ESTCP

FINAL REPORT

Remote Monitoring of Natural Source Zone Depletion Using Temperature Data to Support Long-Term Passive Management Strategies

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February 2023

ESTCP Project ER19-5091

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 10-02-2023	**2. REPORT TYPE** ESTCP Final Report	**3. DATES COVERED** *(From - To)* 4/25/2019 - 4/23/2023

4. TITLE AND SUBTITLE Remote Monitoring of Natural Source Zone Depletion Using Temperature Data to Support Long-Term Passive Management Strategies	**5a. CONTRACT NUMBER** W912HQ19C0017 **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Walker, Jr., Kenneth L.; Robinson, Schuyler T.; McHugh, Thomas GSI Environmental Inc. Sale, Thomas; Askarani, Kayvan K., Colorado State University Lewis, Travis, NAVFAC EXWC	**5d. PROJECT NUMBER** ER19-5091 **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) GSI Environmental Inc. 2211 Norfolk Street Suite 1000 Houston, TX 77098	**8. PERFORMING ORGANIZATION REPORT NUMBER** 5186
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Environmental Security Technology Certification Program 4800 Mark Center Drive Suite 16F16 Alexandria, VA 22350-3605	**10. SPONSOR/MONITOR'S ACRONYM(S)** ESTCP **11. SPONSOR/MONITOR'S REPORT NUMBER(S)** ER19-5091

12. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Many DoD sites are affected by historical releases of light non-aqueous phase liquids (LNAPL). Recently, natural source zone depletion (NSZD) has emerged as a passive remedy approach that offers the potential for greater rates of LNAPL destruction when compared to active remedies, a more sustainable remediation approach, and lower long-term costs. Analogous to the generation of heat from a compost pile, the biological degradation of petroleum in the subsurface generates heat. This heat signature allows use of an innovative temperature-based technology to quantify biologically-mediated depletion of LNAPL in the subsurface. Across 40 sites where NSZD rates have been measured by various parties, NSZD was documented to occur at all sites. The measured NSZD rates did not vary by fuel type. NSZD was also documented at the two demonstration sites under both paved and unpaved locations. Different methods used to quantify rates yielded a range of rates that were generally within an order of magnitude. While offering some clear advantages, additional work may be required to fully validate 2nd generation monitoring equipment and background correction methods, especially to resolve short-term NSZD rates (e.g., monthly or seasonal). The primary cost driver is the cost of the temperature sensor stations. While one-time measurements of NSZD, such as Carbon Traps, may be cheaper for single measurements, the temperature-based methods offer clear cost advantages at sites where long-term monitoring is required or advantageous.

15. SUBJECT TERMS

LNAPL, NSZD, Thermal NSZD, natural source zone depletion, internet of things, dashboard, data analytics

16. SECURITY CLASSIFICATION OF: UU (Unclassified Unlimited)			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Thomas McHugh
a. REPORT UU	**b. ABSTRACT** UU	**c. THIS PAGE** UU	UU (Unclassified Unlimited)	213	**19b. TELEPHONE NUMBER** *(include area code)* 713-522-6300

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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ACRONYMS AND ABBREVIATIONS

ADC	analog-to-digital converter
AOC	Area of Concern
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
AW	Airlift Wing
bgs	below ground surface
CO_2	carbon dioxide
CH_4	methane
CRCCare	Cooperative Research Center for Contamination Assessment and Remediation of the Environment
CSU	Colorado State University
CSURF	Colorado State University Research Foundation
DCC	dynamic closed chamber
DoD	Department of Defense
EXWC	Naval Facilities Engineering and Expeditionary Warfare Center
ERDC	Engineer Research and Development Center
ESTCP	Environmental Security Technology Certification Program
ft	feet
gal/acre/yr	gallons per acre per year
GAS Plots	Gallo-Askarani-Sale Plots
GSI	GSI Environmental Inc.
HCP	Hydrocarbon Proof
IDW	investigation-derived waste
ITRC	Interstate Technology and Regulatory Council
LNAPL	light non-aqueous phase liquid
L/ha/yr	liters per hectare per year
MDH	Minnesota Department of Health
MNA	monitored natural attenuation
MN ANGB	Minnesota Air National Guard Base
NAVFAC	Naval Facilities Engineering Systems Command

NSZD	natural source zone depletion
O_2	oxygen
OD	outer diameter
ORP	oxidation-reduction potential
OWS	oil/water separator
PCB	printed circuit board
PID	photoionization detector
ppm	parts per million
PVC	polyvinyl chloride
QA	quality assurance
QC	quality control
SS	stainless steel
SWMU	solid waste management unit
SVE	soil vapor extraction
TEAD-S	Tooele Army Depot – South
TCEQ	Texas Commission on Environmental Quality
TI	Technical Impracticability
UST	underground storage tank

ACKNOWLEDGMENTS

This project would not have been possible without the support and contribution of numerous individuals and organizations. The authors thank project team members David Gent (Army Engineer Research and Development Center (ERDC)), and Justin Meredith (Tennessee Department of Environment and Conservation). For hardware and software support, we are grateful to Sam Gallo (S3NSE Technologies LLC). For invaluable project support, we also thank Andrea Leeson and the ESTCP program staff at Noblis. We are also grateful for the many people involved with demonstration site access and support, including Ms. Paige Walton, Mr. Troy Johnson, Ms. Samantha Girtz, and Mr. James King.

ABSTRACT

INTRODUCTION AND OBJECTIVES

Many Department of Defense (DoD) sites are affected by historical releases of light non-aqueous phase liquids (LNAPL), with costly active technologies traditionally being applied as the presumptive remedy for most LNAPL sites. Recently, monitoring of natural source zone depletion (NSZD) has emerged as a passive remedy approach that offers the potential for greater rates of LNAPL destruction when compared to active remedies, a more sustainable remediation approach, and lower long-term costs. The specific objectives of this demonstration program were to: (1) demonstrate the use of innovative, inexpensive 2^{nd} generation temperature monitoring systems developed by Colorado State University to improve data quality and reduce costs; (2) demonstrate improved methods to separate the heat signal associated with biodegradation of petroleum from seasonal and other sources of temperature fluctuations in soils; (3) demonstrate that temperature-based approaches to quantifying NSZD rates are particularly suited for LNAPL source areas located below paved surfaces; and (4) compile results from monitoring of NSZD at many sites and utilize these results to i) document the range of NSZD rates and ii) identify site factors that may be predictive of higher or lower NSZD rates at individual sites.

TECHNOLOGY DESCRIPTION

Analogous to the generation of heat from a compost pile, the biological degradation of petroleum in the subsurface generates heat. This heat signature allows use of an innovative temperature-based technology to quantify biologically-mediated depletion of LNAPL in the subsurface.

PERFORMANCE AND COST ASSESSMENT

Across 40 sites where NSZD rates have been measured by various parties, NSZD was documented to occur at all sites. The measured NSZD rates did not vary by fuel type. NSZD was also documented at the two demonstration sites under both paved and unpaved locations. Different methods used to quantify rates yielded a range of rates that were generally within an order of magnitude. While offering some clear advantages, additional work may be required to fully validate 2^{nd} generation monitoring equipment and background correction methods, especially to resolve short-term NSZD rates (e.g., monthly or seasonal). The primary cost driver is the cost of the temperature sensor stations. While one-time measurements of NSZD, such as Carbon Traps, may be cheaper for single measurements, the temperature-based methods offer clear cost advantages at sites where long-term monitoring is required or advantageous.

IMPLEMENTATION ISSUES

There are no known implementation issues for temperature-based methods, which have been validated previously and discussed in multiple guidance documents and standards around the world. Despite general acceptance of NSZD as a scientific process, and the efficacy of different measurement methods, regulatory acceptance remains a concern in some locales. The results of these two demonstration sites, a review of 40 sites in the published literature, and recent guidance documents (e.g., ITRC 2018; ASTM E3361-22 2022) indicate the presence and magnitude of NSZD processes and provide further guidance for reliable methods to quantify NSZD rates. The 2^{nd} generation monitoring sensors and communication equipment can be procured from S3NSE Technologies as newly commercialized, custom-built equipment. Colorado State University

Research Foundation (CSURF) currently owns the patent (Sale et al. 2015; US Patent No. 10,094,719) for devices and methods for measuring the thermal flux and estimating the NSZD rate.

PUBLICATIONS

Kulkarni, P.R., K.L. Walker, C.J. Newell, K.K. Karimi Askarani, Y. Li, and T.E. McHugh, 2022. *Natural source zone depletion (NSZD) insights from over 15 years of research and measurements: A multi-site study.* Water Research. Accepted for publication. doi: 10.1016/j.watres.2022.119170.

EXECUTIVE SUMMARY

BACKGROUND

Many Department of Defense (DoD) sites are affected by historical releases of light non-aqueous phase liquids (LNAPL), including fuels, lubricants, and heating oil. Traditionally, costly active treatment technologies (e.g., hydraulic recovery, air sparging, multi-phase extraction, soil vapor extraction (SVE), etc.) have been applied as the presumptive remedy for most LNAPL sites. Except for complete excavation, in our experience, none of these in-situ remediation technologies have been able to completely remove all LNAPL. Today, monitoring of natural source zone depletion (NSZD) is gaining broad acceptance as a viable and cost-effective remedy for mature LNAPL releases (e.g., Sale et al. 2018; ITRC 2018; ASTM E3361-22 2022), while ensuring that the goals of protection of human health and the environment are met while progressing towards site cleanup. Key factors supporting NSZD-based remedies include natural LNAPL depletion rates that may exceed what can be achieved with active remedies, greater sustainability, and reduced costs. Similar to a compost pile, the bacterial degradation of LNAPL in the subsurface generates heat. One accepted approach to documenting LNAPL NSZD is real time monitoring of subsurface temperatures and use of the heat generated by NSZD to resolve NSZD rates (e.g., Stockwell 2015; Sale et al. 2015; Warren and Bekins 2015; Karimi Askarani et al. 2018; Karimi Askarani and Sale 2020).

OBJECTIVES OF THE DEMONSTRATION

This project sought to demonstrate that temperature-based quantification of NSZD rates will:

Provide Continuous Measurement of NSZD Rates: Other existing technologies for measuring NSZD rates rely on one-time (or short-term) snapshots of the NSZD rates (on the order of minutes to approximately 2-3 weeks). By continuously recording temperatures within the LNAPL source area, the on-going NSZD processes can be documented and quantified, enhancing the regulatory acceptance of the technology. In addition, continuous monitoring can be used to document seasonal variations in NSZD rates and gain an improved understanding of how changes in site conditions affect NSZD rates.

Permit Monitoring of NSZD Below Paved Surfaces: Many DoD facilities with hydrocarbon LNAPL issues are covered with low permeability surfaces (e.g., parking lots, repair buildings and facilities, tarmacs, etc.). Although current DoD efforts have utilized Carbon Traps to measure NSZD rates (Environmental Security Technology Certification Program [ESTCP] Project ER-201582), Carbon Traps are not suitable for deployment inside buildings or on paved surfaces because Carbon Traps are unable to obtain a representative measurement of carbon dioxide (CO_2) flux when installed on top of or through a paved surface. In contrast, temperature-based monitoring directly measures the heat generated by petroleum biodegradation, and the temperature sensors can be installed through either open ground or paved surfaces (including building foundations).

Reduce Treatment and Monitoring Cost: At many sites, active treatment of LNAPL reaches a point of diminishing returns, especially once LNAPL transmissivity declines as a result of active treatment. For example, Interstate Technology and Regulatory Council (ITRC) (2018) notes that the practical limits of LNAPL recovery are represented by an LNAPL transmissivity of 0.1 to 0.8 ft^2/day, and at lower transmissivities, the majority of LNAPL at a site is in a state of lesser mobile and residual saturation. At this stage, the volume of LNAPL destroyed by NSZD can be one or more orders of magnitude greater (e.g., median site-wide average of 1,020 gallons/acre/year; Kulkarni et al. 2022b) than the volume removed with low efficiency, late-stage existing active systems, such as hydraulic recovery systems, which may only recover a few gallons or tens of gallons per year. Accurate quantification of NSZD rates supports significant cost savings at these sites by transitioning from the current active technology to a passive technology that verifies LNAPL destruction quantitatively on a continuous basis. In addition, automated uploads and processing of the temperature-based monitoring data allow for low-cost long-term monitoring and can reduce greenhouse gas emissions by reducing on-site visits.

TECHNOLOGY DESCRIPTION

Based on thermodynamic principles, biological degradation of petroleum in the subsurface generates the same amount of heat per volume of petroleum degraded as combustion of petroleum (for example, combustion of petroleum in an oil furnace used for home heating). At remediation sites, heat from oxidation of hydrocarbons allows use of innovative temperature-based methods to quantify biologically-mediated depletion of LNAPL in the subsurface. The break-through method for the conversion of generated heat to NSZD rates is based on thermodynamics. Methods were originally developed by Colorado State University (Stockwell 2015; Karimi Askarani et al. 2018), with collaborative work by others (e.g., Sweeney and Ririe 2014; Warren and Bekins 2015). Well documented, peer reviewed guidance has been developed for this technology since then (ITRC 2018; ASTM E3361-22 2022). Based on monitoring done at several sites, soil temperatures within LNAPL source areas are commonly observed to be 1˚C to 3˚C above the temperatures at matched background locations. NSZD-related temperature differences can be readily measured with available temperature sensors (e.g., thermocouples with a stated accuracy +/- 0.1˚C, resolution 0.01˚C).

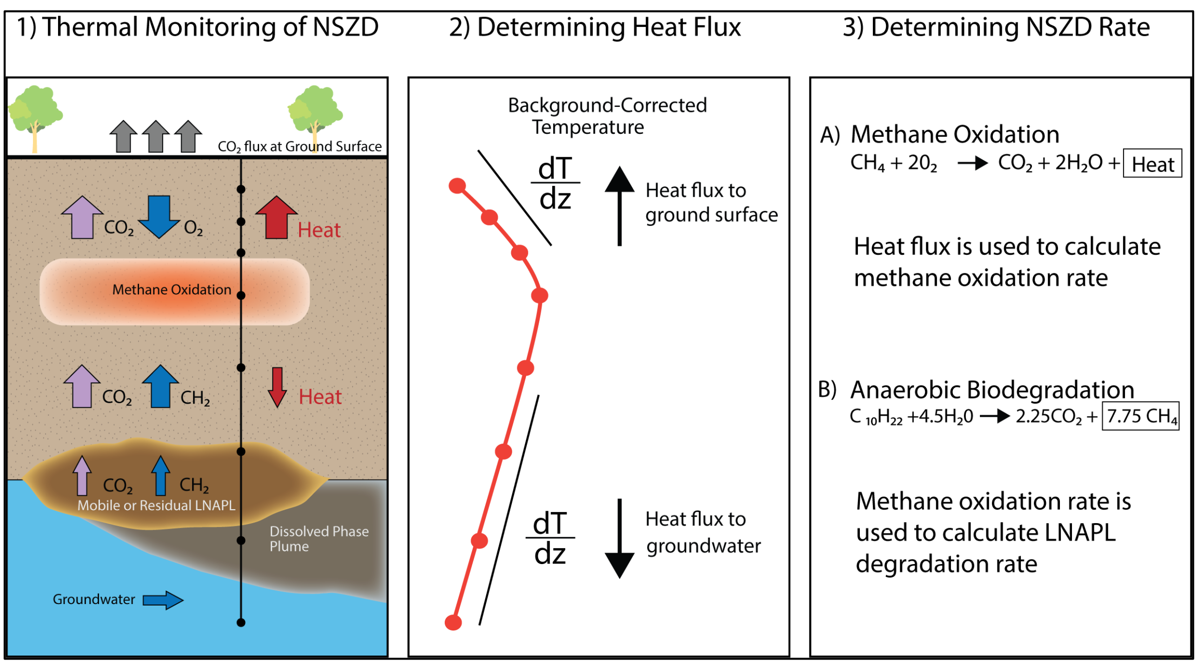


Figure ES.1. Conceptual Model for Temperature-Based Monitoring of NSZD

The application of temperature-based monitoring to determine NSZD rates is illustrated in Figure ES.1. Multiple vertically-spaced temperature sensors (e.g., thermocouples) are installed in the LNAPL impacted area (and at least one non-impacted (i.e., background) location for background-based methods). A "background-correction" step is required to separate the biogenic heat signal produced by NSZD processes from other sources of heat to the subsurface (e.g., solar heating and cooling, pipelines, etc.). The background-corrected vertical temperature profile is used to determine the upward and downward temperature gradients, which, in turn, are used to calculate the heat flux, which corresponds to the amount of heat being generated from the biodegradation. Based on the amount of heat energy produced from NSZD according to the thermodynamics of petroleum combustion/degradation, the volume of petroleum being degraded per area per unit time (i.e., the NSZD rate) is calculated. Within the United States, NSZD rates are commonly expressed in units of gallons of petroleum degraded per acre per year. Quantification of the NSZD rate allows the mass of petroleum removed by NSZD to be compared to that removed by other remedies.

PERFORMANCE ASSESSMENT

The demonstration was completed at two sites: Solid Waste Management Unit (SWMU) 13, located at Tooele Army Depot – South (TEAD-S) in Tooele County, Utah and AOC ZZ013, located at the Minnesota Air National Guard Base (MN ANGB), Minneapolis, Minnesota. At each demonstration site, the monitoring locations included: one unpaved non-impacted background location, one paved non-impacted background location, one unpaved source area location, and two paved source area locations. At each of the two demonstration sites, field testing involved: i) installation of temperature monitoring stations; ii) deployment and collection of Carbon Traps; iii) measurement of oxygen, carbon dioxide, and methane soil gas concentrations along a vertical transect; iv) 18 to 24 months of temperature data collection; and v) decommissioning of monitoring locations.

Table ES-1 summarizes the performance objectives and a brief summary of key results, which are explained in more detail below.

