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TECHNICAL MEMORANDUM

DATE March 10, 2022   **Project No.** 923-1000-007

TO Jerome Cruz
Washington State Department of Ecology

CC Landsburg Mine Site PLP Group

FROM Andrew Madison, PhD   **EMAIL amadison@golder.com**

EVALUATION OF THE FEASIBILITY AND IMPLEMENTABILITY OF ENHANCED *IN SITU* BIOREMEDIATION OF 1,4-DIOXANE AT THE LANDSBURG MINE SITE

1.0   INTRODUCTION

The Amendment to the Cleanup Action Plan (CAP) (Ecology 2021) states that an evaluation of 1,4-dioxane *in situ* bioremediation shall be submitted to Ecology to assess if this approach could safely and effectively remediate the 1,4-dioxane detected in groundwater at the Landsburg Mine Site (Site), without degrading groundwater quality. In this technical memorandum, I evaluate the feasibility, effectiveness, and potential environmental impacts associated with implementing *in situ* bioremediation of 1,4-dioxane at the Site. I am a bioremediation specialist with over 10 years of experience and direct experience with *in situ* bioremediation of 1,4-dioxane. My resume is attached to this technical memorandum.

2.0   1,4-DIOXANE *IN SITU* BIOREMEDIATION

This section presents a summary of 1,4-dioxane and the general application of *in situ* bioremediation as a remediation technology. Much of the information provided in this section is derived from the Interstate Technology and Regulatory Council (ITRC) Technical Resources for Addressing Environmental Releases of 1,4-Dioxane (ITRC 2021). The ITRC guidance documents were prepared by leading scientists, representatives from state and federal regulatory agencies, and industry representatives who routinely deal with addressing releases of 1,4-dioxane into the environment. I participated in the development of the 1,4-dioxane ITRC guidance documents.

2.1   Characteristics of 1,4-Dioxane

1,4-Dioxane was used as a stabilizer in chlorinated solvents (particularly 1,1,1-trichloroethane [TCA]) starting in the 1970s until its use as a stabilizer was phased out in 1995 (Mohr et al. 2020). 1,4-Dioxane is also present as a by-product (meaning it is not added during production of a product, but instead results from various reactions during the production of the product or as a trace contaminant in chemicals used during product production) of various surfactants, resins, aircraft de-icing fluids, polyethylene terephthalate (PET) plastics, chemical food additives, and other compounds that are used in common commercial and household products (EPA 2017). Some common household products like laundry detergents, shampoos, and dish soaps have measured

concentrations of 1,4-dioxane exceeding 10,000 micrograms per kilogram (μg/kg; Mohr 2017). The wide-spread use of 1,4-dioxane as a stabilizer in TCA and in various consumer and commercial products combined with the release of these products to the environment has resulted in 1,4-dioxane being found in groundwater at sites throughout the United States (EPA 2017).

1,4-Dioxane is a synthetic chemical that is completely miscible in water (i.e., it is soluble in water). Unlike many organic compounds, 1,4-dioxane does not readily adsorb to natural organic carbon that is present in most soils. The high solubility and weak retardation of the compound in soil results in migration of 1,4-dioxane from soil to groundwater. As compared to biodegradation of chlorinated solvents, 1,4-dioxane biodegrades more slowly especially under anoxic (i.e., anaerobic) conditions. This slower rate of degradation and high mobility in groundwater often result in 1,4-dioxane migrating greater distances from the source area than most other organic compounds. A comprehensive list of 1,4-dioxane physicochemical properties is provided in Appendix B of the ITRC guidance documents (ITRC 2021).

2.2 Biodegradation

Biodegradation is the microbially-mediated transformation of a substance into separate components via biochemical reactions. Microorganisms use a variety of organic contaminants as carbon and energy sources by performing oxidation-reduction reactions that transfer electrons from one constituent to another (Madigan et al. 2015). Biodegradation via oxidation is the primary known destructive process for 1,4-dioxane in the subsurface. This process occurs most readily aerobically (i.e., with oxygen).

2.2.1 Aerobic Metabolic Biodegradation

Aerobic microorganisms can biodegrade 1,4-dioxane through two physiologically distinct processes. The first of these processes is direct metabolic biodegradation. Microorganisms have been identified that metabolize 1,4-dioxane as a carbon growth substrate resulting in metabolic energy gain (Mahendra and Cohen 2006, Gedalanga et al. 2014).

In general, if oxygen is present, metabolic 1,4-dioxane biodegradation rates are expected to depend on 1,4-dioxane concentrations (first-order kinetics). However, robust metabolic biodegradation is likely only to be supported at 1,4-dioxane concentrations sufficient to meet energy demands under favorable environmental conditions. The 1,4-dioxane substrate concentrations needed to support microbial activity and growth are likely in the range of hundreds of micrograms to milligrams per liter (Barajas-Rodriguez et al. 2019). The ITRC document (ITRC 2021) indicates concentrations of at least 250 μg/L are required to provide the energy needed to maintain the activity and viability of 1,4-dioxane-metabolizing microorganisms. If concentrations of 1,4-dioxane in groundwater are less than the amounts necessary for microbial growth, metabolic biodegradation may not occur at meaningful rates.

2.2.2 Aerobic Cometabolic Biodegradation

In addition to metabolic biodegradation processes, certain microorganisms may also degrade constituents, including 1,4-dioxane fortuitously through a process called cometabolism as a side effect of degradation of a different growth substrate. During cometabolism, microorganisms produce enzymes to metabolize a different primary growth substrate that can also degrade 1,4-dioxane without resulting in energy gain for the organism. Microorganisms do not have the capability to harvest carbon or energy from degradation of 1,4-dioxane because they do not make the additional enzymes needed to perform subsequent reactions in the degradation pathway or do not have a pathway to assimilate intermediate breakdown products.

Because cometabolic degradation does not provide a source of carbon or energy to the microorganisms that mediate the reaction, the reaction is controlled by the availability of the primary growth substrate(s). In the cometabolic case, 1,4-dioxane degradation rates depend on the availability of the primary substrate, oxygen, and nutrients. Since cometabolic micoorganisms are not using the 1,4-dioxane for metabolic energy, cometabolic degradation of 1,4-dioxane can occur at relatively high and low 1,4-dioxane concentrations (several mg/L to <100 µg/L).

Cometabolic treatment in groundwater typically entails the addition of a primary growth substrate (e.g., an alkane gas such as propane, ethane, or methane) to maintain sufficient availability to promote growth and activity of cometabolic microorganisms. Inorganic nutrients such as nitrogen and phosphate compounds (e.g., diammonium phosphate [DAP]) may also be added. Additionally, bioaugmentation with a culture of cometabolic microoogranisms such as propanotrophs may also be performed to expedite growth of the microbial population needed to cometaboligically degrade 1,4-dioxane. If the receiving groundwater is oxygen deficient, air or oxygen must be sparged into the groundwater to achieve the aerobic conditions required for 1,4-dioxane biodegradation to occur.

