site and has been shown to treat 1,4-DX in landfill leachate to below 0.32 ppb. The AOP system could be integrated with the current extraction system and housed within the current control center in-place at the landfill Site. Daniel Summa (KPWT'S CEO/Founder) made a verbal quote of between **$250K-300K in capital costs** for a system that treat 20 GPM of 1,4-DX contaminated water and is willing to provide a more precise quote with projected O&M costs for the landfill Site upon request. Daniel's contact info is listed below and a copy of a small-scale system AOP system that his company produced can be found at the back of this report.

Contact: Daniel F. Summa (CEO/Founder)
Cell: 917.885.0057
Work: 570.397.6120
Email: dan@keystonepurewater.com
Website: www.keystonepurewater.com

Emerging Compounds Treatment Technologies (ECT2)

ECT2 provides a synthetic media[48]-based adsorption treatment system that has been proven to reduce concentrations of 1,4-DX in extracted groundwater below 0.32 ppb[49]. ECT2's claims its system is easy to operate, relatively automatic, free of hazardous chemicals, able to work throughout the entire pH range, and that its filters have long life-spans because they can be regenerated with steam. ECT2s system

---

[48] AMBERSORB
[49] (ECT2, 2015)

could be integrated into the current extraction system at the landfill site. As an adsorption-based treatment system, ECT2's system would generate concentrated 1,4-DX that would require disposal. ECT2's system is capable of vaporizing the concentrate and venting it on site, though an analysis of NH's air waste-disposal regulations would need to be performed to ensure system compliance. Capital costs for a system capable of treating 10 GPM have been quoted at **$279K with an additional $29K for on-site systems training**. Annual **O&M costs are estimated to run between $8.7K and $9K**. ECT2's contact info has been provided below and a copy of their proposal is available upon request from myself or Ronald Guerin of Calex Environmental Consulting.

Contact: John C. Barry P.E. (Process Design Leader)
Cell: 603.566.0751
Direct: 603.391.3305
Email: jbarry@ect2.com
Website: http://www.ect2.com/

Further Considerations

1,4-DX remedial efforts have generally focused on removing 1,4-DX from drinking water resources[50]. Colebrook is fortunate in that currently drinking water resources are not directly threatened by landfill leachate contaminants. Still, a survey of current remediation technologies reveals a dearth of remediation systems designed to cost-effectively lower 1,4-DX concentrations in situ. Given that Colebrook's current remediation priorities are system wide reduction of 1,4-DX and not simply reductions of 1,4-DX in extracted groundwater, Colebrook faces the challenge of determining whether it is cost-effective to treat water on-site or continue with the pump and treat system for the time being. Since the remediation system currently operating at the landfill Site seems to have arrested the groundwater plume and led to a generally decreasing trend in 1,4-DX concentrations throughout the site, the current impetus to

[50] (USEPA, 2006)

find an alternative remediation results from long-term rather than immediate concerns. The town is searching for a more cost-effective way of managing landfill contamination over time and there is some concern that future regulatory trends may reduce the viability of current remediation operations.

For Colebrook's remediation goals, in-situ treatment options do seem to represent a desirable method of contaminant source treatment. Though many of the technologies reviewed for this report have not made substantial advances as viable remedial options since REMSERV produced a revised RAP for the town, in-situ oxidation and bioremediation systems have received far more attention and pilot funding in the past few years[51]. While bioremediation will likely require more research, there is a report anticipated to come out in 2018 in that investigates the cost-effectiveness of in-situ oxidation as a 1,4-DX remediation option[52]. Given that the town is not under immediate pressure to find an alternative solution, it could be worthwhile to hold off on making remediation system modifications until in-situ technologies have had a chance to develop further or impending regulatory standards changes force action.

Conclusions

1,4-DX is a stable, highly mobile chemical contaminant present at the Colebrook landfill Site that has experienced increased scrutiny and regulation by state and federal organizations. The Colebrook landfill site currently has a remediation system that effectively constrains 1,4-DX contaminant plume growth and appears to be gradually reducing 1,4-DX concentrations throughout the site[53]. At the moment, it is difficult to give a precise estimate of the total amount of time it will take for the extraction system to bring subsurface 1,4-DX concentrations throughout the entire system into compliance with the current NH AGQ of 3ppb. After a decade of remediation efforts, 9 of 26 active monitoring wells still record 1,4-DX concentrations above AGQS at a range

[51] (Mohr, 2010) (SERDP, 2014) (EPA, 2018)
[52] (SERDP, 2014)
[53] (Calex, Report, 2018)

of 4.1-17 ppb[54]. Given that concentrations of 1,4-DX were as high as nearly 40 ppb when 1,4-DX was originally discovered at the landfill site in 2008, it seems possible that the current remediation system could be expected to remain in operation for anywhere between several more years to decade. Based on the current annual landfill monitoring costs, it has been estimated that monitoring the landfill for another 10-years would cost roughly $255,000 and running the extraction system for another 10-years would cost approximately $375,000[55]. Should NH's AGQS for 1,4-DX drop to 0.32 as NHDES has proposed, operation of the remediation system at the landfill site will doubtless require significantly more time than the current AGQS might require.