Table ES.1. Performance Objectives and Summary of Results

Performance Objective	Success Criteria	Results Summary
1. Collection of a Complete Dataset	Collection of temperature measurements for >95% of planned measurement locations/days and >90% of planned alternative method measurements.	For vertical soil gas profiles of oxygen, carbon dioxide, and methane, and for Carbon Traps, 100% of planned data were collected. For temperature and ORP data, at TEAD-S, data set completeness (>99%) exceeded the performance objective of 95% at each sensor location. At the MN ANGB, data set completeness (72%) was below the performance objective of 95% at the site level, and below 95% at four of five sensor locations.
2. Improved Background Correction for Temperature-Based Monitoring of NSZD	Attainment of more stable background-corrected temperature gradients and NSZD rates compared to 1st generation methods. More accurate short-term (weekly to monthly) NSZD rates compared to 1st generation methods.	Three different temperature-based methods were used to calculate NSZD rates: Method 1 (annual average), Method 2 (background correction), and Method 3 (Single Stick). Although the daily rates at both TEAD-S and the MN ANGB were highly variable and may not be reliable for estimating short-term NSZD rates (daily to weekly), they do provide a reliable estimate of annual NSZD rates.
3. Comparison between NSZD rates from temperature-based monitoring and other NSZD methods	Comparability of NSZD rates between temperature and alternative methods. Agreement between methods within a factor of 2X (or evidence that temperature-based monitoring method is more accurate based on, for example, lower spatial and temporal variability).	The background correction method yielded NSZD rates closer to the annual average method than the Single Stick method. However, the agreement in NSZD rates between the individual temperature-based methods and the alternative methods was more variable. Additional field demonstration is needed to determine which temperature-based method yields the most accurate estimates of NSZD rates across a larger number of sites.
4. Demonstration of 2nd Generation Equipment	Lower costs and more detailed vertical temperature dataset compared to 1st generation equipment.	At both sites, the 2nd generation equipment was able to record temperatures at more than twice as many depths as the 1st generation equipment, with less cost per sensor and in total.
5. Documentation of NSZD Below Paved Surfaces	Temperature profile consistent with NSZD. Methane/carbon dioxide/oxygen distribution consistent with NSZD.	The weight of evidence suggests NSZD in paved areas at TEAD-S, but the NSZD rates appear to be lower than those at the unpaved location. At the MN ANGB, each temperature-based and alternative method support the occurrence of NSZD beneath paved surfaces. These results and results published by Smith et al. (2021) provide evidence that temperature-based methods are suitable for quantification of NSZD rates beneath paved surfaces.
6. Compilation of NSZD Rates Across NSZD Monitoring Sites	Documentation of typical range of NSZD rates across sites. Identification of site factors predictive of higher or lower NSZD rates.	At 40 impacted sites, NSZD rates were compiled using the following temperature-based methods: Gradient Method, Carbon Traps, Dynamic Closed Chamber (DCC), and Thermal Monitoring. Site-average NSZD rates ranged from 650 to 152,000 L/ha/yr (70 to 16,250 gallons per acre per year (gal/acre/yr)), with a median value of 9,540 L/ha/yr (1,020 gal/acre/yr). No clear bias was observed between NSZD rate measurement methods, with the difference between any two methods generally within a factor of 2-3x. Although NSZD rates vary across sites, fuel type is not the primary factor explaining observed differences in rates.

Performance Objective 1: Collection of a Complete Dataset

At each monitoring location, the data collection included i) vertical soil gas profiles of oxygen, carbon dioxide, and methane; ii) Carbon Traps; and iii) temperature monitoring locations that recorded temperature and the oxidation-reduction potential (ORP).

- For oxygen, carbon dioxide, methane, and Carbon Traps, 100% of planned data were collected. However, methane data from the MN ANGB were rejected due to quality assurance (QA) problems in the field.
- For temperature and ORP, at TEAD-S, data set completeness (>99%) exceeded the performance objective of 95% completeness for planned measurement days for temperature measurements. At the MN ANGB, the data set completeness (72%) over the performance period was below the performance objective of 95% at the site level, and data set completeness was below 95% at four of five sensor locations. Since the performance objective was not met for temperature measurements at the MN ANGB, linear interpolation was used to estimate missing hourly measurements, and the likely effect of the data interpolation on calculated NSZD rates was assessed to determine whether failure to meet the performance objective meaningfully affected the validity of the NSZD results. These analyses and limitations associated with data gaps are discussed further in Section 6.2.4.

Performance Objectives 2 & 3: Improved Background Correction for Temperature-Based Monitoring of NSZD and Comparison between NSZD rates from temperature-based monitoring and other NSZD methods

To quantify NSZD rates, the increase in soil temperature attributable to petroleum biodegradation must be separated from other factors that affect the soil temperature. The primary driver of other heat sources is solar insolation, which leads to seasonal variations in soil temperature (i.e., summer warming and winter cooling), although other anthropogenic sources such as pipelines may also need to be considered. At the two demonstration sites, no apparent alternate sources of heat existed near the temperature monitoring locations. At TEAD-S, all buildings have been decommissioned, and there are no active facilities or utilities near the temperature monitoring locations. At the MN ANGB, based on underground utility diagrams provided by the facility, one location, background location BG-1, was located approximately 13 feet away from a water line (Figure 4.2), and it is unlikely that the underground water line impacts the subsurface temperature data at this location. Each of the other temperature monitoring stations were located at least 35 feet from the nearest utility line. For this demonstration, we have evaluated three methods for "background correction" (i.e., removing non-biodegradation-related heat sources): Annual Average Temperature Method (Method 1), Correction Using Background Location (Method 2), and the Single Stick Method (Method 3) (see Table ES.2).

Table ES.2. Comparison of Net NSZD Rates (gal/acre/yr)

Temperature Monitoring Station Location	Method 1 - Annual Temperature Method	Method 2 - Correction Using Background Location Method	Method 3 - Single Stick Method
TEAD-S			
L-1 (paved)	-90	-140	570
L-2 (paved)	170	180	1,320
L-3 (unpaved)	300	360	800
MN ANGB			
L-1 (unpaved)	630*	610*	850*
L-2 (paved)	2,060	2,060	3,090
L-3 (paved)	850	1,020	2,810

Note: NSZD rates rounded to the nearest 10

Absolute NSZD rates at each of the five locations at each demonstration site are shown in Table ES.3, and net NSZD rates for the three impacted locations are shown in Table ES.2. The background corrected method yielded NSZD rates closer to the annual average method than the Single Stick method. The Single Stick method consistently calculated higher NSZD rates than the other two methods, with larger differences at TEAD-S than the MN ANGB. However, the agreement in NSZD rates between the individual temperature-based methods and the other non-temperature-based alternative methods to estimate NSZD rates was more variable. Additional field demonstration is needed to determine which temperature-based method yields the most accurate estimates of NSZD rates across a larger number of sites.

Table ES.3. Absolute NSZD Rates (gal/acre/yr) for Carbon Trap Method and Qualitative Evidence of NSZD Based on Gas Gradients

Temperature Monitoring Station Location	NSZD Rate by Method 1 - Annual Temperature Method (gal/acre/year)	NSZD Rate by Method 2 - Background Location Method (gal/acre/year)	NSZD Rate by Method 3 - Single Stick Method (gal/acre/year)	NSZD Rate by Carbon Trap Method (gal/acre/year)	Evidence of NSZD Based on Soil Gas Gradients
TEAD-S					
L-1 (paved)	150	-140	370	295	Strong
L-2 (paved)	420	170	1,150	84	Medium
L-3 (unpaved)	640	360	1,080	1,105	Medium
BG-1 (paved)	250	NC	-200	Not Detectable	No Evidence of NSZD
BG-2 (unpaved)	370	NC	270	Not Detectable	No Evidence of NSZD
MN ANGB					
L-1 (unpaved)	1,220	610*	730	72	Weak
L-2 (paved)	2,710	2,060	3,180	1,856	Medium
L-3 (paved)	1,440	1,020	2,910	404	Medium
BG-1 (unpaved)*	570*	NC	-120*	129	Weak
BG-2 (paved)	610	NC	100	37	Weak

Note: * LNAPL observed in monitoring well at this intended background location
NC – net NSZD rate cannot be calculated with Method 2

Performance Objective 4: Demonstration of 2nd Generation Equipment

At the TEAD-S demonstration site, the 2nd-generation equipment performed as expected (>99% data recovery with no significant data gaps). At the MN ANGB demonstration site, however, the 2nd generation equipment at times failed to record temperature data throughout the demonstration period, resulting in data gaps and an incomplete temperature record. The equipment vendor, S3NSE Technologies, was unable to fully resolve the issues despite numerous attempts over the course of the demonstration. At both sites, the 2nd generation equipment was able to record temperatures at more than twice as many depths as the 1st generation equipment. Additional temperature data at these two demonstration sites improved the performance of the Method 3 Single Stick method, whereas the impact of using the 2nd generation equipment appears to be less for the Method 1 annual average and Method 2 background-correction methods. The soil gas analyses from the 2nd generation equipment soil gas sample ports were comparable to the result obtained from adjacent stand-alone soil gas sample points, and the ORP data provided a secondary line-of-evidence for the qualitative evaluation of NSZD at each site. The 2nd generation equipment provides additional sensors (i.e., soil gas, ORP) at less per sensor and total cost than the 1st generation equipment. In summary, if the equipment vendor is able to fully resolve the equipment data reliability issues, the 2nd generation equipment provides an improvement over the 1st generation equipment.

Performance Objective 5: Documentation of NSZD Below Paved Surfaces

At TEAD-S, while the soil gas profiles (see Section 5.7.1; Figures 5.5 and 5.6; Section 6.3.2) are consistent with the expected profiles and demonstrate the occurrence of NSZD below paved surfaces, the Method 1 average annual vertical temperature profiles at the paved locations at TEAD-S did not correspond to the average annual vertical temperature profiles expected for NSZD processes (i.e., no clear evidence of elevated soil temperatures in the subsurface at the impacted locations compared to the non-impacted background location). Likewise, the Method 2 background-corrected NSZD results were low (or negative), suggesting little to no NSZD, and the Carbon Trap results indicated low NSZD rates at the paved locations. In contrast, the Method 3 Single Stick method indicated measurable NSZD results notably higher than the rates indicated by the other methods. In summary, the weight of evidence suggests NSZD in paved areas at the first demonstration site, TEAD-S, but the NSZD rates appear to be lower than those at the unpaved location.

At the MN ANGB, in contrast, the two paved locations, L-2 and L-3, did show average annual vertical temperature profiles consistent with NSZD, and the calculated NSZD rates based on temperature-based monitoring methods and Carbon Traps at these locations supports the occurrence of NSZD beneath paved surfaces.

In addition, Smith et al. (2021) demonstrated the use of temperature-based methods beneath paved sites at a retail fuel station in Europe. Thus, the general theory and results from other published studies (e.g., Smith et al. 2021) provide further evidence that temperature-based methods are suitable for quantification of NSZD rates beneath paved surfaces, although additional field verification may be desirable to support the limited data to date.

Performance Objective 6: Compilation of NSZD Rates Across NSZD Monitoring Sites

The project demonstration included a data mining component to characterize rates of NSZD measured across a wide range of petroleum-contaminated sites. The goals of the data mining study were to i) characterize the range of site-wide average NSZD rates measured across a wide range of sites, ii) evaluate the impact of fuel type on NSZD rates, iii) evaluate the comparability of different methods to measure NSZD rates, and iv) characterize how NSZD rates vary at individual sites over a time scale of a few months to a few years.

At each site, the following data were compiled: i) general site location; ii) LNAPL fuel type; iii) measurement method, number of locations, and number of measurements per location; and iv) calculated sitewide average NSZD rate and the associated measurement method (i.e., Gradient Method, Carbon Traps, Dynamic Closed Chamber (DCC), or Thermal Monitoring). The resulting dataset showed average sitewide NSZD rates that ranged from 650 to 152,000 liters per hectare per year (L/ha/yr) (70 to 16,250 gallons per acre per year (gal/acre/yr)), with a median value of 9,540 L/ha/yr (1,020 gal/acre/yr).

No clear bias was observed between the four NSZD rate measurement methods. When comparing the different NSZD measurement methods applied to the same sites, the site-average NSZD rates differed by a median factor (i.e., ratio of faster rate to slower rate) of 2.1 times. Despite the variability from measurement methods, seasons, and time-scales, a reasonable estimate of the long-term NSZD rate (e.g., within a factor of 2 or 3) can be achieved at the majority of sites by: i) a single measurement method employed at 3-7 locations per site; and ii) spanning at least two semi-annual (fall and spring) or four seasonal measurements per location.

Additionally, based on a limited dataset of four sites, NSZD rates were typically higher during the summer and fall (when subsurface temperatures are highest) compared to winter and spring (when subsurface temperatures are lowest), which suggests that biodegradation rates are enhanced by low-level increases in temperature. This is discussed in various literature studies (Kulkarni et al. 2022b). As such, increasing the mean annual soil temperature with engineered methods could potentially increase the biodegradation rate at a site. Although NSZD rates vary across sites and over time at an individual site, the fuel type does not appear to be the primary factor explaining the observed differences in NSZD rates.

The findings of this study have recently been published in the journal Water Research. Additional citation information on this paper (Kulkarni et al. 2022b) is provided in Appendix F.

COST ASSESSMENT

Table ES.4 shows the estimated costs for installing temperature monitoring stations at a representative field site. It is assumed that five temperature monitoring stations are installed at relatively shallow depth (less than 20-25 feet below ground surface), that installation takes 4 10-hour days, and that the site is local (i.e., no travel expenses, lodging, per diem, etc.).

Comparable costs (2023) for Carbon Traps are approximately $2,500 per Carbon Trap. Assuming similar costs for project planning and preparation, data evaluation and reporting, and field program implementation (excluding the cost of the drilling subcontractor and equipment rental), the total cost for implementing five Carbon Traps for a one-time sampling event is approximately $24,000.

Each additional sampling event with Carbon Traps would be expected to cost approximately \$13,300 (assuming 2 days of field work for installation and retrieval). Thus, for sites requiring a one-time NSZD rate, Carbon Traps may be more cost effective, but for those sites requiring continuous monitoring over multiple sampling events or long-term monitoring over a period of years to decades, there are cost advantages to utilizing the temperature-based NSZD continuous monitoring technology.

Table ES.4. Estimated Cost for Installation of 5 Temperature Monitoring Stations at 1 Site

Cost Element	Cost Element	Units	Cost Per Unit	Estimated Cost
Project planning and preparation	Senior Project Scientist/Engineer,	8 hours	\$200	\$1,600
	Project Scientist/Engineer	24 hours	\$125	\$3,000
Hardware procurement	Temperature Monitoring Stations	5 units per site	\$8,000	\$40,000
Field Program Implementation	Labor hours: Senior Project Scientist/Engineer	4 hours	\$200	\$800
	Labor hours: Project Scientist/Engineer	40 hours	\$125	\$5,000
	Drilling Subcontractor	1 per site	\$20,000	\$20,000
	Supplies	1 per site	\$50	\$50
	Equipment Rental, Supplies, Shipping	4 days	\$220	\$880
Data evaluation and reporting	Senior Project Scientist/Engineer,	8 hours	\$200	\$1,600
	Project Scientist/Engineer	16 hours	\$125	\$2,000
			TOTAL	**\$74,930**

IMPLEMENTATION ISSUES

There are no widespread barriers to the implementation of temperature-based methods. Further guidance on NSZD methods, and the temperature-based (thermal or biogenic heat) methods specifically, is available in various guidance documents, including API (2017), ITRC (2018), Cooperative Research Center for Contamination Assessment and Remediation of the Environment (CRCCare) (2018), and CL:AIRE (2019). In addition, temperature-based methods and their application are described in the recently published ASTM guidance document (E3361-22) on NSZD.

To our knowledge, there are no current regulations or permits that are required to implement the technology as a monitoring technology, although site-specific application and use of the NSZD data should be considered within the larger site conceptual model and in consultation with any applicable State or Federal regulators. While reluctance to implement natural remedies that rely on NSZD remains among some regulators, other regulatory bodies have included the qualitative evaluation of NSZD when considering whether site closure is acceptable even with LNAPL remaining in-place (e.g., VA 2012; WV 2019). The continual advancement of guidance documents such as ITRC (2018) and ASTM E3361-22 (2022) provides the fundamental scientific basis for NSZD and accepted measurement methods. A continuing body of evidence reviewed during this project, including that collected at the two demonstration sites, indicates that NSZD has been measured at all sites in the literature (Kulkarni et al. 2022b; Appendix F).

The 2nd generation monitoring sensors and communication equipment can be procured from S3NSE Technologies as newly commercialized, custom-built equipment. Colorado State University Research Foundation (CSURF) currently owns the patent (Sale et al. 2015; US Patent No. 10,094,719) for devices and methods for measuring the thermal flux and estimating the NSZD rate, which GSI has exclusively sublicensed.

1.0 INTRODUCTION

1.1 BACKGROUND

Many Department of Defense (DoD) sites are affected by historical releases of light non-aqueous phase liquids (LNAPL), including fuels, lubricants, and heating oil. Traditionally, costly active treatment technologies (e.g., hydraulic LNAPL recovery, air sparging, multi-phase extraction, soil vapor extraction (SVE), etc.) have been applied as the presumptive remedy for most LNAPL sites. Except for complete excavation, none of these in-situ remediation technologies have been able to remove all the LNAPL. Today, natural source zone depletion (NSZD) is gaining broad acceptance as a viable and cost-effective remedy for mature LNAPL releases (e.g., Sale et al. 2018; ITRC 2018; ASTM E3361-22 2022). Key factors supporting NSZD-based remedies include natural LNAPL depletion rates that may exceed what can be achieved with active remedies, greater sustainability, and reduced costs.