3.0   1,4-DIOXANE AT THE LANDSBURG MINE SITE

1,4-Dioxane is detected in three groundwater monitoring wells located at the north end of the Site: LMW-2, LMW-4, and LMW-12. 1,4-Dioxane is not detected in any other Site groundwater monitoring wells, including three groundwater monitoring wells installed north of the Site. Figure 1 shows the location of Site groundwater monitoring wells and monitoring well construction details are provided in Table 1. Figure 2 provides a cross-section showing the monitoring well locations, screen intervals, and groundwater flow direction.

1,4-Dioxane was first detected in groundwater monitoring wells LMW-2, LMW-4, and LMW-12 in November 2017, which was the first sampling round that included analysis for 1,4-dioxane at the Site. These wells and the other wells located on the north end of the Site (LMW-10 and LMW-13R) have been monitored quarterly since the initial detection of 1,4-dioxane. Table 2 provides a summary of 1,4-dioxane analytical results for the wells located on the north end of the Site. Figure 3 provides trend graphs of the 1,4-dioxane concentrations reporting in wells LMW-2, LMW-4, and LMW-12. Concentrations reported in LMW-2 and LMW-4 have remained relatively constant, ranging from 1.5 to 2.5 µg/L, with no apparent trend. Concentrations reported in LMW-12 have been lower since approximately August 2018, and 1,4-dioxane was not detected in LMW-12 above the method detection limit of 0.04 µg/L in the December 2019, November 2020, and June 2021 sampling rounds. Except for the 1,4-dioxane detections, and occasional trace detections of chloroethane and 1,1-dichloroethane reported in samples from LMW-12, there are no other organic compounds detected in LMW-2, LMW-4, and LMW-12. Naturally occurring metals typical of groundwater in contact with coal seam and coal mine water are detected in these wells. Table 3 presents a summary of the metals analytical results and detected organic compounds reporting during the most recent groundwater monitoring completed in December 2021. Field measured groundwater chemical parameters (temperature, pH, conductivity, dissolved oxygen [DO], oxidation reduction potential [ORP], and turbidity), recorded during the December 2021 sampling round are also listed in Table 3.

4.0   EVALUATION OF IMPLEMENTING *IN SITU* BIOREMEDIATION OF 1,4-DIOXANE AT THE LANDSBURG SITE

This section evaluates *in situ* bioremediation of 1,4-dioxane in consideration of the specific characteristics of the Landsburg Site. The evaluation is performed to meet the requirements of the Amendment to the CAP and

determine if *in situ* bioremediation could safely and effectively remediate the 1,4-dioxane exceedances at the Site, without degrading groundwater quality. This section only discusses aerobic cometabolic biodegradation, because direct metabolic biodegradation has not been found effective at 1,4-dioxane concentrations less than 250 µg/L (see discussion in Section 2.2.1), and the concentrations at the Site are typically less than 2 µg/L. The design considerations discussed in this section are hypothetical and based on existing Site data and the known design requirements needed to successfully implement *in situ* bioremediation of 1,4-dioxane.

4.1   Conceptual Treatment Area and Hydrogeologic Parameters

Groundwater data from the Site indicate that the 1,4-dioxane could be present at low concentrations along the coal seam from LMW-12 downgradient to LMW-2 and LMW-4; a distance of approximately 250 feet. The coal seam is approximately 12 to 15 feet wide. The vertical separation between LMW-2 (screened 28 to 38 feet bgs) and the deeper well LMW-4 (screened 195 to 210 feet bgs) is approximately 200 feet. As such, a rough estimate of the groundwater area for treatment is approximately 750,000 cubic feet (250 x 200 x 15 feet).

The geology in the treatment area consists of intact coal bedrock and collapsed mine workings. The hydraulic conductivity is estimated from hydraulic testing conducted during the remedial investigation at between 7 and 14 feet per day (0.0025 to 0.0049 centimetres/second). The groundwater is anerobic and reducing with DO less than 1 mg/L and ORP below -50 millivolts (mV). Data is not available on the total organic carbon (TOC), chemical oxygen demand (COD), or biochemical oxygen demand (BOD) of the groundwater, but the high carbon content and reduced geochemical nature of the coal seam likely indicates potential for elevated TOC, COD and BOD.

4.2   System Requirements for Hypothetical *In Situ* Bioremediation Implementation

The initial requirement necessary to create conditions favorable for cometabolic biodegradation is to convert the groundwater from the current anerobic, reduced state to aerobic conditions. This would require sparging the groundwater with direct air, concentrated oxygen, or by injecting an oxidizer such as hydrogen peroxide. Considering the large treatment area (approximately 250 feet in length and 200 feet depth), and the likely high natural oxygen demand of the aquifer matrix, numerous injection points at various depths would be required to provide proper distribution of oxygen sufficient to promote aerobic conditions. Field pilot testing to determine the radius of influence would be required to estimate the number of sparge points, but for the purpose of this evaluation, sparge points would likely need spacing of no greater than 40 feet separation both vertically and horizontally. This equates to seven locations spaced along LMW-12 to LMW-2/LMW-4, inclusive of sparging at LMW-12 and LMW-2/LMW-4. At each location, sparging would be needed at three to five different depth intervals to cover the vertical zone of 1,4-dioxane presence. As such, 21 to 35 sparge points would be required under this hypothetical scenario, but significantly more sparge points could be required if the radius of influence was smaller than assumed or if the rate of oxygen consumption of the aquifer matrix were great. Continuous sparging may be required to create and sustain aerobic conditions. Cycling of the sparging (pause for several hours to days) can occur if the rate at which the aquifer reverts to natural anaerobic conditions is slow.

In addition to the sparging to create and sustain aerobic conditions, sparging to introduce the primary growth substrate (e.g., an alkane gas such as propane, ethane, or methane), inorganic nutrients, and bioaugmentation with propanotrophic bacteria will be needed. Bench-testing and field pilot-scale testing would be required to determine the correct dosing to optimize conditions required for cometabolic biodegradation. Special care is required when sparging the alkane gases, especially combined with oxygen injection, to ensure that

concentrations do not exceed the lower explosive limit (LEL) of the gas. For safety, sparge concentrations of 25% of the LEL are typically utilized and defines the upper limit to mass of alkane gas and oxygen that can be introduced to the treatment area. Additionally, establishing groundwater concentrations of the primary substrate that are within the acceptable concentration range is critical. Insufficient delivery of the primary substrate will not sustain cometabolic microorganism growth and activity required to produce the monooxygenase enzymes needed for the fortuitous biodegradation. Conversely, too much primary substrate and the produced monooxygenase enzymes will not have a chance to degrade the 1,4-dioxane (i.e., the enzymes will be expended on excess primary growth substrate). As such, there is a limited zone around each injection point where the concentrations will be correct for the cometabolic biodegradation to occur. The radius of this "bioactive zone" can be significantly smaller than the oxygen injection radius of influence, thus requiring significantly more sparge points for the injection of the primary substrate.