Colebrook has sponsored the investigation of alternative 1,4-DX remediation methods in hopes of finding a way to simultaneously reduce the amount of time remediation operations will have to occur at the site and ensure that the town is able to comply with future regulatory trends. In-situ and ex-situ remediation systems were evaluated. Ultimately, in-situ remediation systems were screened out because they were either not cost-effective or have not developed sufficiently to serve as viable remediation options. Screening of ex-situ remediation options presented two viable on-site treatment options, AOP and adsorption, that could be integrated with the town's current groundwater extraction system. Vendors for each system were identified and contacted. Quotes for an AOP system capable of treating 20 GPM and an adsorption system capable of treating 10 GPM were obtained and vendor contact information was recorded for potential follow up. AOP was recommended as the most cost-effective treatment option upon initial inspection.

While on-site treatment systems would not treat contaminated water at its source, they could open the possibility of running the current extraction system more continuously to increase the reduction in 1,4-DX concentrations by increasing the daily volume of water extracted from the site. When considering new technology, the town must balance whether capital and O&M costs associated with modifying the current remediation system with on-site treatment and disposal/re-infiltration technology will

---

[54] (Calex, *Comments,* 2018)
[55] (Calex, *Comments,* 2018)

prove more cost-effective than continuing to transport extracted water to the WWTF – so long as the WWTF remains a viable disposal location. Given that the most viable remediation options currently appear to be ex-situ options that will augment rather than replace the current remediation system, the town may be able to wait to modify its system until further developments in in-situ technologies or potential groundwater and surface water regulatory changes reduce the viability of the current remediation system.

Acknowledgments

I would like to thank the American Geophysical Union (AGU)'s Thriving Earth Exchange for creating the Community Science Fellowship that provided me with an opportunity to travel to Colebrook and work with members of its community. Furthermore, I would like to thank both the Town of Colebrook and the Tillotson Foundation for providing funding for my fellowship. I would like to thank Ronald Guerin of Calex Environmental Consulting and David Ellerbroek of Brown and Caldwell and Thriving Earth Exchange scientist for offering their knowledge and support as professional mentors, Brian Sullivan and David Brooks for showing me Colebrook's WWTF and current remediation system, the community members of Colebrook for welcoming me into their town, the wonderful men and women working in the Colebrook Town office for helping me hit the ground running, and Colebrook's Town Manager Becky Merrow for inviting me to Colebrook and serving as liaison between the town and Thriving Earth Exchange. Finally, I would like to acknowledge that many of the graphs, trend-lines, and maps I used in this report were produced for the Town of Colebrook by Calex Environmental Consulting, REMSERV, and GeoInsight.

References

Calex Environmental Consultants, LLC (Calex). (January 29, 2018). *2017 Annual Groundwater Monitoring Summary Report – Closed Colebrook Municipal Landfill.* Colebrook, NH. Calex Environmental Consultants, LLC.

Calex. (February 1, 2018). *Submission of Public Comments: Ammendments to Ambient Groundwater Quality Standards (AGQS) Rule Number Env-Or 603.03(c), Table 600-1.* Colebrook, NH. Calex Environmental Consultants, LLC.

Emerging Compounds Treatment Technologies (ECT2). (2011). *Mobile treatment of 1,4-dioxane at fractured bedrock site.* Retrieved from http://www.ect2.com/case-studies/water/id/16/mobile-treatment-of-14-dioxane-at-fractured-bedrock-site

ECT2. (2015). *Proposal for Conceptual Synthetic Media System.* ECT2.

GeoInsight, Inc. (June 25, 2005). *Remedial Action Plan GeoInsight, Inc, June 25, 2005.*

Keystone Pure Water Tech, Inc. (2018). *Treatment of Groundwater Contaminated with 1,4-Dioxane.* Mayfield, PA. Keystone Pure Water Tech, Inc.

Remediation & Environmental Management Services, Inc (Remserv). (June 4, 2013). *Revised Remedial Action Plan Addendum – Colebrook Municipal Landfill.* Winchester, MA: Remediation and Environmental Management Services, Inc.

Strategic Environmental Research and Development Program (SERDP). (2014). *Facilitated Transport Enabled In-situ Chemical Oxidation of 1,4-Dioxane-Contaminated Groundwater.* Retrieved from https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-2302

Town of Colebrook. (2018). *Conversations with David Brooks and others.* Colebrook, NH. Town Offices of Colebrook.

Thomas K.G. Mohr, Julie Stickney, Bill DiGiuseppi. (2010). *Environmental Investigation and Remediation – 1,4-Dioxane and other Solvent Stabilizers.* CRC Press Taylor and Francis Group, LLC.

United States Environmental Protection Agency (USEPA). (2006). *Treatment Technologies for 1,4-dioxane: Fundamentals and Field Applications.* Office of Solid waste and Emergency Response. Retrieved from http://clu-in.org/542R06009

USEPA. (2017). *Technical Fact Sheet – 1,4-Dioxane.* Office of Land and Emergency Management. Retrieved from https://www.USEPA.gov/sites/production/files/201403/documents/ffrro_factsheet_contaminant_14-dioxane_january2014_final.pdf