NSZD has the potential to be an effective and relatively low-cost passive remedy for LNAPL source zones. Garg et al. (2017) present an overview of the research and key processes controlling NSZD. The advancement of LNAPL NSZD is analogous to monitored natural attenuation (MNA) technologies to address dissolved phase contaminant plumes in groundwater. Regulatory acceptance of NSZD is reflected in the Interstate Technology and Regulatory Council (ITRC) guidance documents *Evaluating Natural Source Zone Depletion at Sites with LNAPL* (ITRC 2009) and *LNAPL Site Management: LCSM Evolution, Decision Process, and Remedial Technologies* (ITRC 2018). Additional international guidance on NSZD has been provided in Australia (CRCCare 2018) and the United Kingdom (CL:AIRE 2019), as well as a recently published ASTM standard on NSZD (ASTM E3361-22 2022).

At many active remediation sites, indirect evidence suggested that NSZD was more effective for source removal than the existing active remedies; however, the volume of LNAPL being removed from the source area due to NSZD was difficult to quantify. In recent years, Gradient (ITRC 2009), Dynamic Closed Chamber (DCC) (Sihota et al. 2011), and Carbon Trap (McCoy et al. 2015) methods have been developed to quantify NSZD rates based on tracking the consumption of oxygen (O_2) and/or the generation of carbon dioxide (CO_2) associated with biological degradation of petroleum (American Petroleum Institute [API] 2017; ITRC 2018; ASTM E3361-22 2022). These approaches have documented LNAPL removal rates of 100s to 1,000s of gallons of LNAPL per acre per year (McCoy et al. 2015; Garg et al. 2017). Despite this progress, these methods exhibit low precision (i.e., the estimated NSZD rates are uncertain), and the technologies are difficult to apply to some LNAPL sources areas, such as those located below paved surfaces. A promising approach to measuring LNAPL NSZD is real time monitoring of subsurface temperatures to resolve NSZD rates (e.g., Sale 2015; Warren and Bekins 2015; Karimi Askarani et al. 2018; Karimi Askarani and Sale 2020; Kulkarni et al. 2020), as the bacterial degradation of LNAPL in the subsurface generates heat (similar to a compost pile).

The overall objective of this project was to further demonstrate the application of temperature-based monitoring to quantify NSZD rates for petroleum LNAPL source areas, including NSZD in new settings. It was also hypothesized that temperature-based monitoring of NSZD using continuous-monitoring temperature sensors provides a more accurate quantification of NSZD compared with the alternative available methods of measuring carbon dioxide gradients or fluxes.

For example, Kulkarni et al. (2020) demonstrated that a side-by-side field comparison of four NSZD measurement methods at a California refinery showed that the DCC and Carbon Trap methods had much more variability when compared with the temperature-based method that continuously recorded NSZD rates. Benefits of temperature-based over Carbon Trap methods were also presented in Karimi Askarani et al. (2018). This project was designed to provide new knowledge about the advantages and disadvantages of temperature-based NSZD measurement technology and to determine if it can be applied at NSZD sites with paved surfaces.

1.2 OBJECTIVE OF THE DEMONSTRATION

This project sought to demonstrate that temperature-based quantification of NSZD rates:

Provide Continuous Measurement of NSZD Rates: Existing technologies for measuring NSZD rates rely on one-time (or short-term) snapshots of the NSZD rates (on the order of minutes to approximately 2-5 weeks). By continuously recording temperatures at the LNAPL source area, the on-going NSZD processes can be documented and quantified, enhancing the regulatory acceptance of the technology. In addition, continuous monitoring can be used to document seasonal variations in NSZD rates and gain an improved understanding of how changes in site conditions affect NSZD rates.

Permit Monitoring of NSZD Below Paved Surfaces: Many DoD facilities with hydrocarbon LNAPL issues are covered with impermeable surfaces (e.g., parking lots, repair buildings and facilities, tarmacs, etc.). Although current DoD efforts have utilized Carbon Traps to try to measure NSZD rates (ESTCP Project ER-201582), Carbon Traps are not suitable for deployment inside buildings or on paved surfaces because Carbon Traps may not obtain a representative measurement of CO_2 flux when installed on top of or through a paved surface. In contrast, temperature-based monitoring directly measures the heat generated by petroleum biodegradation, and the temperature sensors can be installed through either open ground or paved surfaces (including building foundations).

Reduce Treatment and Monitoring Cost: At many sites, active treatment of LNAPL reaches a point of diminishing returns, especially once LNAPL transmissivity declines as a result of active treatment. At this point, the volume of LNAPL destroyed by NSZD can be an order of magnitude higher than the volume removed with low efficiency, late-stage existing active systems. Accurate quantification of NSZD rates supports significant cost savings at these sites by transitioning from the current active technology to a passive technology that verifies LNAPL destruction quantitatively on a continuous basis. In addition, automated uploads and processing of the temperature-based monitoring data allow for low-cost long-term monitoring.

1.3 REGULATORY DRIVERS

Many state and federal contaminated site remediation programs require removal or treatment of LNAPL source areas. For example, regulations require removal of LNAPL at sites with a measurable thickness of LNAPL in site monitoring wells (e.g., Florida, Iowa, North Carolina, Virginia; Naval Facilities Engineering Systems Command [NAVFAC] 2017). In addition, some regulatory programs require that site clean-up objectives be achieved within “a reasonable timeframe” (e.g., Texas Commission on Environmental Quality [TCEQ], 2008).

This timeframe may vary based on site-specific factors but in some cases can be for long periods of time such as the likely operating timeframe of a particular facility. Historically, the inability to quantify the source removal rates associated with NSZD have made it difficult to evaluate whether NSZD can be applied as a remediation technology to achieve these regulatory requirements.

This project demonstrated temperature-based monitoring as a cost-effective technology for monitoring NSZD and quantifying NSZD rates. In addition, the demonstration documented the occurrence of NSZD in LNAPL source areas located below paved surfaces. For the DoD, the ability to quantify NSZD rates in LNAPL source areas across a broad range of environmental settings will support the selection of NSZD as a cost-effective technology capable of satisfying regulatory requirements for removal of LNAPL from LNAPL source areas.

2.0 TECHNOLOGY

Similar to the natural attenuation of dissolved petroleum constituents in groundwater, the current LNAPL conceptual model is that biologically-mediated NSZD occurs at ALL sites monitored to date where petroleum LNAPL source areas are present in the subsurface.

The overall objective of this project was to demonstrate the use of temperature-based methods (i.e., thermal or biogenic heat methods) to accurately measure NSZD rates (i.e., gallons of LNAPL degraded per acre per year) in LNAPL source areas.

2.1 TECHNOLOGY DESCRIPTION

Consistent with the first law of thermodynamics (conservation of energy), the biological degradation of petroleum in the subsurface generates the same amount of heat per volume of petroleum degraded as combustion of petroleum (for example, combustion of petroleum in an oil furnace used for home heating). At remediation sites, heat from oxidation of hydrocarbons allows use of innovative temperature-based methods to quantify biologically-mediated depletion of LNAPL in the subsurface. The break-through method for the conversion of generated heat to NSZD rates is based on thermodynamics. Methods were originally developed by Colorado State University (Stockwell 2015; Karimi Askarani et al. 2018). Based on monitoring done at multiple sites (e.g., Sweeney and Ririe 2014; Warren and Bekins 2015), soil and groundwater temperatures within LNAPL source areas are commonly observed to be 1˚C to 3˚C above the temperatures at matched background locations. NSZD-related temperature differences can be readily measured with available temperature sensors (e.g., thermocouples with a stated accuracy of +/- 0.1˚C, and resolution of 0.01˚C).

The application of temperature-based monitoring to determine NSZD rates uses multiple vertically-spaced temperature sensors (e.g., thermocouples) installed in the LNAPL impacted area (and at least one non-impacted (i.e., background) location for background-based methods). A "background-correction" step is required to separate the biogenic heat signal produced by NSZD processes from other sources of heat to the subsurface (e.g., solar heating and cooling, pipelines, etc.). The background-corrected vertical temperature profile is used to determine the upward and downward temperature gradients, which, in turn, are used to calculate the heat flux, which corresponds to the amount of heat being generated from the biodegradation. Based on the amount of heat energy produced from NSZD according to the thermodynamics of petroleum combustion/degradation, the volume of petroleum being degraded per area per unit time (i.e., the NSZD rate) is calculated. Within the United States, NSZD rates are commonly expressed in units of gallons of petroleum degraded per acre per year. Quantification of the NSZD rate allows the mass of petroleum removed by NSZD to be compared to that removed by other remedies.

First-generation temperature monitoring equipment used by GSI Environmental Inc. (GSI) and Colorado State University (CSU) during early field deployments included commercially-available thermocouples, dataloggers, modems, and solar panels. This demonstration used novel second generation (2nd generation) temperature monitoring systems developed by CSU, which are now available commercially by S3NSE Technologies. These 2nd generation systems rely on cheaper Internet-of-Things (IoT) sensors connected in-line to IoT dataloggers and cellular modems. By utilizing the IoT sensors, which are available at a lower cost than the first-generation approach, approximately twice as many vertical temperature sensors at each location can be installed, as well as sensors such as oxidation-reduction potential (ORP) sensors fabricated by S3NSE.

2.2 TECHNOLOGY DEVELOPMENT

The temperature-based Thermal NSZD technology was developed jointly by CSU and GSI, as described in Sale et al. 2015 (U.S. Patent No. 10,094,719). Complementary information is presented in Sale et al. (2018), Stockwell (2015), Karimi Askarani et al. (2018), and Kulkarni et al. (2020).

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Three primary methods have been developed to quantify NSZD rates in LNAPL source areas: i) vadose zone oxygen/methane gradient, ii) CO_2 flux, including both Dynamic Closed Chamber (DCC) methods and passive CO_2 flux traps (i.e., Carbon Traps), and iii) temperature-based monitoring, sometimes referred to as the biogenic heat method, thermal method, or Thermal NSZD (e.g., API 2017; ITRC 2018; CRCCare 2018; ASTM E3361-22 2022). Temperature-based monitoring, the technology being demonstrated for this project, has several potential advantages over the other two methods.

2.3.1 Advantages of Temperature-Based Monitoring

Provide Continuous Measurement of NSZD Rates: The gradient and CO_2 flux methods to quantify NSZD rates rely on one-time (or short-term) snapshots of the NSZD rates (on the order of minutes to approximately 2-5 weeks). By continuously recording temperatures at the LNAPL source area, the on-going NSZD processes can be continuously documented and quantified, enhancing the regulatory acceptance of the technology. In addition, continuous monitoring can be used to document seasonal variations in NSZD rates and gain an improved understanding of how changes in site conditions affect NSZD rates.

Application to LNAPL Sources Below Paved Surfaces: Paved surfaces are unlikely to inhibit NSZD because paved surfaces rarely act as significant barriers to oxygen entry into the subsurface (Fischer et al. 1996; McHugh et al. 2006; Lundegard et al. 2008). However, both the gradient method and the CO_2 flux methods for quantification of NSZD rates were originally designed for deployment in uniformly permeable ground cover so that the movement of carbon dioxide (and other gases) between the aerobic oxidation zone and the ground surface can be approximated as 1-dimensional diffusion. With paved surfaces, gas exchange between the atmosphere and the subsurface does occur but is most commonly dominated by advection and/or diffusion through preferential pathways, such as cracks and expansion joints (i.e., transport processes are much more complex than 1-D diffusion). Although O_2, CO_2, methane (CH_4) (and other gas) concentrations can be measured in soils below paved surfaces, it is more difficult to accurately determine NSZD rates based on either the gradient method or the carbon flux method because the required conditions of 1-D transport are not applicable (Smith et al. 2021).

In contrast, the temperature method for quantification of NSZD is uniquely suited to application at LNAPL source areas located below paved surfaces. Even though the paved surfaces modify the flow pathways for oxygen and carbon dioxide (e.g., flow through cracks), the heat gradients are not disrupted by the presence of paved surfaces above the LNAPL source area (i.e., heat is conducted through the paved surface so that heat flux can be evaluated assuming 1-D transport).

Reduce Treatment and Monitoring Cost: At many sites, active treatment of LNAPL reaches a point of diminishing returns. At this stage, the volume of LNAPL destroyed by NSZD can be an order of magnitude higher than the volume removed with low efficiency, late-stage existing active systems. Accurate quantification of NSZD rates supports significant cost savings at these sites by transitioning from the current active technology to a passive technology that verifies LNAPL destruction quantitatively on a continuous basis. In addition, given automated data uploads and data processing, temperature-based monitoring of NSZD allows low-cost long-term monitoring.

2.3.2 Limitations of Temperature-Based Monitoring

Equipment Costs: The continuous temperature-based monitoring of NSZD requires installation of permanent subsurface monitoring equipment at the site. As a result, the upfront cost of this method is higher than a single round of field measurements for the gradient or CO_2 flux methods. For example, equipment and installation of 1st generation equipment at four monitoring locations and one background location costs \$40,000 to \$50,000. In contrast, a single round of gradient or CO_2 flux measurements at a site typically costs \$10,000 to \$15,000. Thus, while gradient or CO_2 flux methods to quantify NSZD rates may be more cost effective at sites where a one-time ballpark evaluation of NSZD rates is sufficient, the proposed 2nd generation equipment has been developed to provide data for lower cost per data point than 1st generation equipment where continuous measurements are desirable. See Section 7 for a detailed analysis of equipment costs of 2nd generation equipment.

Quantification of NSZD Rates: In areas where NSZD is occurring, soil temperature is affected by two sources of heat: i) surface heating and cooling associated with daily and seasonal variations in solar heating and ii) heat generated in the subsurface as a result of biodegradation of LNAPL (i.e., NSZD). Accurate quantification of NSZD rates requires a method to separate these two heat sources in order to accurately determine the heat associated with NSZD. This study has evaluated three methods for separating heat associated with NSZD from surface heating and cooling.

3.0 PERFORMANCE OBJECTIVES

The overall objective of this project was to demonstrate the use of temperature-based methods to accurately measure NSZD rates (i.e., gallons of LNAPL degraded per acre per year) in LNAPL source areas. The basic application of temperature-based methods to quantify NSZD rates has already been validated through laboratory and field testing sponsored by industry partners (e.g., Karimi Askarani et al. 2018). This demonstration improves and expands the validation of temperature-based monitoring of NSZD, resulting in increased regulatory acceptance and reduced cost for application as a site remedy. The specific objectives of this demonstration program were to:

- Demonstrate the use of second-generation temperature monitoring systems to improve data quality and reduce costs;
- Demonstrate improved methods to separate the heat signal associated with biodegradation of petroleum from other heat sources, including surficial heating and cooling, as well as other sources of temperature fluctuations in soils (i.e., improved "background correction");
- Demonstrate (through field deployment) that temperature-based approaches to quantifying NSZD rates are particularly suited for LNAPL source areas located below paved surfaces; and
- In addition to the field demonstration, compile results from application of NSZD monitoring, using a variety of methods, at additional sites and utilize these results to i) document the range of NSZD rates observed and ii) identify site factors that may be predictive of higher or lower NSZD rates at individual sites.

The successful demonstration of temperature-based monitoring to quantify NSZD rates provides an additional tool for quantification of NSZD in LNAPL source areas that is more accurate, more informative, and more widely applicable than methods focused on measuring vadose zone concentration gradients or CO_2 flux, such as Carbon Traps or DCC methods.

The specific objectives and success criteria are summarized in Table 3.1 and discussed in more detail below.

Table 3.1. Performance Objectives for Temperature-Based Monitoring of NSZD Demonstration

Performance Objective	Data Requirements	Success Criteria
Quantitative Performance Objectives		
1. Collection of a complete dataset.	• For each of the two demonstration sites, collection of the samples required to determine i) the NSZD rate using the temperature-based method and ii) the NSZD rate using the alternative method.	• Temperature measurements for >95% of planned measurement locations/days. • >90% of planned alternative measurements.
2. Improved background correction for temperature-based monitoring of NSZD.	• More detailed temperature dataset obtained using 2nd generation equipment. • Newly developed background correction algorithms.	• Attainment of more stable background-corrected temperature gradients and NSZD rates compared to 1st generation methods. • More accurate short-term (weekly to monthly) NSZD rates compared to 1st generation methods.
3. Comparison between NSZD rates from temperature-based monitoring and other NSZD methods.	• Temperature gradient measurements and supporting NSZD rate calculations. • NSZD rate calculations based on CO_2 flux and/or CO_2 gradient measurements.	• Comparability of NSZD rates for temperature method and alternative method. Agreement between methods within a factor of 2X (or evidence that temperature-based monitoring method is more accurate based on, for example, lower spatial and temporal variability).
4. Demonstration of 2nd generation equipment and methods for temperature-based monitoring of NSZD.	• Temperature gradient measurements collected using 2nd generation equipment. • Documentation of equipment costs.	• Lower costs compared to 1st generation equipment. • More detailed vertical temperature dataset compared to 1st generation equipment.
Qualitative Performance Objectives		
5. Documentation of NSZD in LNAPL Source Zones Below Pavement.	• Temperature gradient measurements for LNAPL source area below pavement. • Supporting data: methane/carbon dioxide/oxygen concentrations.	• Temperature profile consistent with NSZD. • Methane/carbon dioxide/oxygen distribution consistent with NSZD.
6. Compilation of NSZD rates across a range of NSZD monitoring sites.	• NSZD monitoring results for sites studied by GSI, CSU, and other parties. • Site characteristics (temperature, soil type, moisture) that may be associated with differences in NSZD rates.	• Documentation of typical range of NSZD rates across sites. • Identification of site factors predictive of higher or lower NSZD rates.

3.1 PERFORMANCE OBJECTIVE 1: ATTAINMENT OF A COMPLETE DATASET

A complete data set that supports validation of the temperature-based monitoring method to quantify NSZD was obtained by ensuring (to the degree feasible) that all planned data measurements were recorded, and all planned samples were collected and analyzed.

3.1.1 Data Requirements

Two field demonstrations were conducted. At each of the two demonstration sites, temperature-based monitoring was conducted at three locations within the LNAPL source zone (2 paved, 1 unpaved) and at two background locations (1 paved, 1 unpaved). This allowed for the calculation of NSZD rates at each of the three impacted locations at each site (2 paved, 1 unpaved), as well as comparison to background. Each temperature monitoring location consisted of 16-19 vertically-spaced temperature sensors (approximately one per foot spacing; deeper sensors were spaced 2 ft apart), resulting in a total of 176 temperature measurement points (i.e., approximately 16-19 sensors points x five locations x two sites; 86 sensors at the Minnesota Air Natural Guard Base (MN ANGB) and 90 sensors at Tooele Army Depot South (TEAD-S)). At each measurement location, daily average temperatures were recorded over an 18-month monitoring period, resulting in a minimum of 95,040 individual daily average temperature measurements collected during the demonstration period at both sites (i.e., 176 sensor locations x 540 days).