It is important to note that implementing aerobic cometabolic biodegradation at any site is not a one-time event and that oxygen and alkane gas sparging frequency to create and sustain the proper conditions to stimulate biodegradation and achieve contaminant reductions that meet regulatory requirements will be continuous or near-continuous (e.g., sparging period every couple hours or days). As such, a permanent and automated sparge system, including alkane gas storage capacity, will need to be constructed and operated with substantial potential energy requirements. Following shut down of active sparging, contaminant concentrations can often rebound from matrix diffusion or continued migration of contaminants into a treatment area if the source is upgradient of the treatment area. Additional rounds of re-initiation of sparging are typically required to achieve permanent reductions in 1,4-dioxane below regulatory limits or remedial action goals.

4.3   Potential Degradation of Groundwater Caused by *In Situ* Bioremediation Implementation

Another component of the evaluation required by the Amendment to the CAP is to consider if implementing aerobic cometabolic biodegradation at the Site could potentially result in degradation of the current groundwater quality. The two primary areas of groundwater degradation of concern relate to the mass injections of the alkane gases such as propane, ethane, or isobutane and the potential geochemical changes that may result from oxygenation of the naturally anaerobic groundwater.

Sparging of significant quantities of alkane gases (likely propane or isobutane) and nutrients will likely be required to achieve desired concentrations of the primary growth substrate across the lateral and vertical extent of the treatment area. As these are flammable gases, special care will be required to limit the concentrations introduced into the groundwater to prevent build-up of potentially explosive gas levels. There is potential that not all the injectants (gases and nutrients) will be consumed in the bioremediation process. Groundwater monitoring would be needed to ensure that groundwater containing elevated concentrations of nutrients and dissolved alkane gases does not migrate offsite towards the Cedar River. Excess phosphates discharging to surface water can cause undesirable algae growth (i.e., eutrophication) and associated decreased levels of DO.

Oxygenation of the groundwater in wells LMW-2, LMW-4, and LMW-12 will result in conditions that are more oxidizing than is presently the case. Although the exact redox endpoint of the treatment is currently unknown, the following is likely to happen:

■   Dissolved sulfur species will transition from more reduced (i.e., sulfide) to more oxidized (i.e., sulfate) species.

- Sulfide minerals commonly present in coal (e.g., pyrite – FeS_2) may become unstable and oxidize, resulting in the release of sulfur, iron, acidity, and trace metals potentially present as impurities (e.g., arsenic, selenium).

- Dissolved iron species will transition from more reduced (i.e., ferrous) to more oxidized (i.e., ferric) species. Unless conditions are highly acidic (i.e., pH < 3.5) which is unfavorable for bioremediation, the ferric iron typically precipitates as a hydroxide (e.g., ferrihydrite – $Fe(OH)_3$) thereby releasing acidity. The formation of this secondary mineral may result in floc generation, clogging of aquifer pore space and impairment of monitoring wells.

- Other redox-sensitive species (e.g., manganese) will undergo similar transitions, also potentially resulting in the formation of their hydroxides, release of acidity, and clogging.

- Other reduced solids present (e.g., containing organic matter, such as coal), may become unstable and oxidize, resulting in the release of acidity.

5.0   CONCLUSIONS OF THE EVALUATION

Considering the nature and extent of the low levels (<2 ug/L) of 1,4-dioxane at the Site, the actions required to implement *in situ* biodegradation, and the potential degradation of groundwater that could result, *in situ* biodegradation is not recommended at the Site. The following expands on each of these considerations:

- 1,4-Dioxane is detected in LMW-2 and LMW-4 at concentrations that are typically around 2 µg/L, and the concentration trends in these wells are steady. The 1,4-dioxane concentrations reported in LMW-12 has been below 1 µg/L since 2020, has decreased since the initial detection, and was not detected during three of the last nine quarterly sampling events. 1,4-Dioxane is not detected in groundwater monitoring wells located north of the Site. There is no known remediation site where *in situ* bioremediation was attempted when the concentration of 1,4-dioxane was at the low levels present at the Landsburg Site. Because of the significant application effort, costs, potential for degradation to the groundwater from the injectants, and uncertainty of success associated with *in situ* bioremediation of 1,4-dioxane, this remedial action is typically only attempted on sites with 1,4-dioxane concentrations in the 100s to 1000s of µg/L.

- The target remediation area at the Site is relatively large and would require an extensive network of injection points at various locations at and between LMW-12 and LMW-2/LMW-4, with multiple injection depth intervals at each location. Although the 1,4-dioxane concentrations at the Site are extremely low, the effort to create groundwater conditions throughout the target area suitable for attempting aerobic cometabolic bioremediation are the same as required at sites where concentrations are high. For example, the groundwater at the Site is naturally anaerobic due to the high natural oxygen demand from the coal bedrock. Significant oxygenation will be needed to change the groundwater to aerobic. Additionally, introduction of substantial masses of alkane gases, nutrients like nitrogen and phosphorous, and potentially propanotrophic bacteria (or other alkane oxidizing bacteria) to the Site groundwater will be required to potentially induce biodegradation of the 1,4-dioxane.

- Except for the 1,4-dioxane detected in the three wells, the groundwater in the north end of the Site is of relatively high quality. This groundwater would be significantly degraded by the sparging of the alkane gases and nutrients and changing of the groundwater geochemistry to more oxidizing may result in acidification of

the water and release of trace metals. The release of secondary minerals as floc can also result in significant clogging of groundwater monitoring and injection well screens.

Overall, given the site conditions and challenges, the implementability and efficacy of an *in situ* cometabolic 1,4-dioxane remedial approach is highly uncertain, while posing a significant risk of degradation to downgradient water quality.

Golder Associates USA Inc.

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Attachments: Table 1 Landsburg Mine Site Groundwater Monitoring Wells Construction Summary
Table 2 Summary of 1,4-Dioxane Detections in Groundwater Monitoring Wells Located on the North End of the Site
Table 3 December 2021 Groundwater Analytical Results Landsburg Mine Site
Figure 1 Landsburg Mine Site MTCA Remedial Action
Figure 2 Cross Section Along Strike at Coal Seam June 2020 Cross Section A-A'
Figure 3 1,4-Dioxane Trend Plot Since November 2017
Attachment Dr. Andrew Madison, Resume'

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6.0   REFERENCES:

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Tables

Table 1: Landsburg Mine Site Groundwater Monitoring Wells Construction Summary

Well ID	Northing	Easting	Installation Date	Date Last Surveyed	Datum	Measuring Point Elevation (ft AMSL)	Measuring Point	Borehole Depth (ft bgs)	Borehole Diameter (inches)	Well Casing Diameter (inches)	Well Materials	Depth to Top of Screen (ft bgs)	Depth to Bottom of Screen (ft bgs)	Elevation Top of Screen (ft amsl)	Elevation Bottom of Screen (ft amsl)	Screen Slot Size (inches)	Depth to Top of Filter Pack (ft bgs)	Comments
LMW-1	138279.52	1354991.57	1/23/1994	8/14/2018	NAVD88	765.36	Top of PVC Casing	180	8	4	Stainless/PVC	162	177	603	588	0.02	158	In area of gangway that connects mine fault off-set
LMW-2	139077.61	1355972.91	2/11/1994	8/14/2018	NAVD88	617.79	Top of PVC Casing	46	8	4	Stainless/PVC	28	38	590	580	0.02	25	Shallow north compliance
LMW-3	135192.23	1353220.37	11/22/2004	11/3/2004	NAVD88	656.75	Top of PVC Casing	76	8	4	Stainless/PVC	50	65	607	592	0.02	47	Shallow south compliance
LMW-4*	139122.67	1355865.52	2/19/1994	8/14/2018	NAVD88	619.27	Top of PVC Casing	233	8	4	Stainless/PVC	195	210	424	410	0.02	210	Deep north compliance
LMW-5	135206.05	1353141.36	12/8/2004	11/3/2004	NAVD88	658.27	Top of PVC Casing	247	8	4	Stainless/PVC	232	242	426	416	0.02	232	Deep south compliance
LMW-6	138714.14	1354126.78	1/13/1994	11/3/2004	NAVD88	632.33	Top of PVC Casing	106	8	4	Stainless/PVC	91	106	541	526	0.02	83	Frasier Coal Seam
LMW-7*	138055.10	1355483.61	1/10/1994	11/3/2004	NAVD88	771.51	Top of PVC Casing	254	8	4	Stainless/PVC	240	254	532	518	0.02	n/a	Landsburg Coal Seam
LMW-8	135074.90	1353229.41	4/7/2004	11/3/2004	NAVD88	646.97	Top of PVC Casing	15	9	2	PVC	7.5	13	639	634	0.02	6	Representative of Portal #3 discharge
LMW-9	135727.33	1353324.04	4/14/2004	11/3/2004	NAVD88	743.99	Top of PVC Casing	160	9	2	PVC	149	159	595	585	0.02	144	Southern Sentinel Well mid-depth
LMW-10	139054.56	1355787.97	5/11/2004	8/14/2018	NAVD88	618.98	Top of PVC Casing	450	9	4	PVC	267	287	352	332	0.02	258	Deep, near bottom of mine, northern end
LMW-11	136159.27	1353317.36	8/24/2005	4/19/2019	NAVD88	802.19	Top of PVC Casing	707	9	4	Stainless/PVC	697	707	105	95	0.02	688	Deep, near bottom of mine, south end
LMW-12	138923.92	1355721.80	3/14/2018	8/14/2018	NAVD88	625.35	Top of PVC Casing	30	8	4	PVC	15.5	25.5	610	600	0.02	11	North Portal Sentinel Shallow Sentinel Well
LMW-13R	138932.43	1355728.92	5/15/2018	8/14/2018	NAVD88	625.86	Top of PVC Casing	151	8	4	PVC	115	140	511	486	0.02	110	North Portal Sentinel Deep Sentinel Well
LMW-14*	137188.61	1353967.91	4/15/2019	4/19/2019	NAVD88	805.12	Top of PVC Casing	176	6	2	PVC	156.5	172.3	649	633	0.01	152.6	15° Incline. Vertical depths reported
LMW-15	136245.07	1353517.07	11/5/2018	4/19/2019	NAVD88	796.46	Top of PVC Casing	248	6	2	PVC	238	248	558	548	0.01	233	South cap effectiveness well
LMW-20	139352.05	1356317.06	11/27/2018	12/26/2018	NAVD88	546.80	Top of PVC Casing	24.5	6	2	PVC	14	24	533	523	0.01	11	Cedar River Valley Rogers Seam
LMW-21	139209.99	1356404.12	11/29/2018	12/26/2018	NAVD88	544.09	Top of PVC Casing	15	6	2	PVC	10	15	534	529	0.01	7	Cedar River Valley East Well
LMW-22	139493.44	1355909.73	11/28/2018	12/26/2018	NAVD88	542.86	Top of PVC Casing	27.5	6	2	PVC	17	27	526	516	0.01	14	Cedar River Valley West Well

Notes:

* LMW-4 and LMW-7 were drilled at a 20° incline; LMW-14 was drilled at 15° incline.

** No filter pack was installed in P-2 due to the open mine shaft at 39 feet to 44 feet. The casing was removed, and the native material collapsed around the well to 15 feet below ground surface.

ft AMSL - feet above mean sea level

ft bgs - feet below ground surface

153.69   251.12

Table 2: Summary of 1,4-Dioxane Detections in Groundwater Monitoring Wells Located on the North End of the Site

Sample Date	LMW-2	LMW-4	LMW-10	LMW-12	LMW-13R
	µg/L	µg/L	µg/L	µg/L	µg/L
11/30/2017	2.0	2.3	0.4 U	NA	NA
2/9/2018	2.1	2.3	NA	NA	NA
5/24/2018	1.8	1.5	0.4 U	1.5	0.4 U
8/15/2018	1.6	1.5	0.4 U	1.6	0.4 U
12/4/2018	1.7	1.6	0.4 U	1.2	0.4 U
3/5/2019	1.5	1.7	0.4 U	1.1	0.4 U
5/22/2019	1.5	2 (1.5)	0.4 U	1.4	0.4 U
8/14/2019	1.8	1.5	0.4 U	1.6	0.4 U
12/10/2019	1.5	1.6 (1.6)	0.4 U	0.4 U	0.4 U
3/10/2020	1.6	1.3 (1.4)	0.4 U	1.0	0.4 U
6/25/2020	1.8 (1.8)	1.8	0.4 U	0.5	0.4 U
9/16/2020	1.6 (1.7)	1.8	0.4 U	0.6	0.4 U
11/23/2020	2.3	2.3 (2.4)	0.4 U	0.4 U	0.4 U
3/29/2021	2.2	2.5 (2.3)	0.4 U	0.9	0.4 U
6/2/2021	1.5 (1.7)	1.8	0.4 U	0.4 U	0.4 U
9/28/2021	2 (1.9)	2	0.4 U	0.5	0.4 U
12/8/2021	1.5 (1.6)	1.6	0.4 U	0.9	0.4 U

Notes:

U - The analyte was not detected above the laboratory method detection limit of 0.04 µg/L.