Two alternative measurements were collected at each location with the CO_2 flux method (i.e., Carbon Traps) and/or the gradient method to provide a qualitative and/or semi-quantitative demonstration that NSZD is occurring at both paved and unpaved locations. First, five Carbon Traps were deployed at each site at the beginning of the Demonstration Period, with one Carbon Trap adjacent to each temperature monitoring station. Second, five subsurface vapor sampling locations were installed at each site, with one sampling location adjacent to each temperature monitoring station. At each vapor sampling location, four individual vapor sampling points were installed in a dedicated borehole to measure the vertical profile of CO_2, O_2, and CH_4 with a landfill gas analyzer (e.g., GEM 5000). In addition, up to five vapor sampling points were installed within the same borehole as the temperature monitoring stations at three of five locations at each of the two field demonstration sites.

3.1.2 Success Criteria

Logging of >95% of planned temperature measurements and collection and analysis of >90% of the planned alternative measurement methods.

3.2 PERFORMANCE OBJECTIVE 2: IMPROVED BACKGROUND CORRECTION

To quantify NSZD rates, the increase in soil temperature attributable to petroleum biodegradation needs to be separated from other factors that affect the soil temperature, such as seasonal heating and cooling of the soil. This separation yields a background-corrected vertical temperature profile (i.e., a profile with non-biodegradation heat sources removed). In the absence of LNAPL biodegradation or other anthropogenic sources of heat (e.g., pipelines), vertical soil temperature profiles are primarily a function of ground surface heating and cooling.

The background correction method that is typically applied involves subtracting subsurface temperatures at fixed depths at a background location (no LNAPL present) from subsurface temperatures at the same depths in LNAPL-impacted areas. This background correction method can result in errors when the factors influencing soil temperature are different between the background temperature measurement location and the measurement locations within the LNAPL area.

In particular, differences in ground cover between locations (e.g., pavement, vegetation, bare soil) and differences in soil properties can affect soil temperature and lead to anomalous high and low estimates of NSZD rates. However, the effects of these differences on soil temperatures are less pronounced with depth, and in general, errors in background correction (and the resulting anomalous NSZD rates) tend to average out over extended monitoring periods (i.e., several months to one year).

This demonstration evaluated two improved background correction methods: i) an improved method for utilizing the background location temperature measurements to obtain a background corrected temperature profile, and ii) a new "Single Stick" mathematical method (i.e., without measured background temperatures) developed by CSU (Karimi Askarani et al. 2020) where the effect of heat sources unrelated to biodegradation are removed using a mathematical procedure that does not require measurements from representative unimpacted background locations.

3.2.1 Data Requirements

Collection of a complete temperature measurement dataset described in Section 3.1.1 above.

3.2.2 Success Criteria

The two improved background correction methods were evaluated against the 1st generation method as follows:

Stability: The improved background correction methods were considered more stable if the monthly NSZD rates calculated using the improved background correction methods showed lower variability (i.e., lower standard deviation) compared to the 1st generation background correction method.

Accuracy: NSZD rates calculated using an average annual temperature from a full year of monitoring data do not require background correction because average annual soil temperatures are not impacted by seasonal ground surface heating and cooling (i.e., the summer heating and winter cooling cancel out in the annual average). The improved background correction methods were considered more accurate if the 1-year average NSZD rates calculated with the improved background correction methods were in better agreement with average annual NSZD rates when compared to the 1-year average of NSZD rates calculated with the 1st generation background correction method.

3.3 PERFORMANCE OBJECTIVE 3: DETERMINATION OF NSZD RATES

The basic application of temperature-based methods to quantify NSZD rates has already been validated through laboratory and field testing sponsored by industry partners (e.g., Karimi Askarani et al. 2018). For example, Kulkarni et al. (2020) compared data from Thermal NSZD, Carbon Traps, and CO_2 efflux [DCC/LiCor] measurements at a site in the southwestern United States and concluded that, at this particular site, temperature-based NSZD methods were more reliable than the Carbon Trap and DCC measurements. Thus, the validation of the temperature-based monitoring method against the alternative methods of CO_2 flux and vadose zone gradient was not a primary objective of this demonstration. As explained previously, at NSZD sites, CO_2 flux measurements exhibit significant spatial and temporal variability, sometimes an order of magnitude or more.

This variability is likely attributable to short-term weather-related variations in methane flux from the LNAPL source zone and/or CO_2 flux to the ground surface rather than spatial or temporal variations in the underlying NSZD processes (Garg et al. 2017). Due to the inherent variability in CO_2 flux measurements, a large number of CO_2 flux measurements would be required at each demonstration site in order to demonstrate close agreement to the temperature-based method NSZD rates. Because the basic temperature-based monitoring method has already been validated against the CO_2 flux method at several sites (e.g., Kulkarni et al. 2020), a data rich, high resolution validation of the basic method at these demonstration sites would do little to advance the overall validation of the technology. Instead, a limited set of comparison measurements were collected at each of the two demonstration sites to evaluate whether the methods yield roughly comparable results at these sites.

3.3.1 Data Requirements

Comparison of NSZD rates measured using the temperature-based method and an alternative method requires collection of the measurements described in Section 3.1.1 above.

3.3.2 Success Criteria

At each demonstration site, the average annual temperature-based method NSZD rate across the three measurement locations were considered accurate if: i) the temperature-based method NSZD rate matches the NSZD rate from the alternative Carbon Trap method within a factor of 2x OR ii) the range of NSZD rates determined using the temperature-based method overlaps with the range determined using the alternative methods but the results using the alternative methods are more variable (indicating a larger uncertainty in the average rate determined for the site).

3.4 PERFORMANCE OBJECTIVE 4: DEMONSTRATION OF 2ND GENERATION EQUIPMENT

The 2nd generation temperature sensors support continuous temperature measurement at up to 20 vertical depths at each location, compared with eight depths typical for 1st generation sensors, thus providing a more comprehensive temperature profile than the 1st generation sensors. The higher vertical resolution temperature data from digital temperature sensors compared with the conventional thermocouples in 1st generation equipment support the application of alternative computational methods to more accurately separate biologically-generated NSZD heat from seasonal heating and cooling (i.e., improved background correction). Simplified wiring supported by the 2nd generation sensors compared with the 1st generation sensors made fabrication and installation of 2nd generation equipment faster and easier than 1st generation equipment at the field site.

The demonstration of increased data density and lower cost was completed by comparing the data density and cost for the two demonstration sites against the historical performance and cost for the 1st generation equipment, which has been documented at a number of temperature monitoring sites (e.g., Kulkarni et al. 2020). The accuracy and resolution of the 2nd generation equipment are based on manufacturer specifications (see Appendix C.1).

3.4.1 Data Requirements

Collection of a complete temperature measurement dataset described in Section 3.1.1 above and documentation of equipment costs.

3.4.2 Success Criteria

Attainment of at least 50% more temperature data at each location (i.e., at least 12 depth intervals) and a 20% or greater reduction in equipment costs per temperature monitoring station.

3.5 PERFORMANCE OBJECTIVE 5: DOCUMENTATION OF NSZD BELOW PAVED SURFACES

The alternative methods for quantification of NSZD (i.e., CO_2 flux and the gradient method) are not suitable for application below paved surfaces because the presence of pavement disrupts the 1-D diffusion of oxygen and carbon dioxide in the vadose zone. While the overall vertical profile should be useful for a qualitative evaluation of the occurrence of NSZD, the violation of the 1-D diffusion assumption and the potential for channelization of vapor flow through openings in the pavement introduce additional uncertainty into the quantification of NSZD rates with these methods. The demonstration of the temperature methods below paved surfaces expands the range of sites where NSZD rates can be quantified.

3.5.1 Data Requirements

Collection of a complete temperature measurement dataset and alternative method measurements described in Section 3.1.1 above for monitoring locations below paved surfaces.

3.5.2 Success Criteria

For the monitoring locations below paved surfaces, the occurrence of NSZD was demonstrated by the attainment of vertical temperature profiles indicative of NSZD and oxygen, carbon dioxide, and methane distributions consistent with biodegradation (i.e., oxygen decreases with depth, carbon dioxide and methane increase with depth).

3.6 PERFORMANCE OBJECTIVE 6: COMPILATION OF NSZD RATES ACROSS NSZD MONITORING SITES

In the 1990s, a number of multiple site studies for groundwater plumes (informally called "plume-a-thon" studies) demonstrated the universality of natural attenuation as a technology for the containment and remediation of dissolved petroleum plumes. These published studies dramatically increased the regulatory acceptance of natural attenuation in groundwater. Today, a similar compilation of NSZD studies has the potential to demonstrate the broad applicability of this technology for treatment of LNAPL sources.

3.6.1 Data Requirements

NSZD rates from the published literature, as well as sites studied by GSI Environmental Inc. (GSI), CSU, and other parties willing to share rates.

3.6.2 Success Criteria

Documentation of the typical range of NSZD rates across sites and identification of site factors predictive of higher or lower NSZD rates.

4.0 SITE DESCRIPTION

4.1 SITE 1: SWMU-13, TOOELE ARMY DEPOT

Solid Waste Management Unit (SWMU) 13, located at Tooele Army Depot – South (TEAD-S) in Tooele County, Utah, was selected as a demonstration site based on the selection criteria documented below.

4.1.1 Site Location and History

TEAD-S was originally developed as Deseret Chemical Depot in 1942 to store, renovate, and dispose of a wide array of chemical munitions. SWMU-13 is located in the southwestern quadrant of TEAD-S and includes the former Chemical Agent Munitions Demilitarization System, which was closed in 2005. Sometime between 1980 and 1985, an underground diesel fuel line released an estimated 38,000 gallons of fuel over an undetermined period of time.

In 2017 and 2018, three LNAPL recovery interceptor trenches with 14 sumps and 8 skimmer pumps were installed to remove LNAPL. However, due to hydrogeological conditions at the site, recovery was minimal (165 gallons over 100 days), with an estimated time to clean up exceeding 200 years with this technology. The Utah Department of Environmental Quality accepted a determination of Technical Impracticability (TI) in August 2019 due to the performance of the interceptor trenches and approved an alternative remediation strategy of long-term monitoring and land use controls.

4.1.2 Site Geology/Hydrogeology

SWMU-13 is located within Rush Valley, part of the Great Basin section of the Basin and Range Physiographic Province. The TEAD-S facility is underlain by basin-fill sediments derived from alluvial and lacustrine processes, and the sediments underneath SWMU-13 were predominantly deposited by Lake Bonneville. The shallow subsurface at the demonstration location consists of an apparently continuous sandy silt/silty sand layer from the surface to approximately 8-14 feet below ground surface (bgs), which is underlain with a continuous clay layer with intermittent sandy silt lenses to a depth of approximately 55 feet bgs or deeper.

Historical depths to water range from 10-13 feet bgs. Groundwater underneath this portion of the facility flows southwest to south, with a typical groundwater gradient of approximately 0.001 foot/foot.

The climate is semi-arid, with the majority of precipitation falling during the winter and early spring as snowfall.

4.1.3 Contaminant Distribution

Figure 4.1 depicts site features and the approximate extent of free product, as reported in April 2019. While there are some differences at the low end of LNAPL thickness (i.e., less than 0.1-foot product thickness), the overall shape of the LNAPL distribution has remained consistent since at least 2014. This figure shows the location of active monitoring wells and the interceptor trenches.

Figure 4.1 also shows the monitoring locations where the monitoring equipment for the demonstration was installed. At this demonstration site, all buildings have been decommissioned, and there are no active facilities or utilities near the temperature monitoring locations.

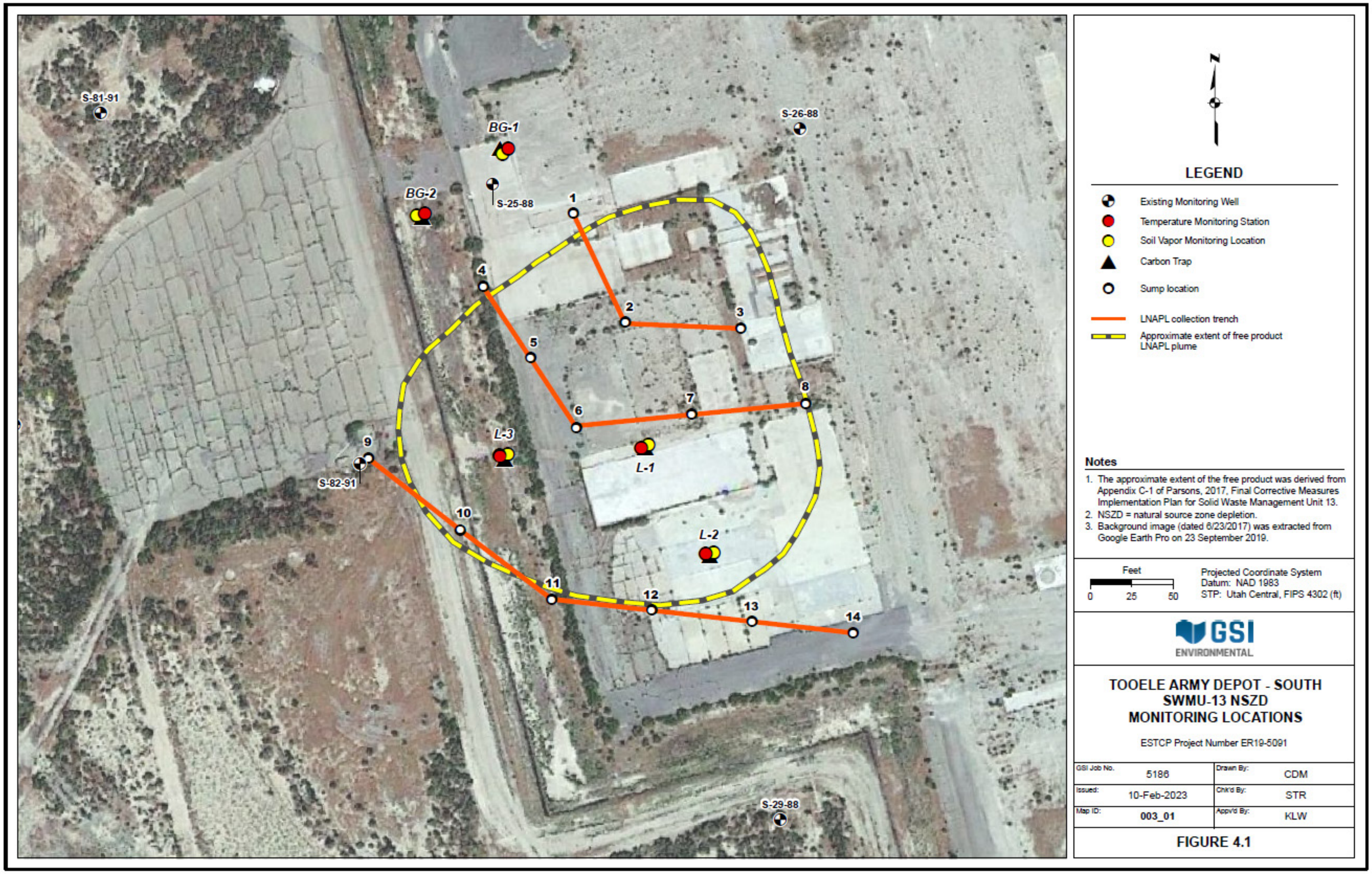


Figure 4.1. Tooele Army Depot TEAD-S SWMU-13 NSZD Monitoring Locations.

4.2 SITE 2: AOC ZZ013, MINNESOTA AIR NATIONAL GUARD BASE

Area of Concern (AOC) ZZ013, located at the Minnesota Air National Guard Base (MN ANGB), Minneapolis, MN, was selected as a demonstration site based on the selection criteria documented below.

4.2.1 Site Location and History

The 133rd Airlift Wing (AW) of the Minnesota Air National Guard (MN ANG) is located north of Minneapolis St. Paul International Airport, approximately 7.5 miles from downtown St. Paul, Minnesota. The 133rd AW is situated on approximately 125 acres within the historic Fort Snelling Military Reservation. The 133rd AW of MN ANG has been present at this location since 1951.

Area of Concern (AOC) ZZ013 is to the north of Building 664 (an open vehicle and equipment shed) and west of the Motor Pool (Building 662) (see Figure 4.2). The Motor Pool (Building 662) is upgradient of the AOC and consisted of multiple potential contamination sources, including a 10,000-gallon gasoline underground storage tank (UST), a 10,000-gallon diesel UST, a 560-gallon waste oil UST, and a 560-gallon oil/water separator (OWS) near the Refueler Bay. The 560-gal OWS was removed in May 1994, and the USTs were removed in 1987/88. No clean closure documentation has been located for these tanks.

Evidence of an LNAPL release in the area was provided through investigation field activities conducted in 2014. Site investigation and delineation activities are on-going.

4.2.2 Site Geology/Hydrogeology

The regional geology of Minneapolis-St. Paul is characterized by a thick sequence of sedimentary bedrock units overlain by unconsolidated glacial deposits and more recent alluvium. Early Paleozoic marine sedimentary rocks form the uppermost bedrock in a unique local geologic structure referred to as the Twin Cities Basin.

Soil in the immediate vicinity of the Base is classified as Dorset sandy loam (D4A, D4B). The Dorset sandy loam is described as well-drained soil on outwash plains. The depth to bedrock is generally greater than 6 feet, with an average depth of approximately 15 feet bgs in the vicinity of AOC ZZ013. Groundwater at the MN ANGB occurs in upper terrace deposits approximately 10 to 15 feet bgs. In general, the groundwater flow direction is toward the north and west at the base, but the localized groundwater flow direction varies.