µg/L = micrograms per liter

Analyses performed by EPA Method 8270

Duplicate results are included in parentheses

MTCA Method B Cleanup Level of 1,4-Dioxane is 0.44 µg/L

1,4-dioxane was not detected in any other Site groundwater monitoring wells

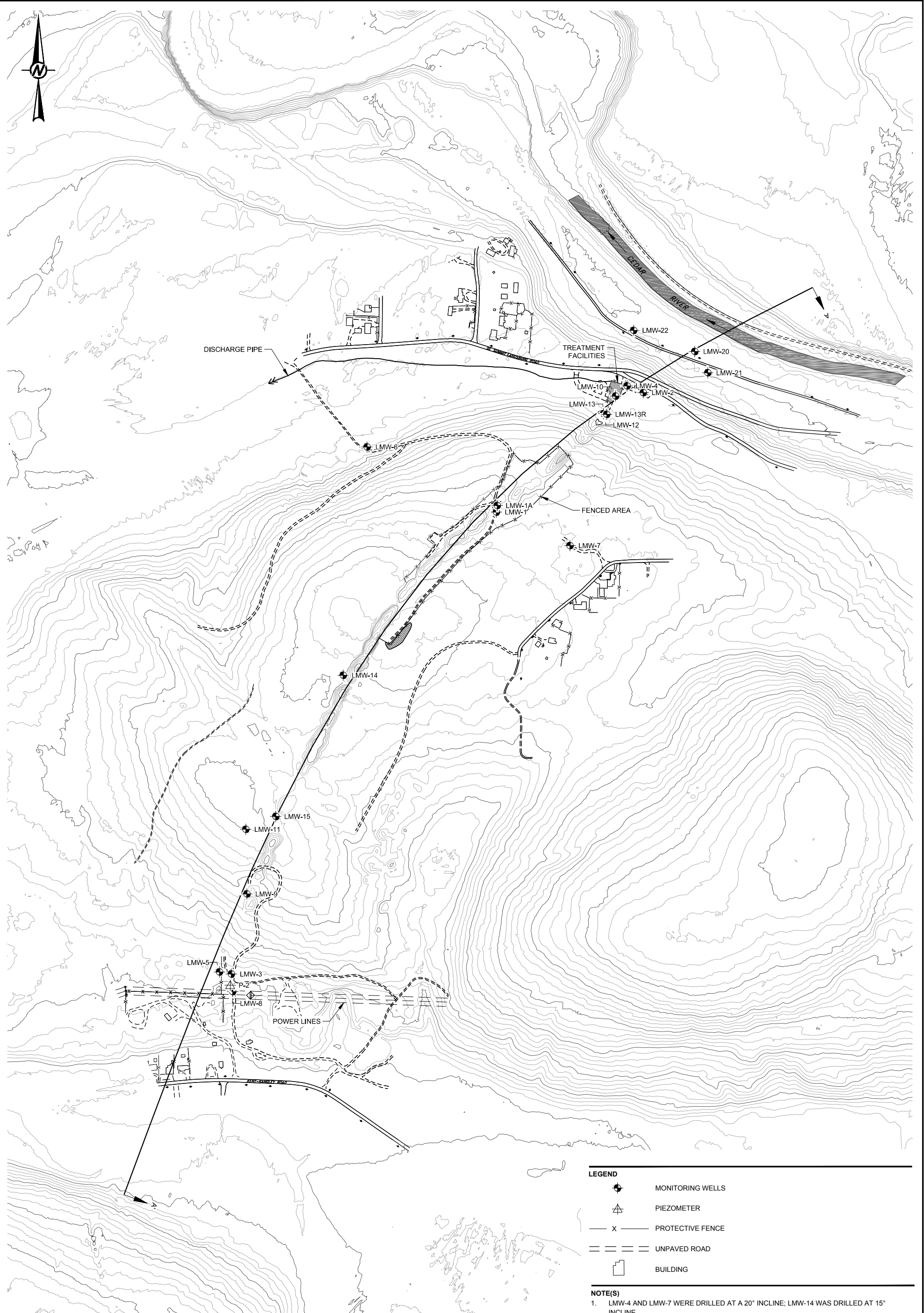**Table 3: December 2021 Groundwater Analytical Results Landsburg Mine Site**

ANALYTE	UNITS	LMW-2	LMW-4	LMW-12
		12/8/2021	12/8/2021	12/7/2021
Field Parameter				
Temperature	°C	11	10.6	10
pH	stnd	6.77	6.8	6.42
Specific Conductance	uS/cm	689	679	599
Dissolved Oxygen	mg/L	0.97	0.97	0.98
ORP	mV	-142.9	-139.1	-65.6
Turbidity	NTU	0.37	1.55	2.74
Metals (Total)				
Aluminum	mg/L	1 U	1 U	1 U
Antimony	mg/L	0.003 U	0.003 U	0.003 U
Arsenic	mg/L	0.003 U	0.003 U	0.003 U
Barium	mg/L	0.5 U	0.5 U	0.5 U
Beryllium	mg/L	0.01 U	0.01 U	0.01 U
Cadmium	mg/L	0.002 U	0.002 U	0.002 U
Calcium	mg/L	**116**	**114**	**92.5**
Chromium	mg/L	0.01 U	0.01 U	0.01 U
Cobalt	mg/L	0.01 U	0.01 U	0.01 U
Copper	mg/L	0.003 U	0.003 U	0.003 U
Iron	mg/L	0.2 U	**0.654**	**14.1**
Lead	mg/L	0.01 U	0.01 U	0.01 U
Magnesium	mg/L	**72.9**	**71.9**	**56.4**
Manganese	mg/L	**0.237**	**0.206**	**0.669**
Mercury	mg/L	0.001 U	0.001 U	0.001 U
Nickel	mg/L	0.01 U	0.01 U	0.01 U
Potassium	mg/L	**3.61**	**3.62**	**3.3**
Selenium	mg/L	0.025 U	0.025 U	0.025 U
Silver	mg/L	0.005 U	0.005 U	0.005 U
Sodium	mg/L	**19.8**	**21.2**	**9.04**
Thallium	mg/L	0.002 U	0.002 U	0.002 U
Vanadium	mg/L	0.003 U	0.003 U	0.003 U
Zinc	mg/L	0.02 U	0.02 U	0.02 U
Volatile Organic Compounds (VOCs)				
Chloroethane	ug/L	0.2 U	0.2	**1.34**
1,1-Dichloroethane	ug/L	0.2 U	0.2 U	**1.17**
Semi-Volatile Organic Compounds (SVOCs)				
1,4-Dioxane	ug/L	**1.5**	**1.6**	**0.9**

Notes:

U - Analyte was not detected above the Reporting Limit (RL).