4.2.3 Contaminant Distribution

The full extent of the LNAPL body has not been identified to date due to the recent discovery of the LNAPL plume. However, existing monitoring locations permit an estimate of the outline, and temperature monitoring stations were placed within the previously defined extent of LNAPL. Figure 4.2 shows the assumed extent of LNAPL at this facility. Based on underground utility diagrams provided by the facility, one location, background location BG-1, was located approximately 13 feet away from a water line (Figure 4.2), and it is unlikely that the underground water line impacts the subsurface temperature data at this location. Each of the other temperature monitoring stations were located at least 35 feet from the nearest utility line.

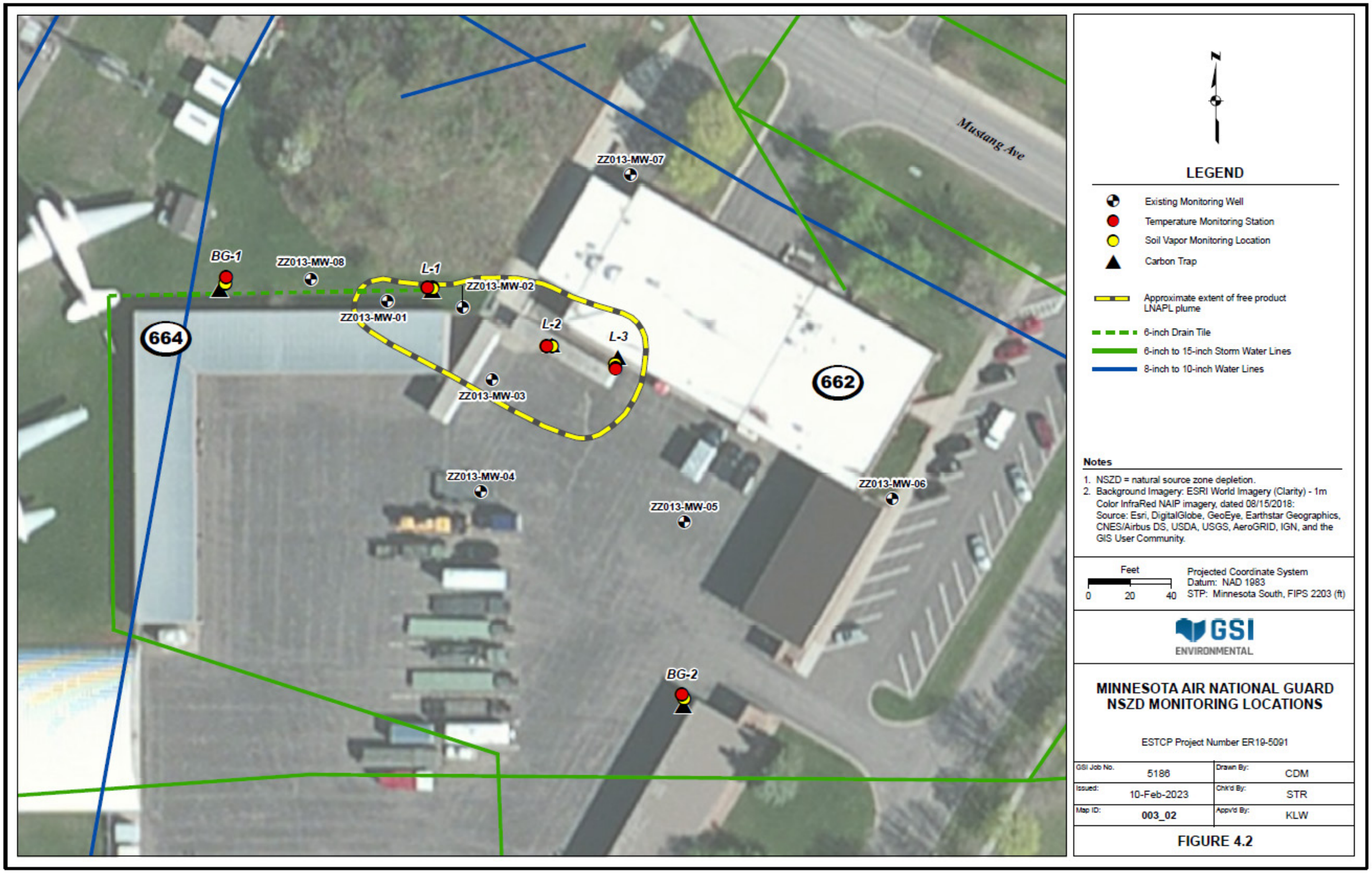


Figure 4.2. MN Air National Guard NSZD Monitoring Locations.

5.0 TEST DESIGN

The overall objective of this project was to demonstrate the use of temperature-based methods to accurately measure NSZD rates (i.e., gallons of LNAPL degraded per acre per year) in LNAPL source areas. The basic application of temperature-based methods to quantify NSZD rates has already been validated through laboratory and field testing sponsored by industry (e.g., Karimi Askarani et al. 2018; Kulkarni et al. 2020). This demonstration improves and expands the validation of temperature-based monitoring of NSZD, resulting in increased regulatory acceptance and reduced cost for application as a site remedy. The specific objectives of this demonstration program were to:

- Demonstrate the use of 2^{nd} generation temperature monitoring systems to improve data quality at reduced costs;
- Demonstrate improved methods to separate the heat signal associated with biodegradation of petroleum from seasonal and other sources of temperature fluctuations in soils (i.e., improved background correction);
- Demonstrate (through field deployment) that temperature-based approaches to quantifying NSZD rates are particularly suited for LNAPL source areas located below paved surfaces; and
- In addition to the field demonstration, compile results from the application of NSZD monitoring at additional sites and utilize these results to i) document the range of NSZD rates observed and ii) identify site factors that may be predictive of higher or lower NSZD rates at individual sites.

5.1 5.1 CONCEPTUAL EXPERIMENTAL DESIGN

At each of the two selected sites, demonstration of the temperature-based method to quantify NSZD consisted of installation of temperature monitoring stations at three locations within the LNAPL source area (2 paved, 1 unpaved) and two background locations (1 paved, 1 unpaved). As illustrated in Figure 5.1, the measured temperatures from the impacted area and the non-impacted location are used to determine the net increase in soil temperature attributable to biodegradation of petroleum (i.e., background corrected temperature, where any heat sources not attributable to biodegradation of petroleum (e.g., seasonal heating and cooling of the soil) are removed; Panel 2). The depth of maximum background-corrected temperature typically corresponds to the depth of the aerobic methane oxidation zone, where methane (generated by the anaerobic degradation of petroleum in the deeper LNAPL zone) and oxygen are converted to carbon dioxide, water, and heat. The background-corrected vertical temperature profile is used to determine the upward and downward temperature gradients (dT/dz; also Figure 5.1, Panel 2). Using Fourier's Law, these temperature gradients, along with the thermal properties of the soil, are used to calculate the heat flux, which corresponds to the amount of heat being generated from the petroleum biodegradation. Based on the known thermodynamics of petroleum combustion/degradation (i.e., the enthalpy of reaction; Panel 3), the volume of petroleum being degraded per area per unit time (i.e., the NSZD rate) is calculated. In the United States, this NSZD rate is commonly expressed in units of gallons of petroleum degraded per acre per year. Quantification of the NSZD rate allows the mass of petroleum removed by NSZD to be compared to that removed by active remedies. As discussed in more detail below, specific objectives of the demonstration will be attained as follows:

Accuracy of NSZD Rates: The accuracy of the NSZD rates determined using the temperature-based method were evaluated by comparing the rates to those determined using a limited set of alternative measurements collected at each site using the Carbon Trap and/or gradient methods. As discussed in Section 3.3, the accuracy of the temperature-based monitoring method has been demonstrated at other sites (e.g., Karimi Askarani et al. 2018; Kulkarni et al. 2020). For this demonstration, the alternative method NSZD rates were used to show general comparability between the methods.

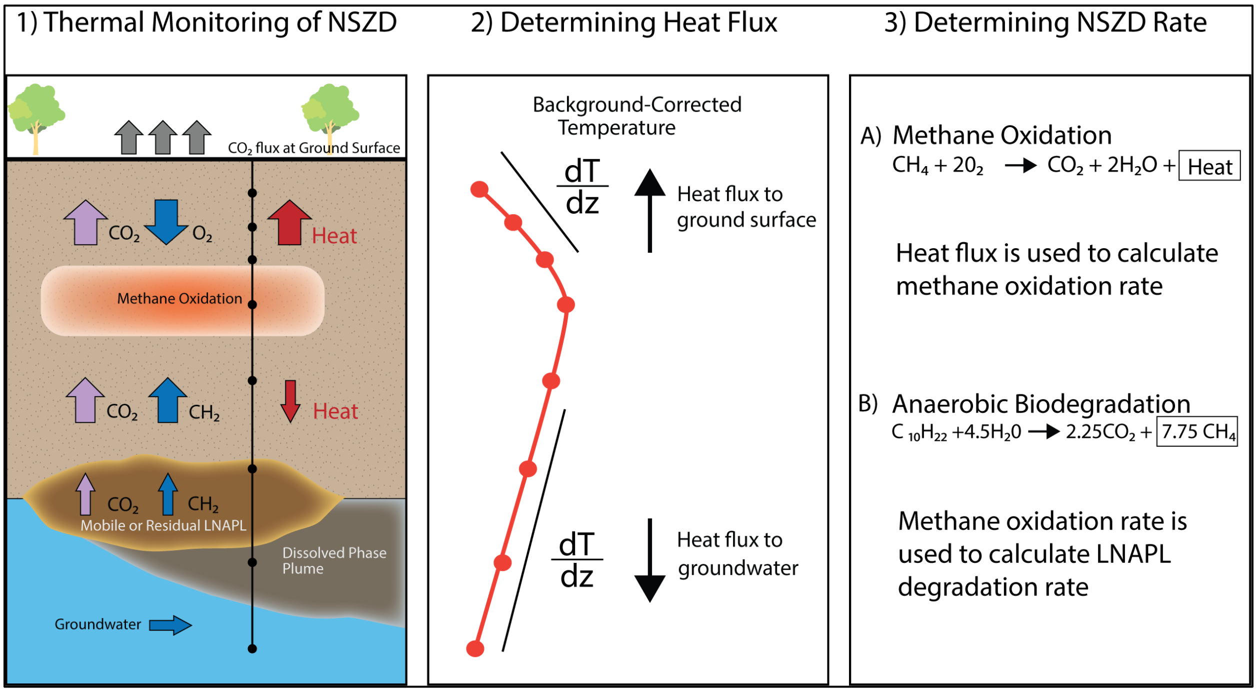


Figure 5.1. Conceptual Model for Temperature-Based Monitoring of NSZD.

2nd Generation Equipment: 2nd generation temperature-based monitoring equipment manufactured by S3NSE Technologies Inc. was used at each of the monitoring locations. This 2nd generation equipment was designed to provide a higher resolution vertical temperature profile with additional temperature sensors at a lower total cost compared with 1st generation equipment but had only undergone limited testing. In addition, the 2nd generation equipment supported additional sensors that measure water levels and oxidation-reduction potential (ORP) (Sale et al. 2021; Blotevogel et al. 2021).

Improved Background Correction: The temperature data were analyzed using two approaches designed to resolve the net temperature associated with biodegradation after accounting for other heat sources not associated with NSZD (i.e., "background correction"): i) the 2nd generation equipment provided a higher resolution background temperature profile that allows for more accurate determination of the net temperature profiles at the LNAPL source area measurement locations, and ii) the higher resolution 2nd generation equipment supported the application of the Single Stick approach as an alternative novel correction method that does not rely on the measurement of the temperature profile at a background location.

Demonstration Below Paved Surfaces: The ability of the temperature monitoring method to quantify NSZD rates below paved surfaces was demonstrated by the installation of two of the three LNAPL source area temperature monitoring stations below paved surfaces at each of the two demonstration sites.

5.2 BASELINE CHARACTERIZATION

Based on prior site investigation activities, both of the demonstration sites were assumed to have been sufficiently characterized to support the selection of the specific locations for installation of the temperature monitoring stations. No additional baseline characterization activities were anticipated to be needed or conducted prior to installation of the temperature monitoring stations.

At the MN ANGB, however, during the installation of the background monitoring locations, and review of subsequent data collected as a part of this project, it is suspected that the initial site characterization was not sufficient to delineate LNAPL impacts at this site. For example, while installing the casing at the upgradient background location, BG-1, there were low readings of volatile organic compounds, as measured with a photoionization detector (PID), within the borehole. Approximately one month after installation of the temperature sensor locations, a strong "hydrocarbon" odor and a thin (i.e., 0.02 ft) layer of product were observed in the well at the same location.

5.3 TREATABILITY OR LABORATORY STUDY RESULTS

No treatability or laboratory study results were conducted as a part of this project. The fundamentals of the temperature-based NSZD technology have been described elsewhere (e.g., Stockwell 2015; Sale et al. 2018; Kulkarni et al. 2020; ITRC 2018; API 2017; CRCCare 2018; CL:AIRE 2019; ASTM E3361-22 2022).

5.4 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

At each demonstration site, five monitoring clusters were installed. Each cluster consisted of one dedicated soil vapor monitoring vertical profile, one Carbon Trap, and one temperature monitoring station, which also contained ORP sensors, located approximately 2-5 feet apart. Three clusters were installed within pavement (2 impacted, 1 background), and two clusters were installed in unpaved areas (1 impacted, 1 background). The locations at each field demonstration site are shown on Figures 4.1 (TEAD-S) and 4.2 (the MN ANGB).

At each demonstration site, one soil vapor monitoring vertical profile was installed adjacent to each temperature monitoring station. Each soil vapor monitoring vertical profile was installed to approximately 8 feet below ground surface (bgs) and consisted of four dedicated soil vapor points installed at depths of 1, 3, 5, and 7 feet bgs within a common borehole (see Figure 5.3). Each soil vapor point consisted of a 3-inch-long stainless steel (SS) mesh screen with vapor implant that was connected to the surface sampling vault via ¼-inch outer diameter (OD) Nylaflow tubing. Each soil vapor point was installed within a six-inch thick sand pack, which was then capped with 6 inches of dry bentonite crumbles, followed by 1 foot of hydrated bentonite. The surface tubing was capped with a 3-way valve and housed within a traffic-rated flush-mounted surface vault.

During field installation of the temperature monitoring stations, three temperature monitoring stations at each demonstration site were equipped with seven vertically-spaced soil gas collection points as a comparison with the dedicated soil vapor monitoring locations (see Table 5.1). These additional soil gas collection points consist of several points installed at depths deeper than the dedicated soil vapor monitoring points.

Table 5.1. Summary of Soil Gas Collection Points at Each Demonstration Site

Type of Monitoring Point	Number of monitoring locations	No. of vertically-spaced soil gas collection points at each location	Total number of sample collection points at each demonstration site
Soil Vapor Monitoring Point	5	4	20
Temperature Monitoring Station	3	7	21
Totals	**8**	**11**	**41**

Carbon Traps are a commercially available technology to measure NSZD rates based on measurement of the carbon flux from the subsurface and are available from E-Flux LLC, Fort Collins, CO. Carbon Traps involve a passive sampling approach that measures the carbon dioxide (CO_2) flux that sorbs to proprietary sorbents within each trap. Modern concentrations of carbon dioxide from natural soil respiration processes are subtracted via a ^{14}C isotopic analysis to calculate the residual hydrocarbon degradation signal from the total flux of measured carbon dioxide (McCoy et al. 2015; E-Flux 2022).

Carbon Traps were installed per manufacturer instructions (E-Flux LLC) by inserting a 4-inch receiver into the ground, and then adding the CO_2 trap, rubber connector, and rain cover. For the locations within paved areas, an approximately 12-inch x 12-inch square was cut through the concrete and/or asphalt to house the Carbon Trap (see Figure 5.2). After installation, the Carbon Traps were deployed in the field for approximately three to four weeks prior to retrieval (21 days at TEAD-S; 27 days at the MN ANGB). After retrieval, the Carbon Traps were sent to E-Flux for analysis.

Figure 5.2. Carbon Trap (E-Flux) Installed within a Paved Location at TEAD-S.

Figure 5.4 depicts the layout of the temperature monitoring stations. Prior to installation, 16-19 temperature and ORP sensors were zip-tied at pre-determined depths to a one- or two-inch diameter solid Schedule 40 polyvinyl chloride (PVC) pipe, with the bottom one foot consisting of 0.010-inch slotted screen. Final sensor depths were selected based on historical depth to water data and depth to bedrock and thus may vary slightly between locations. At select locations, soil vapor monitoring ports were also installed by zip-tying 1/8-inch outer diameter (OD) polytetrafluoroethylene (PTFE) tubing with 10 µm Nitex cloths at their points. An 8.25-inch diameter borehole was drilled with a hollow-stem auger at the MN ANGB for most locations, and a 4.5-inch borehole was drilled with a sonic drill rig at TEAD-S. Due to issues during installation, there were two locations at the MN ANGB that were drilled with a larger 12.25-inch borehole to keep the temperature sensors in place. The sensors and PVC casing were lowered down the borehole, and the outer annular space was backfilled with sand. After installation, a pressure transducer and reference electrode (for the ORP sensors) were lowered down the inner PVC casing and secured at a depth below the water level. As-built characteristics for each temperature monitoring station location are provided in Table 5.2.

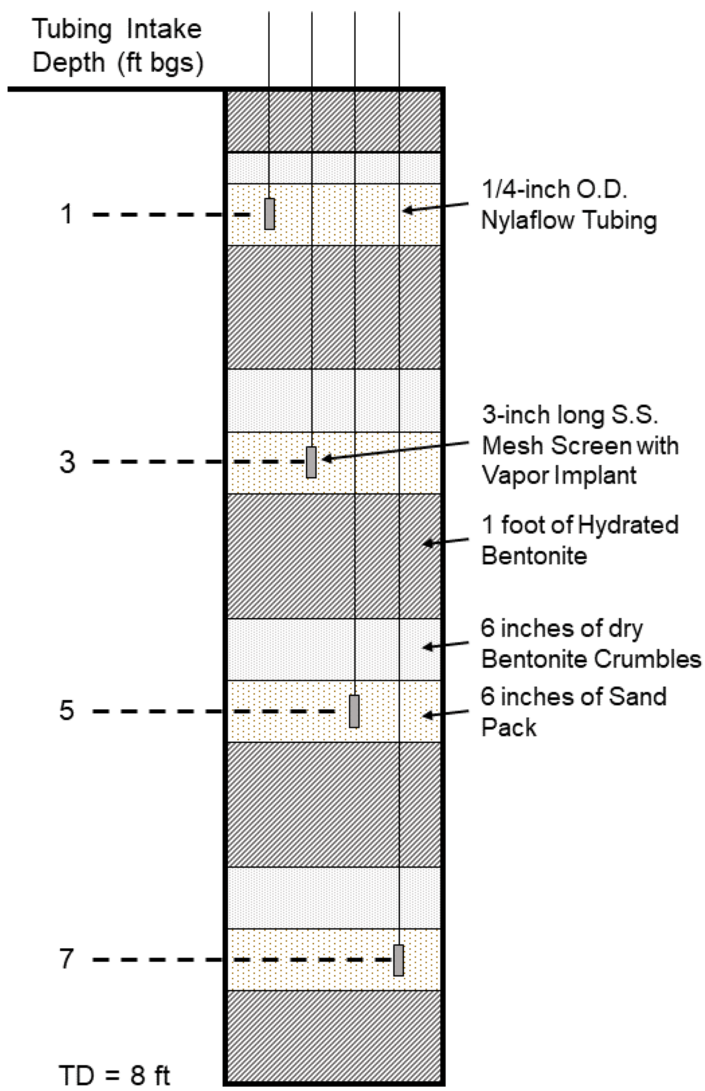


Figure 5.3. Soil Vapor Monitoring Construction Schematic

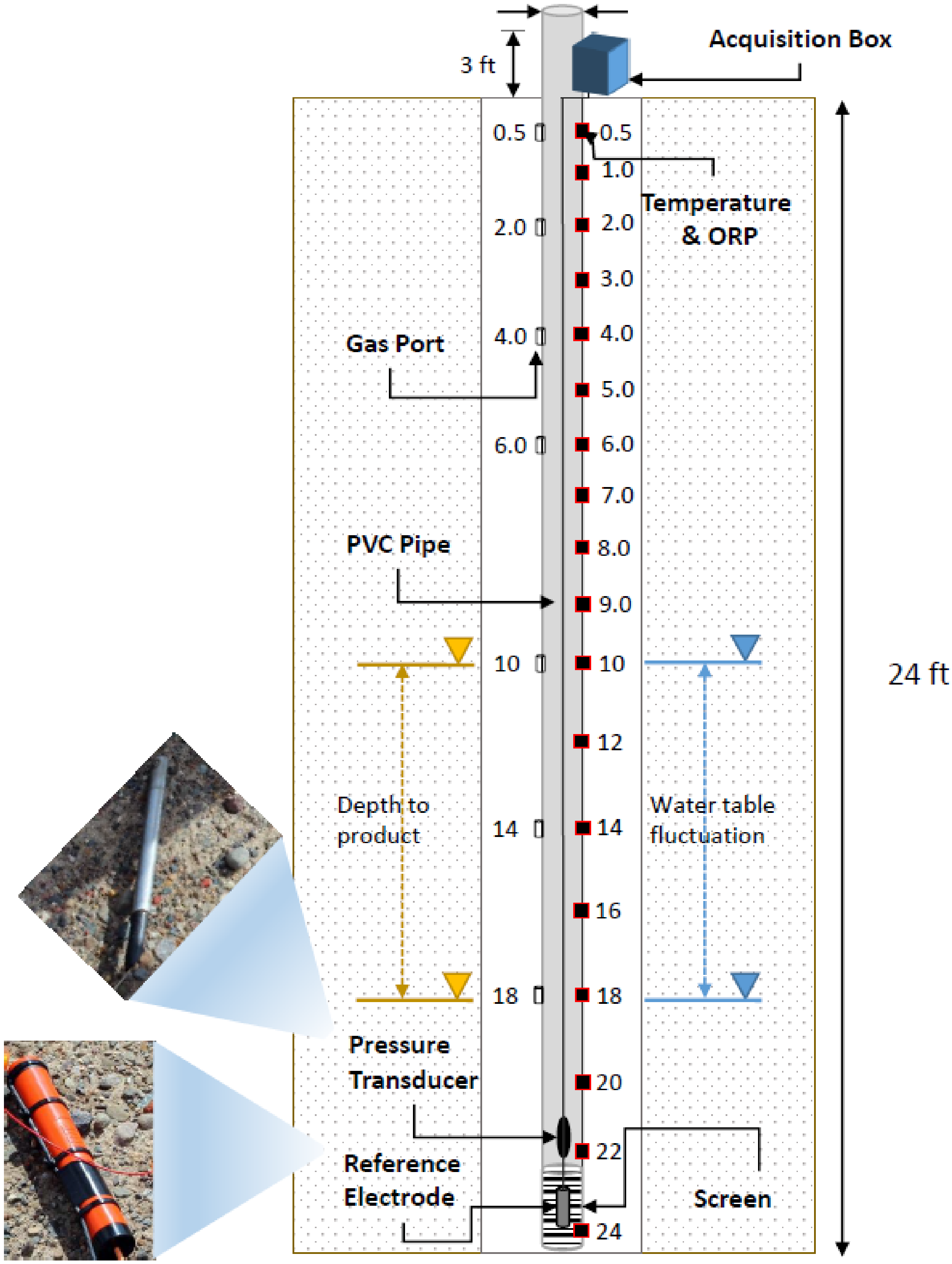


Figure 5.4. Temperature Monitoring Station Diagram for Field Assembly and Installation of Equipment.

(Figure provided by Colorado State University)

Table 5.2. As-Built Characteristics of Each Temperature Monitoring Station at the Two Demonstration Sites

Temperature Monitoring Station Location	Total Depth (ft bgs)	Depths of Temperature Sensors (ft bgs)	Depth of Water Level Sensor (ft bgs)	Depths of Gas Ports (ft bgs)
TEAD-S				
L-1 (Paved)	24.8	0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18, 20, 22, 24	--	--
L-2 (Paved)	25.0	0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18, 20, 22, 24	24.5	0.5, 2, 4, 6, 10, 14, 18
L-3 (Un-Paved)	24.8	0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18, 20, 22, 24	24.3	0.5, 2, 4, 6, 10, 14, 18
BG-1 (Paved)	25.0	0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18, 20, 22, 24	24.5	--
BG-2 (Un-Paved)	24.7	0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18, 20, 22, 24	--	0.5, 2, 4, 6, 10, 14, 18
MN ANGB				
L-1 (Un-Paved)	17.0	0.5, 1, 1.5, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17	16.5	--
L-2 (Paved)	14.0	0.25, 0.5, 1, 1.5, 2.5, 3.5, 4.5, 5.5, 6.5, 7.5, 8.5, 9.5, 10.5, 11.5, 12.5, 13.5	--	0.5, 2, 4, 6, 8, 10, 14
L-3 (Paved)	14.5	0.5, 1, 1.5, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14	--	0.5, 2, 4, 6, 8, 10, 14
BG-1 (Un-Paved)	17.5	0.5, 1, 1.5, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17	17.0	--
BG-2 (Paved)	14.8	0.5, 1, 1.5, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14	14.3	0.5, 2, 4, 6, 8, 10, 14

5.5 FIELD TESTING

At each of the two demonstration sites, field testing involved: i) installation of the temperature monitoring station monitoring points; ii) deployment and collection of Carbon Traps; iii) measurement of oxygen, carbon dioxide, and methane concentrations; iv) 18 to 24 months of temperature monitoring station data collection; and v) decommissioning of monitoring locations. Table 5.3 shows the timeline for completion of each of these tasks.

Table 5.3. Time Period for Completion of Field-Testing Tasks

Field Testing Task	TEAD-S	MN ANGB
Installation of monitoring points	June 3, 2020 – June 5, 2020	July 21, 2020 – July 25, 2020
Carbon Traps	June 5, 2020 – June 25, 2020	July 25,2020 – August 20, 2020
O_2, CO_2, and CH_4 measurements	June 25, 2020 April 6, 2021 April 4, 2022	August 20, 2020 March 30, 2021
Temperature monitoring station data collection	June 5, 2020 – September 12, 2022	July 25, 2020 – June 27, 2022
Decommissioning	September 12, 2022	June 27-28, 2022

During installation activities, soil and water investigation-derived waste (IDW) were contained in 55-gallon drums. Composite soil and water samples were collected, analyzed at an accredited laboratory, and waste profiles were generated prior to transport and disposal at an approved landfill. ACT Enviro coordinated the IDW disposal at both locations. Signed waste manifests are provided in Appendix E.

Following completion of the demonstration period, each MN ANGB paved and unpaved temperature and vapor monitoring locations were plugged and abandoned with bentonite grout per Minnesota Department of Health (MDH) regulations on 27 June 2022. The three paved locations (i.e., L-2, L-3, and BG-2) were not regulated by MDH because these holes were drilled less than 15 ft bgs. These paved locations were capped with asphalt to match the surrounding parking lot. The two unpaved locations (i.e., L-1 and BG-1) were drilled to 17 ft bgs, which mandated a well and boring sealing record. These sealing records are on file with the MDH. The unpaved locations were filled nearly to the surface with bentonite grout and a thin layer of soil and seed on top to match the surrounding grassy conditions.

Following completion of the demonstration period, each TEAD-S paved and unpaved temperature and vapor monitoring locations were plugged and abandoned with bentonite grout per Utah Department of Environmental Quality regulations on 12 September 2022.

5.6 SAMPLING METHODS

The sampling methods for each field-testing task are described below.

5.6.1 Oxygen, Carbon Dioxide, and Methane

Soil gas profiles were measured three times at TEAD-S and two times at the MN ANGB in accordance with procedures described in Jewell and Wilson (2011). A GEM 2000-5000 series landfill gas meter was used for each sample event. The landfill gas meter was calibrated prior to each day of sampling. A 3-way valve connected to the subsurface soil vapor points sealed each gas port at the surface. Prior to sampling, three volumes of air within the Nylaflow sample tubing were purged using a Luer lock syringe. The landfill gas meter was then attached to the 3-way valve using Masterflex tubing. Readings were recorded after stabilization occurred for oxygen, carbon dioxide, and methane. Clean air was used between samples to purge the landfill gas meter per guidance from the user's manual (Landtec 2008). Several 3-way valves were clogged with swollen bentonite and were replaced prior to sampling.

Both sites contain hydrocarbons in the subsurface and thus may be susceptible to high-biased methane readings from the landfill gas meter due to positive interference from petroleum hydrocarbon vapors. Jewell and Wilson (2011) showed that these high biased methane readings can be resolved by placing a charcoal filter between the sample port and the gas meter (see Figure 6 in Jewell and Wilson 2011). Activate charcoal adsorbs petroleum vapors but not methane, oxygen, or carbon dioxide. Following this guidance, charcoal filters provided by the landfill gas meter vendor were utilized during each sampling event. At the MN ANGB, very high methane and implausible methane readings were recorded at some locations (e.g., 100% methane at locations with detectable concentrations of oxygen and carbon dioxide), suggesting that the charcoal filter was not removing petroleum hydrocarbons from the sample stream.

Based on these observations, methane readings for the MN ANGB were rejected as unreliable and likely biased high. The gas meters were calibrated and the carbon dioxide and oxygen data from the MN ANGB were reasonable and expected, which gives validity to the non-methane data (Appendix C.2).

5.6.2 Carbon Traps

Carbon dioxide flux at the ground surface was measured using Carbon Traps, as described by McCoy et al. (2015). At each demonstration site, Carbon Traps were procured from E-Flux, installed per manufacturer instructions, and returned to E-Flux for analysis after the field deployments. More detailed analytical procedures and results are provided in the laboratory reports produced by E-Flux (see Appendix H.1 and H.2).

5.6.3 Temperature Monitoring Stations

Following the general approach outlined by Warren and Bekins (2015), Stockwell (2015), and Kulkarni et al. (2020), subsurface temperatures were measured along a vertical profile using temperature monitoring stations. Each temperature monitoring station included 16 to 19 sensors to measure temperature and 16 to 19 sensors to measure ORP. At each demonstration site, S3NSE included three locations with a pressure transducer to measure water levels.

The temperature sensors used during this demonstration project have a stated accuracy of ±0.5° C for temperature measurements ranging from -10° C to +85° C, and a typical performance curve provided by the sensor vendor indicates that the temperature sensors have an actual accuracy of ±0.2° C from 0° C to 60° C. The sensor accuracy is less than previous published research, with reported accuracy of sensors of ±0.07°C to ±0.2°C (Karimi Askarani et al. 2018; Kulkarni et al. 2020; Warren and Bekins 2015; Wozney et al. 2022). The accuracy of the temperature sensors was further assessed by the equipment manufacturer and vendor, S3NSE Technologies, prior to field installation (see Appendix C.1). Temperature and ORP sensor data were collected at each temperature monitoring station. Data were uploaded via cellular signal to a Ubidots dashboard hosted by S3NSE Technologies, where the data appeared in near real-time. The dashboard displays time series temperature data as interactive charts, and raw data can be downloaded from the dashboard for further processing. The dashboard was observed frequently to monitor for potential data gaps during the demonstration period. Measures taken to address loss of data are described in Section 6.4.1.

One potential limitation of the 2nd generation technology is data loss due to poor cellular connectivity. During periods of poor cellular connectivity or an unreliable network, the monitoring device may fail to connect to the cellular network and transmit the collected data to the database, causing data loss and gaps in the data. While the project specifications included a secondary backup of all collected data on a non-volatile memory card for local data collection, the backup process failed to properly store all collected data on the included non-volatile memory card. Despite several attempts by the vendor to resolve the issue, this issue was not fully resolved by the end of the demonstration period.

For the purposes of the data analyses contained within this report, data collection at the MN ANGB began 1 September 2020 and ended 27 June 2022 at decommissioning. The analysis period at TEAD-S began 1 July 2020 and ended 31 June 2022. Data collection at TEAD-S continued through decommissioning, which occurred 12 September 2022, although data after 30 June 2022 are not included in the analyses in this report. At both sites, the data for approximately the first month of data collection were not analyzed to allow for the subsurface and sensors to equilibrate after sensor installation.

5.7 SAMPLING RESULTS

The field demonstration yielded a large dataset of measurement results. As discussed in Section 6.3.2, the oxygen, carbon dioxide, and methane data were used to provide a qualitative evaluation of NZSD, while the Carbon Trap and temperature data were used to quantify NSZD rates.

Figure 4.1 shows the location of key sensors and monitoring devices at TEAD-S, and Figure 4.2 shows the location of key sensors and monitoring devices at the MN ANGB.

5.7.1 Oxygen, Carbon Dioxide, and Methane

Three rounds of soil gas measurements were completed at TEAD-S, and two rounds of soil gas measurements were completed at the MN ANGB (see Table 5.3). The soil gas measurement results are summarized in Figures 5.5 and 5.6 for TEAD-S and the MN ANGB, respectively; vapor sample results are presented in tabular form in Appendix H.3 and H.4. As described in Section 5.6.1, the methane results at the MN ANGB were rejected as unreliable and are not shown on Figure 5.6. In Figures 5.5 and 5.6, the impacted locations are L-1, L-2, and L-3, and the background locations are BG-1 and BG-2. Each sampling event (see Table 5.3) is indicated by a separate line.

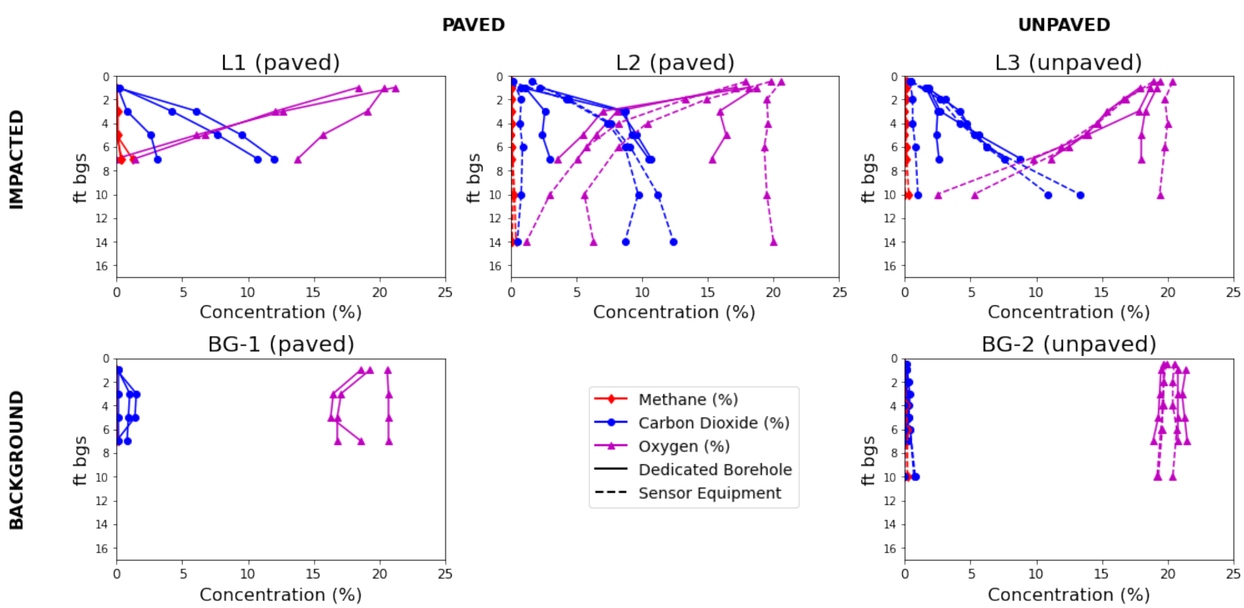


Figure 5.5. Soil Gas Measurements at TEAD-S Collected in June 2020, April 2021, and April 2022.