J - Analyte was detected above the Method Detection Limit (MDL) but below the RL.

GOLDER
MEMBER OF WSP

Figures

DISCHARGE PIPE

CEDAR RIVER

LMW-22
LMW-20
LMW-21

TREATMENT FACILITIES

LMW-10
LMW-4
LMW-2
LMW-13
LMW-13R
LMW-12

LMW-6

LMW-1A
LMW-1

FENCED AREA

LMW-7

LMW-14

LMW-15
LMW-11

LMW-9

LMW-5
LMW-3
P-2
LMW-8

POWER LINES

LEGEND

Symbol	Description
⊕	MONITORING WELLS
△	PIEZOMETER
—— X ——	PROTECTIVE FENCE
= = = =	UNPAVED ROAD
▢	BUILDING

NOTE(S)

1. LMW-4 AND LMW-7 WERE DRILLED AT A 20° INCLINE; LMW-14 WAS DRILLED AT 15° INCLINE

CLIENT	PROJECT
LANDSBURG MINE SITE PLP GROUP	LANDSBURG MINE SITE MTCA REMEDIAL ACTION

CONSULTANT			TITLE
	YYYY-MM-DD	2019-04-25	**SITE MAP**
	DESIGNED	XXX	
	PREPARED	XXX	
GOLDER	REVIEWED	XXX	
	APPROVED	XXX	

PROJECT NO.	PHASE	REV.	SHEET
9231000005	1200	A	1

0   300   600
1" = 300'   FEET

Waste Disposal Area

A / NE

A' / SE

Deep North Sentinel Well LMW-13R (616.61)

Shallow North Sentinel Well LMW-12 (616.60)

South Sentinel Well LMW-14 (644.19)

South Sentinel Well LMW-15 (644.44)

Fault offset coal seam approximately 75 feet

LMW-4 (610.60)
LMW-2 (610.66)
LMW-20
LMW-10
LMW-1 (626.38)
LMW-11 (644.37)
LMW-9 (644.05)
LMW-5 (643.99)
LMW-3 (644.07)
LMW-8 (642.51)

Cedar River

RI/FS STUDY AREA BOUNDARY

Qvt'
Qvr
Qva
Qu

Qvr
Qvt
U D
?
?
?
?

Rock Creek

Depiction of Faults or Fractures

Mine Gangways

Elevation (feet msl): 1000, 900, 800, 700, 600, 500, 400, 300, 200, 100, Sea level 0
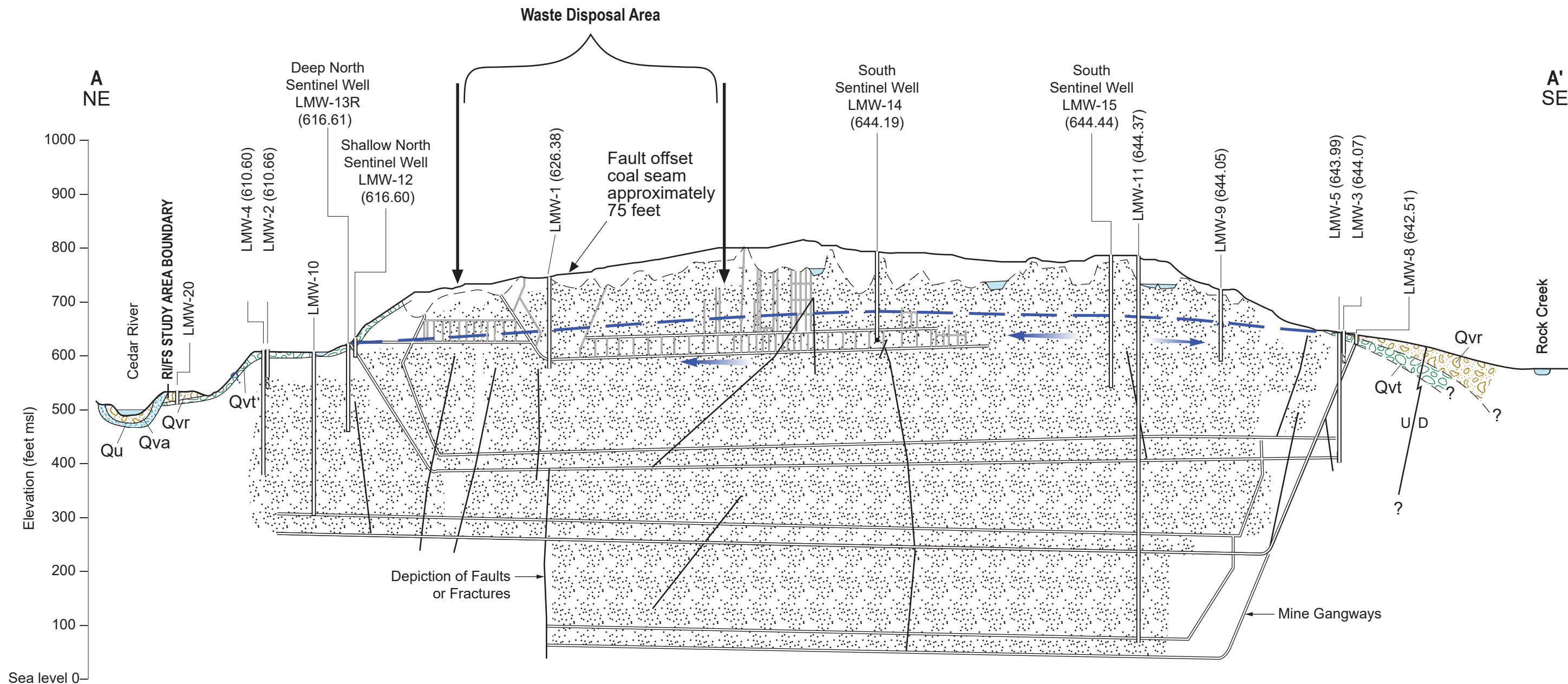
EXPLANATION

— — Potentiometric surface

⌃⌃⌃ Outline of trench bottom

LMW-2 (609.99) Well ID (water level in ft. amsl)

Qvt Till, compact mixture of gravel occasional boulders in clayey silty sand matrix

Sandstone

Surface water feature

Anticipated collapsed zone within mine

Qu Drift, till, fluvial sand and gravel, lacustrine sand, silt, clay and peat

Qvr Recessional outwash, well sorted sand and pebble-cobble

Qva Advanced outwash pebble-cobble gravel may include very fine sand

Monitoring Interval

← Groundwater Flow Direction

Sources for the Geology and Mine Information:
J.E. Luzier 1969; surficial geology
State of Washington, Water Well reports
Mine Superintendant's Records
Landsburg Well Logs