Each line represents a different sampling event.

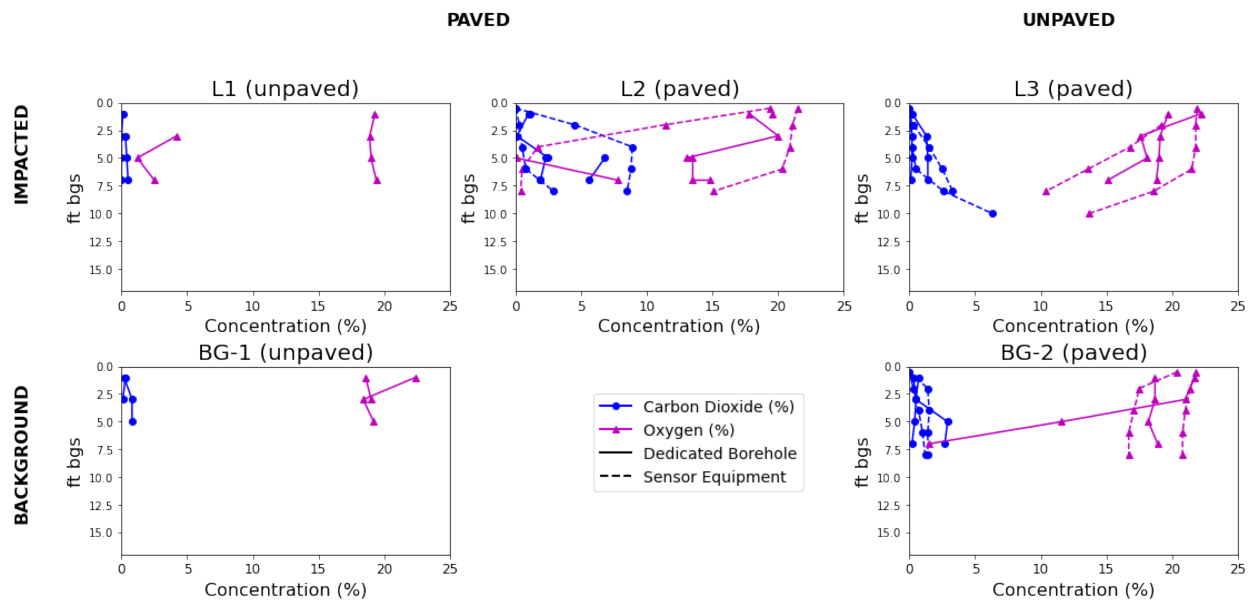


Figure 5.6. Soil Gas Measurements at the MN ANGB Collected in July 2020 and March 2021.

Each line represents a different sampling event.

5.7.2 Carbon Trap Results

One round of Carbon Trap testing was conducted at each demonstration site. At each site, Carbon Traps were deployed at the two background locations and the three source area locations. As described in Sections 5.4 and 5.6.2, the Carbon Trap vendor, E-Flux, used the measured carbon dioxide flux to calculate an NSZD rate. The E-Flux analytical reports are provided in Appendix H.1 and H.2. The resulting NSZD rates are summarized in Table 5.4.

Table 5.4. NSZD Rates at Each Location from Carbon Traps

Location	NSZD Rate (gal/acre/year) Carbon Trap
TEAD-S	**June 2020**
L-1 (Paved)	295
L-2 (Paved)	84
L-3 (Un-paved)	1105
BG-1 (Paved)	ND
BG-2 (Un-paved)	ND
MN ANGB	**August 2020**
L-1 (Un-paved)	72
L-2 (Paved)	1856
L-3 (Paved)	404
BG-1 (Un-paved)	129
BG-2 (Paved)	37

Note: ND = NSZD rate not calculated, as fossil fuel CO_2 flux was not detected.

5.7.3 Temperature Measurements

At each demonstration site, temperature data were recorded for a period of at least 18 months (see Table 5.5).

Table 5.5. Summary of Temperature Data Collected at Each Demonstration Site

Demonstration Site	Number of Monitoring Locations	No. of Vertically-Spaced Soil Temperature Sensors at Each Location	Data Collection Period	Data Analysis Period	Total No. of Temperature Measurements Recorded
TEAD-S	5	18	5 June 2020-12 September 2022	1 July 2020-30 June 2022	1,618,675 (through 1 July 2022)
MN ANGB	5	16 or 19	25 July 2020 – 27 June 2022	1 Sept. 2020-27 June 2022	1,017,893

The raw temperature data are summarized in Figures 5.7 for TEAD-S and 5.8 for the MN ANGB; raw temperature data are provided in tabular form in Appendix H.5 and H.7. In Figures 5.7 and 5.8, the red shading indicates data gaps where the monitoring equipment failed to record hourly temperature readings for as-yet-unidentified reasons. As shown in Figure 5.7, Table 6.2, and discussed in Section 6.1.3, the data gaps at TEAD-S were minor. At TEAD-S, temperature values were recorded for more than 99% of the days during the data collection period, and data gaps were typically only one or a few hours in duration. However, the data gaps at MN ANGB were more significant. As summarized in Table 6.2, at the MN ANGB, temperature values were recorded for at least 12 hours per day for 60% to 95% of days, depending on the monitoring location. At the MN ANGB, some data gaps were several weeks in duration or longer. These data collection issues and corrective measures implemented during the demonstration are discussed further in Section 6.4.1.

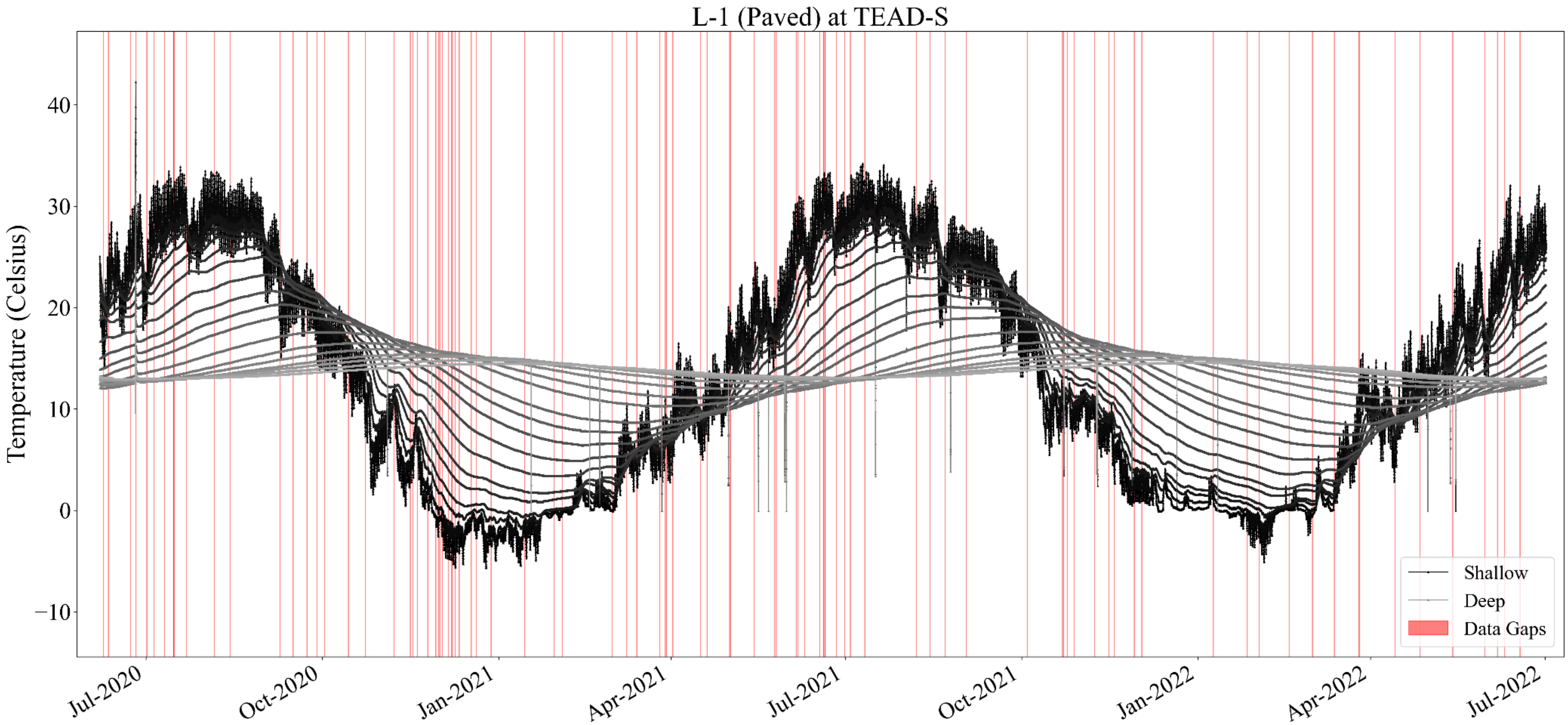
A complete dataset of average daily temperatures is required to calculate NSZD rates using the temperature-based methods. Therefore, data interpolation algorithms were used to estimate temperature values for the hours with missing data. Three interpolation methods were evaluated (i.e., linear, quadratic, and cubic), and linear interpolation was determined to provide the most reasonable results for each location. These expanded datasets of measured and estimated hourly temperature values were used for the NSZD rates determinations for each of the NSZD calculation methods evaluated in Section 6. The resulting temperature data sets are provided in Appendix H.6 and H.8 and summarized in Figures 5.9 and 5.10. In Figures 5.9 and 5.10, the green shading indicates the time periods with estimated, rather than measured, temperature values.

Because subsurface soil temperatures deeper than the upper 1-2 feet bgs change more slowly than the upper 1-2 feet, and the data gaps at TEAD-S were small (usually only one or a few hours in duration), the uncertainty associated with the estimated temperature values is very small and almost certainly had no meaningful effect on the determination of NSZD rates.

However, the potential uncertainty or error associated with the estimation of missing temperature values at the MN ANGB was potentially much higher because there was much more missing data, and the data gaps were much longer in duration (see Figure 5.8). At the MN ANGB monitoring location L-3, no temperature data were recorded between early January 2022 and the end of the data collection period in July 2022. As a result, interpolation could not be used to estimate temperatures for this time period, and NSZD rates were not computed after January 2022 at this location.

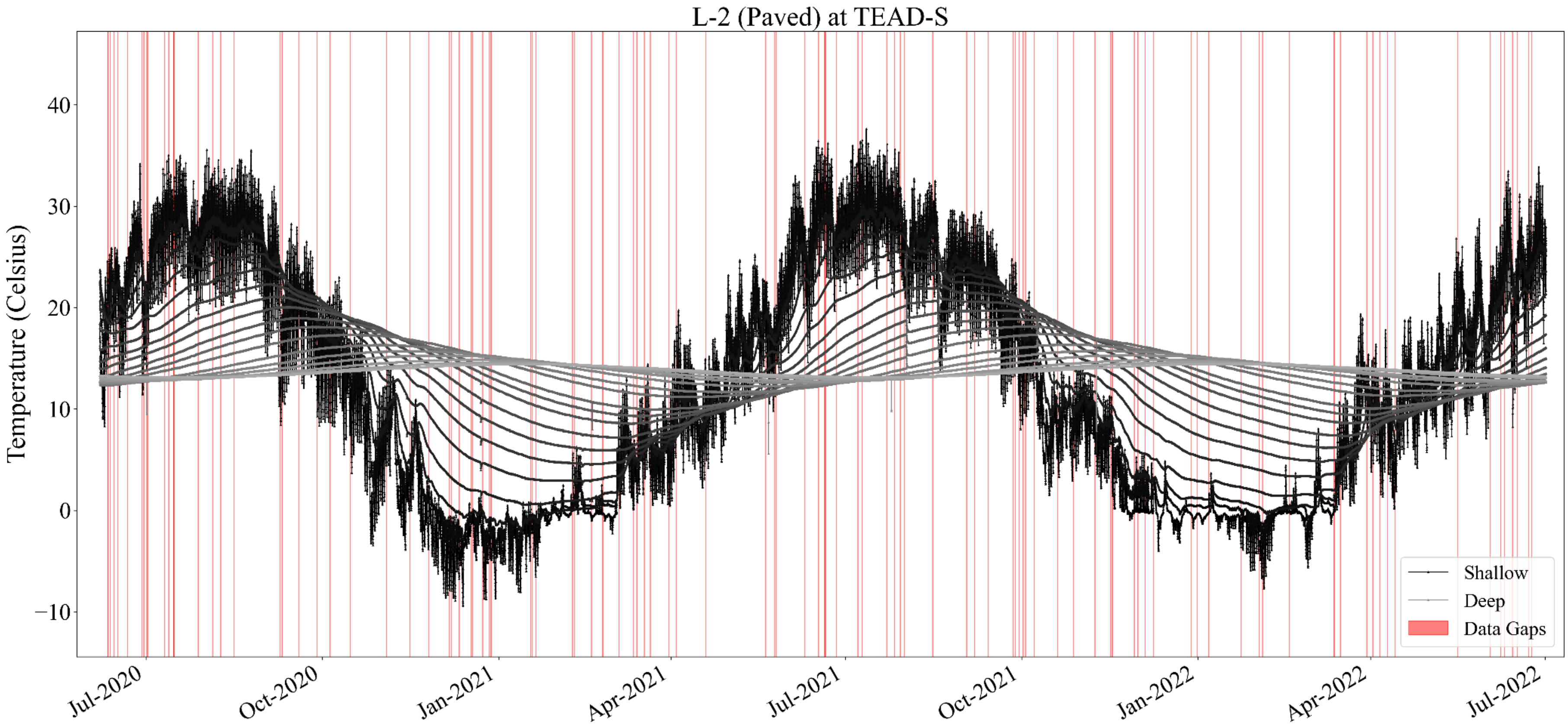
To evaluate the effect of estimating the missing temperature values at the MN ANGB on the calculated NSZD rates, the same data gaps in the MN ANGB dataset were imposed on the much more complete dataset from TEAD-S, and then the same linear interpolation method was used to provide estimates of the missing temperature readings. Next, NSZD rates were calculated for both TEAD-S datasets (i.e., the original dataset and the dataset with artificial data gaps matching the MN ANGB dataset filled by linear interpolation). The results of this analysis are discussed in Section 6.2.4.

Further discussion of the calculated NSZD rates is provided in Section 6.

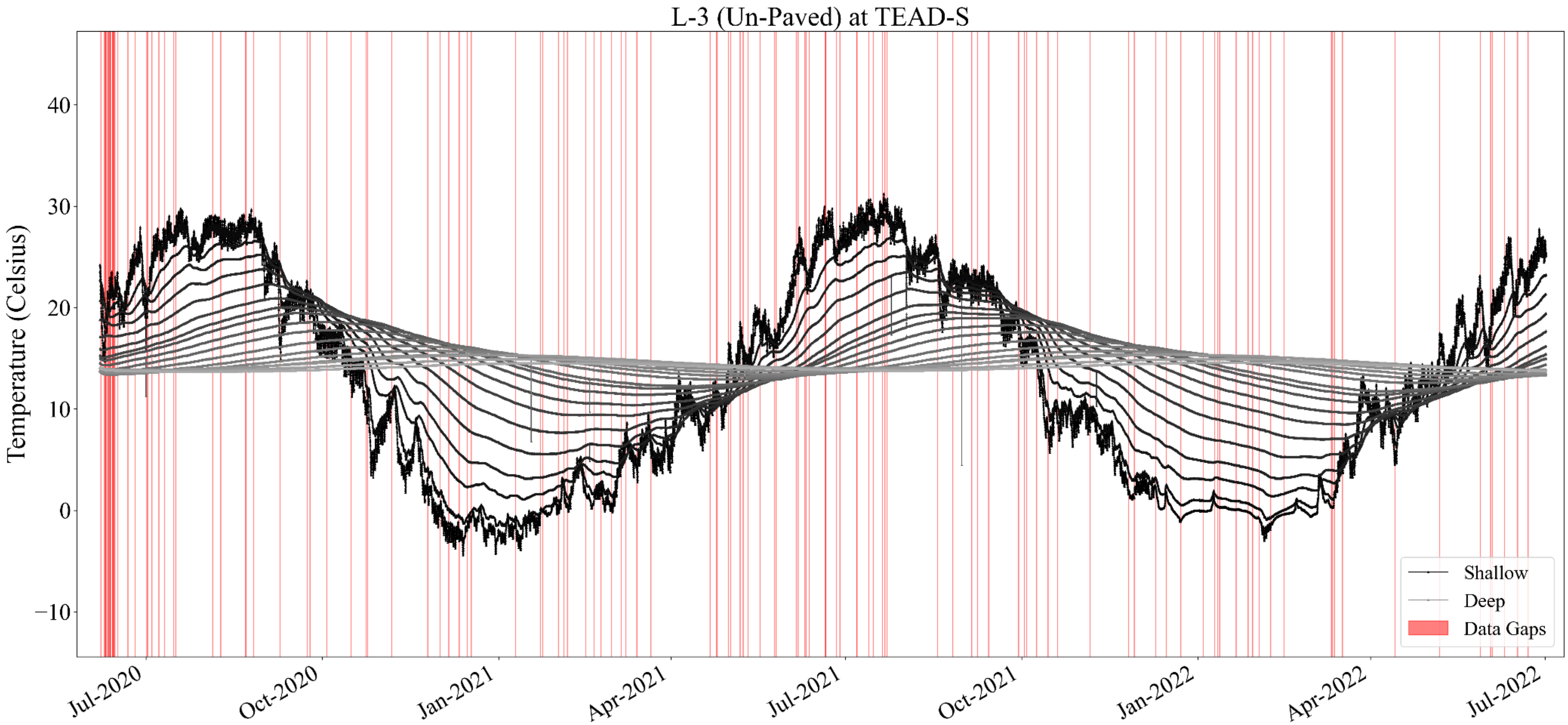


Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 24 ft bgs.