NOTE: Vertical to horizontal scale ratio is 2.5:1
Wells are project normal into the strike of the Cross-Section
A-A' Groundwater elevation obtained 6/25/2020

0   500
FEET

CLIENT
LANDSBURG PLP GROUP

PROJECT
LANDSBURG MINE SITE

CONSULTANT

GOLDER

YYYY-MM-DD	2020-08-17	
PREPARED	REDMOND	
DESIGN		
REVIEW		
APPROVED		

TITLE
CROSS-SECTION ALONG STRIKE AT COAL SEAM JUNE 2020
CROSS-SECTION A-A'

PROJECT No.
923-1000-006

PHASE
2020

FIGURE
2

G:\Palmer Coking Coal\CoalLandsburgMineWA99_PROJECTS\9231000002_Ph1_RemediationR154\02_PRODUCTION\INDD\9231000_002_R154_003.indd

Figure 3: 1,4-Dioxane Trend Plot Since November 2017

Attachment

Golder Associates Inc. – Mount Laurel
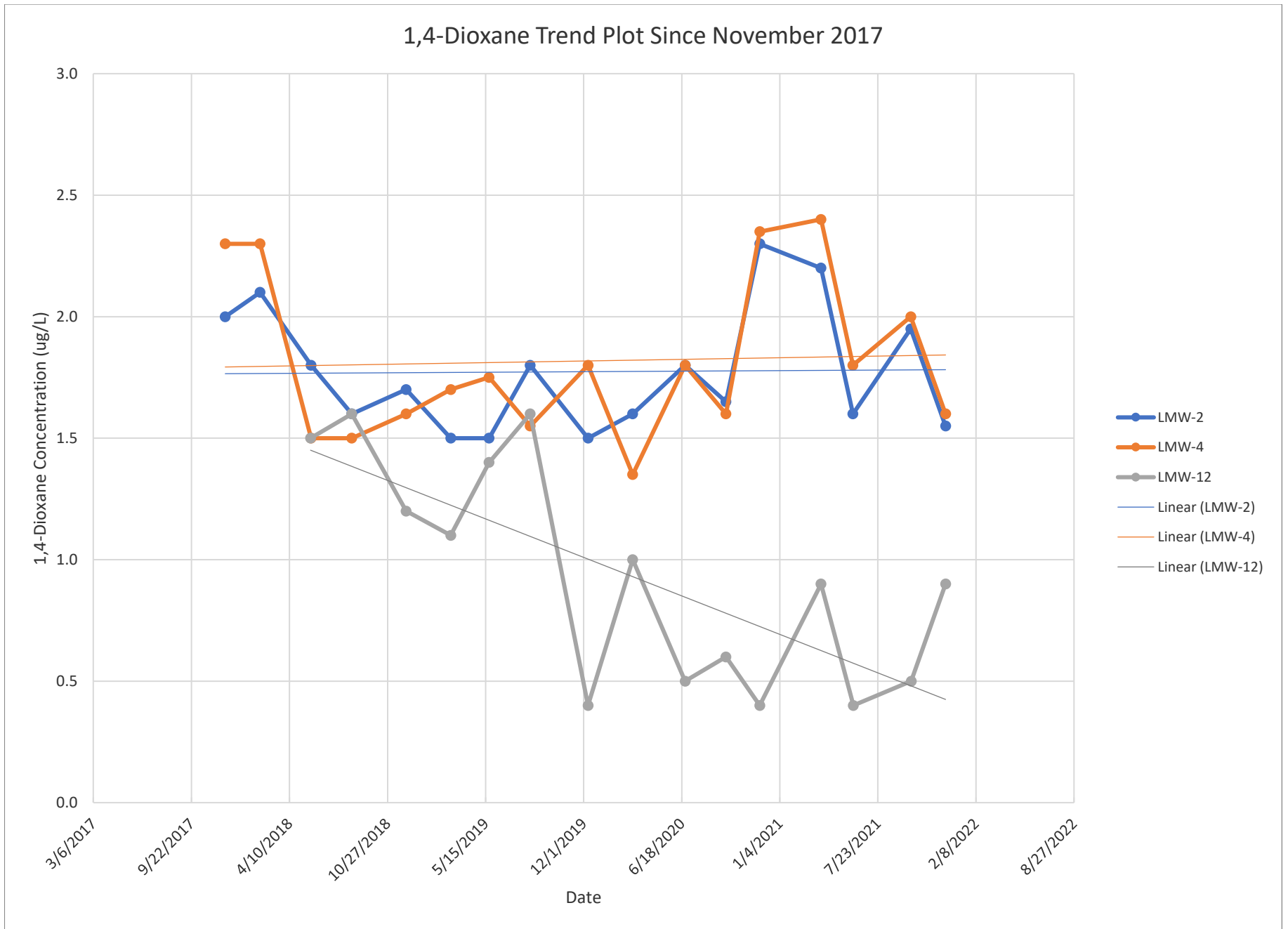
Education

PhD Geochemistry, University of Delaware, Lewes, DE, 2012

BS with Distinction Chemistry with Environmental Concentration, University of Delaware, Newark, DE, 2007

Professional Affiliations

Contributing Member for 1,4-Dioxane and PFAS Teams, Interstate Technology & Regulatory Council
Co-lead for ASTM Molecular Biological Tools Work Group

Associate and Senior Consultant

Dr. Madison is an Associated and Senior Geochemist with over 14 years of applied research and consulting experience in environmental remediation. Dr. Madison is one of the leaders of Golder's global investigation and remediation practice where he works with a team of professionals to identify, manage, investigate and remediate contaminants such as chlorinated solvents, petroleum hydrocarbons, inorganics and emerging contaminants. As part of this work, he has experience with soil and groundwater geochemical and microbiological investigations, contaminant hydrogeology, implementation of bench and pilot-scale studies, and selection, development and implementation of innovative remedial technologies with an emphasis on in situ engineered bioremediation and in situ remediation systems using chemical oxidants and reductants. He is a recognized expert in remedy optimization and has led and worked with teams at environmental sites under CERCLA programs across the US.

Prior to joining Golder, Dr. Madison was a researcher working on the geochemical and biological aspects that govern the fate of contaminants in the environment. Dr. Madison has published over 20 peer-reviewed articles and book chapters in the environmental chemistry and microbiology fields. Dr. Madison has presented research and projects at conferences and workshops around the globe.

RELEVANT PROJECT EXPERIENCE

KL Avenue Landfill Superfund Site Kalamazoo, Michigan, USA	Lead geochemist for a Region 5 CERCLA project at a former landfill at which 1,4-dioxane and tetrahydrofuran are the primary contaminants of concern in an off-site plume that extends for three miles. Led a team that included academic researchers to evaluate the effectiveness of the monitored natural attenuation remedy by using a multiple lines of evidence approach (microbiological tools, isotopic analyses and traditional data analyses). Designed bench-scale and field-scale studies that demonstrated successful in situ treatment of groundwater contaminated by 1,4-dioxane. Technical lead for ongoing PFAS investigation. Represented client as technical advocate during USEPA Region 5 negotiations.
Scientific Chemical Processing Superfund Site Carlstadt, New Jersey, USA	Designed bench- and pilot-scale studies for in situ treatment of groundwater contaminated by chlorinated solvents and 1,4-dioxane on a Superfund Project.
Folcroft Landfill Superfund Site Folcroft, Pennsylvania	Technical support for Groundwater FS for Region 3 CERCLA site to address chlorinated VOC and 1,4-dioxane impacts in source areas and downgradient, dissolved plumes. Currently lead bench-scale treatability testing to evaluate enhanced bioremediation and chemical oxidation in situ approaches.

Berry's Creek Superfund RI/FS and RD Berry's Creek, New Jersey	Key team member supporting a large PRP (Scientific Chemical Processing) for a major sediment RI/FS and RD. Participant in development of work scope including sediment, surface water, and biota sampling; risk assessment; and treatability/pilot studies of sediment amendment in major urban watershed. Reviewer of project deliverables for multi-year remedial investigation, feasibility study and ongoing remedial design.
Lower Passaic River (Confidential Client) Newark, New Jersey	Lead technical expert supporting a party involved in litigation associated with the Lower Passaic Site. Provide expert services in reviewing and evaluating sediment, surface water, hydrodynamic and risk assessment data to support legal counsel.
Henderson Road Superfund Site Pennsylvania, USA	Lead geochemist as part of Focused Feasibility Study (FFS) team for LNAPL/groundwater impacts in carbonate bedrock aquifer at a Region 3 CERCLA site. Utilized advanced site characterization technologies including molecular analyses and stable isotopes in combination with traditional data analyses approaches to demonstrate intrinsic biodegradation of source impacts was effective mass removal mechanism. Involved in remedial alternatives/technology evaluations and meetings with USEPA Region 3 and other stakeholders.
Former Pfizer/Biocor Facility Omaha, Nebraska, USA	Team Leader and lead biogeochemist for the remedial action through the Nebraska Voluntary Clean-up Program of a chlorinated solvent site in Omaha, NE. Designed and implemented the pre-design investigation, including using membrane interface probe (MIP) technology and 3-dimensional data visualization to develop a conceptual site model to describe the fate and transport of impacts at the site. Designed and implemented a pilot-scale and full-scale enhanced bioremediation and bioaugmentation program resulting in site closure. Represented the client during agency negotiation of the remedy and throughout the implementation.
Confidential Site New Jersey, USA	Team Leader and lead biogeochemist for the remedial investigation and action for a former solvent storage facility. Conducted delineation of on- and off-site chlorinated solvent impacts. Designed a full-scale enhanced in situ biodegradation system utilizing horizontal injection wells to treated chlorinated solvent impacts.
Confidential Site Middlesex County, New Jersey	Technical lead for investigating and developing the management strategy for sediment impacts in the Arthur Kill related to a former smelter facility. Developed and implemented pre-design investigation work scope including sediment sampling, bathymetric surveying, and hydrodynamic monitoring. Leading data evaluation using multivariate statistical methods to develop a fingerprint for the site to distinguish and delineate site-related impacts from urban background and to minimize the potential remediation area.
Former FMC Facility South Charleston, WV	Technical lead for investigating and developing the management strategy for sediment and surface water impacts in a large, navigable river. Developed scope of work including sediment and surface water sampling, benthic and fish surveys, fish tissue sampling, and groundwater-surface water discharge. Represented client as technical advocate to state regulatory agency (WVDEP).

Confidential Superfund Site **New Jersey, USA**	Technical lead for assessing PFAS-related impacts in overburden and bedrock groundwater including evaluating potential receptors and potential off-site source(s) of PFAS in an industrialized area.
Nease Chemical Superfund Site Salem, Ohio	Lead geochemist/microbiologist for the design and implementation of a combined ZVI and enhanced biodegradation approach in overburden and fractured bedrock to mitigate chlorinated solvents impacts at Region 5 CERCLA site.
Former ExxonMobil/ADC Facility Everett, WA, USA	Technical lead and project manager for site evaluation to assess the natural attenuation potential of residual hydrocarbon impacts. A multiple lines of evidence (MLOE) approach was employed that included traditional data analyses and state-of-the-art molecular analyses (function genes analyses and next generation sequencing). The evaluation demonstrated that residual impacts are attenuating over time in compliance with regulatory requirements.
Former Metec Inc. Site Winslow, NJ, USA	Lead geochemist for the remedial investigation and remedial action at a former molybdenum processing facility. Led a multi-disciplinary team to evaluate natural attenuation of site impacts (molybdenum and selenium) in large, off-site plume using multiple line of evidence approach including spatial and concentration trends analysis, fate and transport modeling, and geochemical evaluation.
Former Satralloy Site Ohio, USA	Lead team developing a complex fate and transport conceptual site model for chromium impacts in a mountain range bedrock aquifer system at a former chromium ore processing facility. Designed a passive sampling approach to sample groundwater seeps to help identify the respective upgradient source. Analyzed geochemical data collected from groundwater, surface water and seeps as part of the remedial investigation activities to support a monitored natural attenuation remedy.
Confidential Site Mississippi	Lead geochemist for site investigation, remedy selection, remedy negotiation, pre-design investigation, pilot-scale implementation, and in situ remediation of a Site impacted by elevated levels of dissolved cadmium and lead utilizing existing microorganisms in the subsurface and adding additional carbon sources to the system to stimulate biological reduction of sulfate and subsequent generation of solid-phase cadmium and lead sulfide mineral phases (cadmium and lead immobilization).
American Cyanamid Superfund Site New Jersey	Involved with a team of hydrogeologists, geologists, and chemists to refine the design of an extraction and treatment system to address site impacts within a complex fracture bedrock system impacted with a variety of organic and inorganic compounds. Lead geochemist on various phases of the work to understand geochemical setting and conditions. Project manager for the re-injection of treated groundwater permitting process.
Confidential New Jersey, USA	Lead geochemist responsible for designing and implementing a pilot-scale study to enhance in situ biodegradation of petroleum hydrocarbons via subsurface sulfate addition. Work included geochemical and microbial characterization of the treatment zone and evaluation of the remedial approach and potential applicability to a larger-scale remedy.