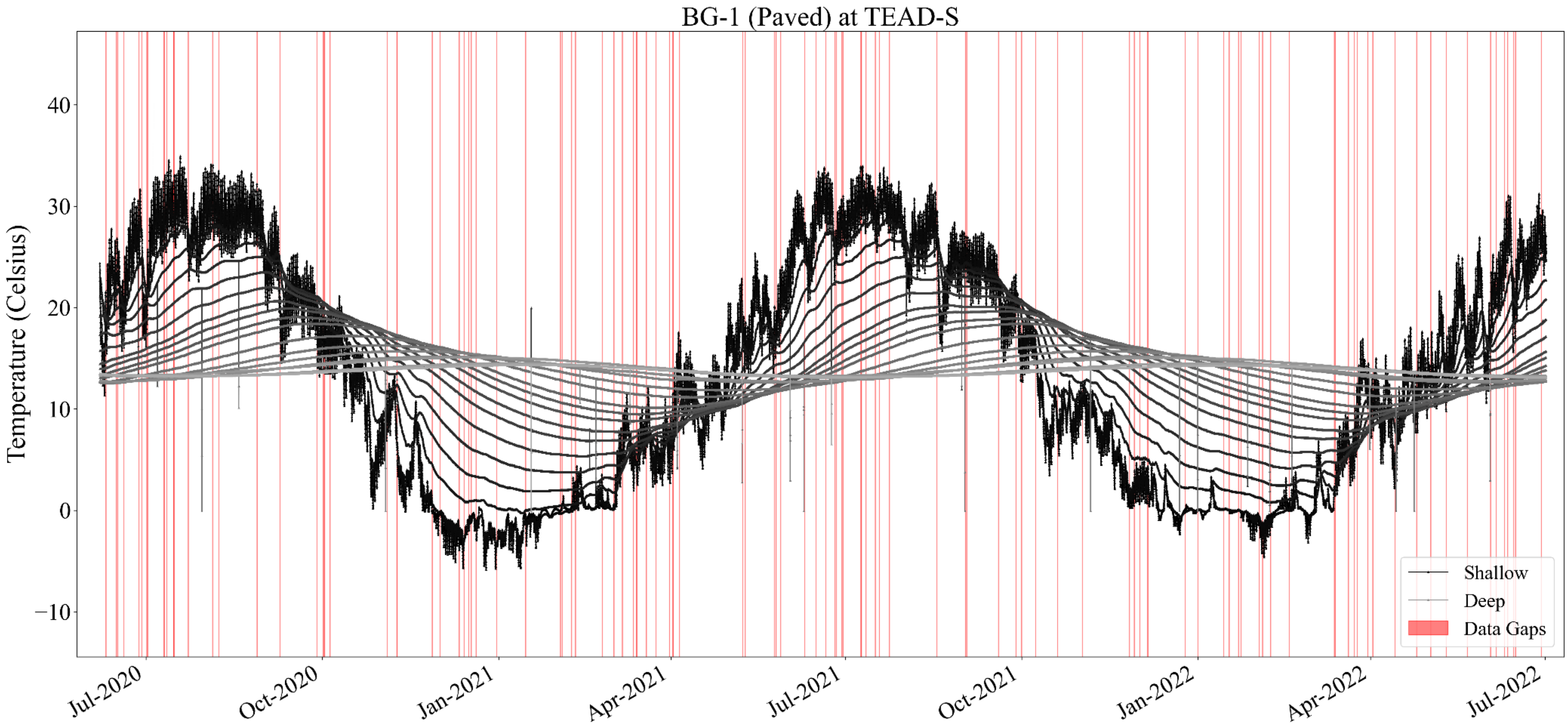
Figure 5.7. Temperature Data at TEAD-S



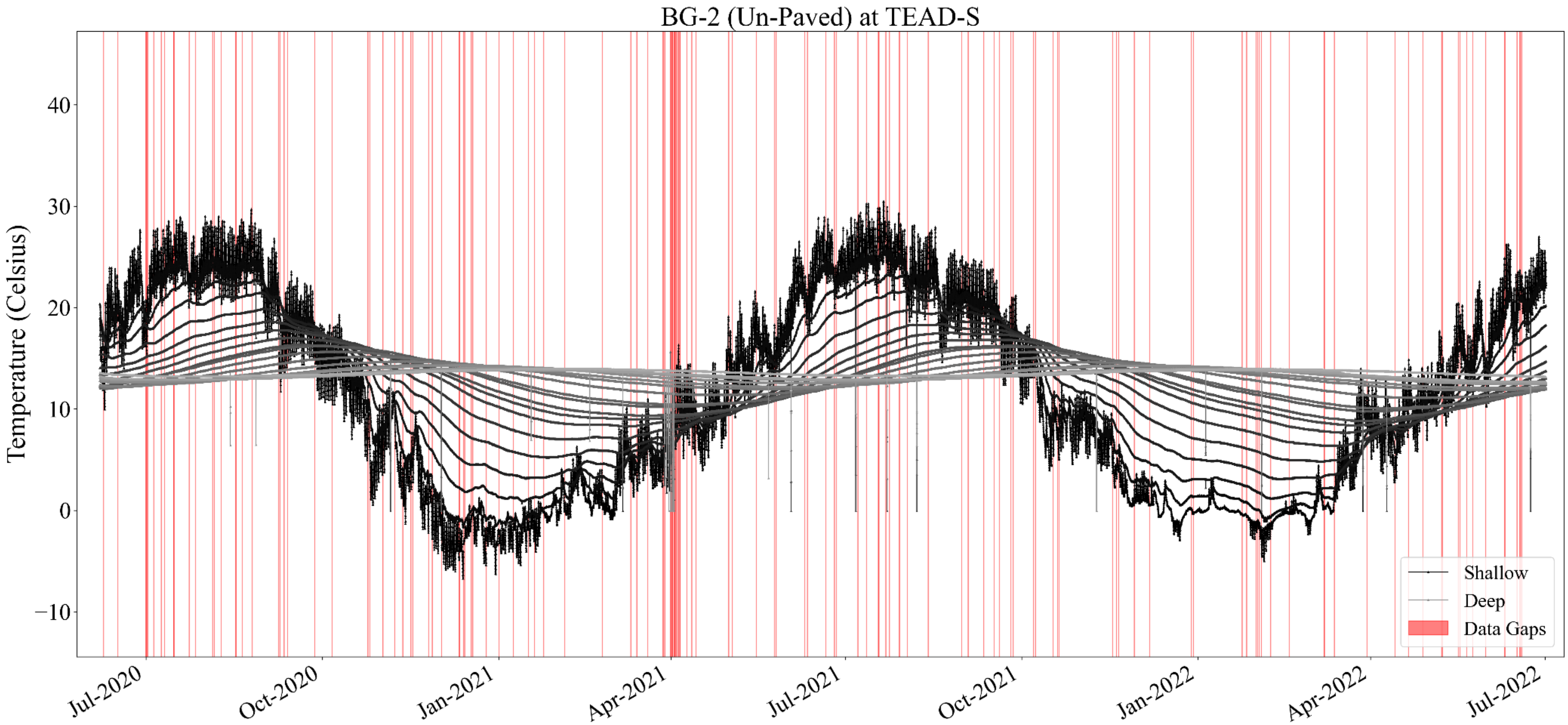
Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 24 ft bgs.



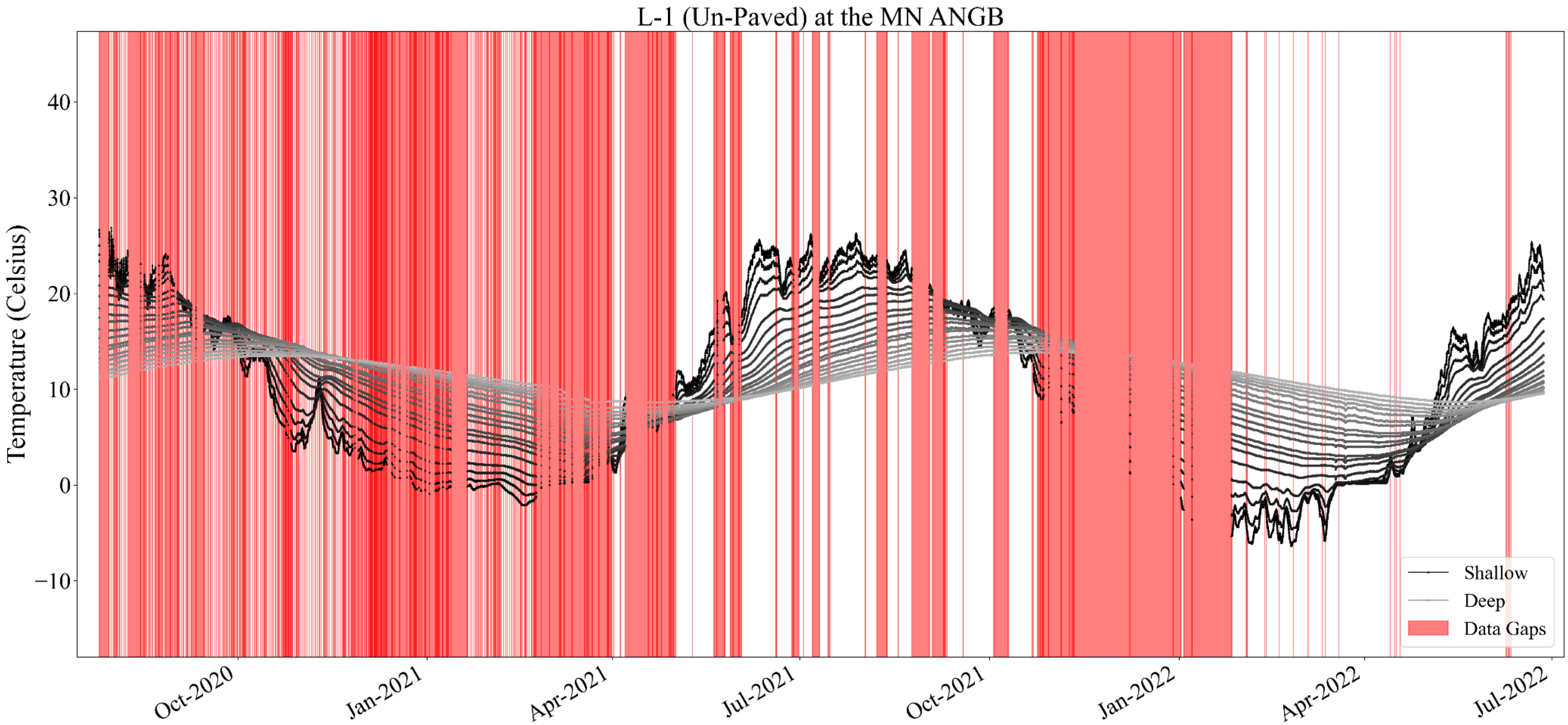
Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 24 ft bgs.



Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 24 ft bgs.

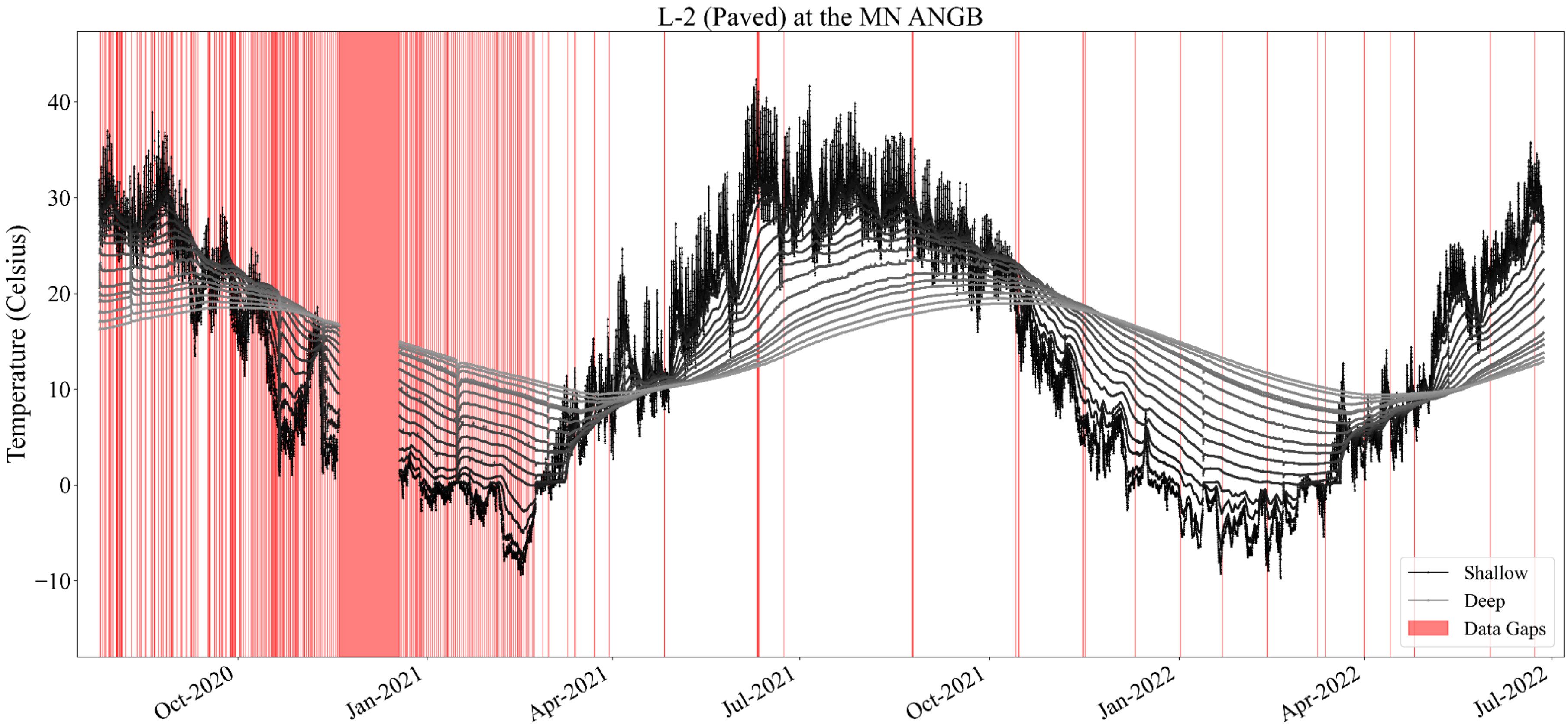


Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 24 ft bgs.

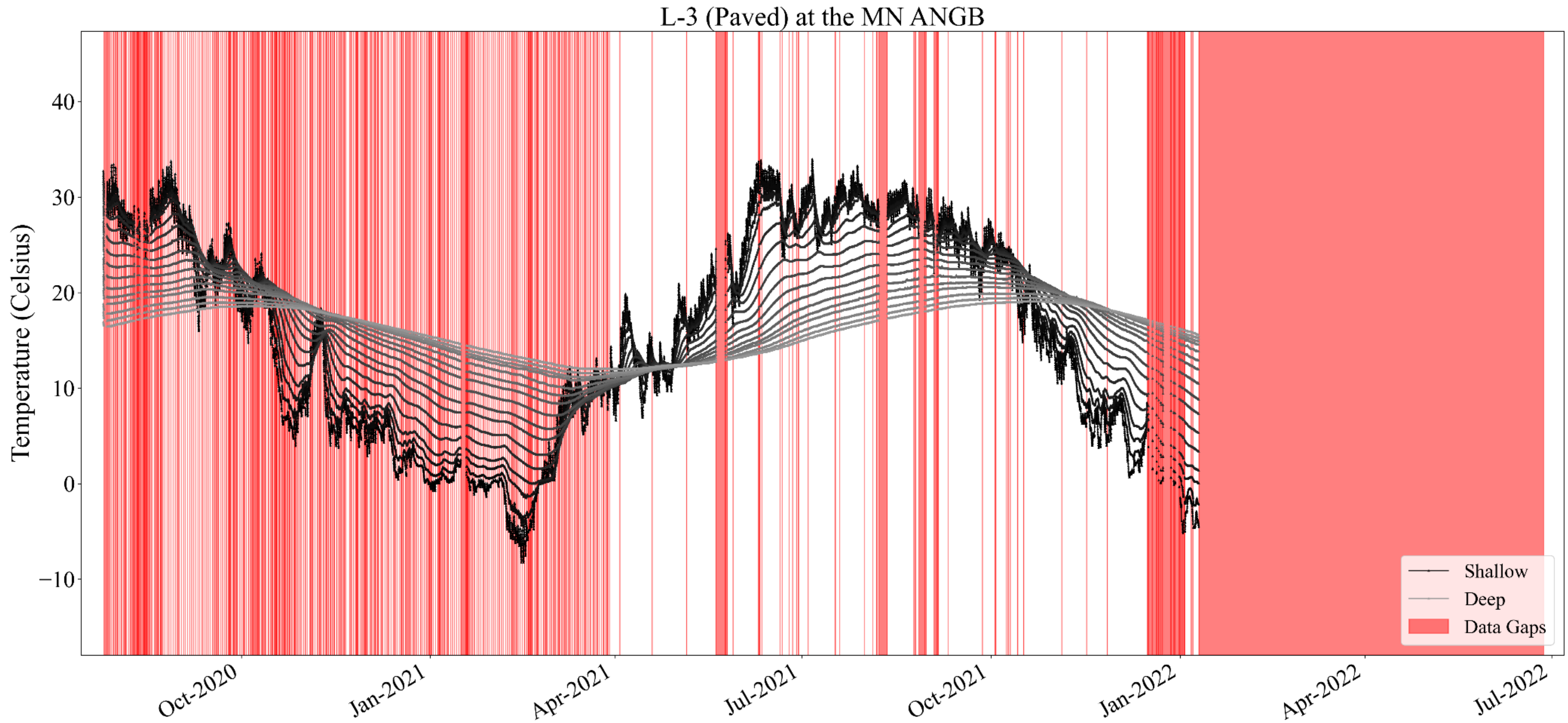


Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 17 ft bgs.

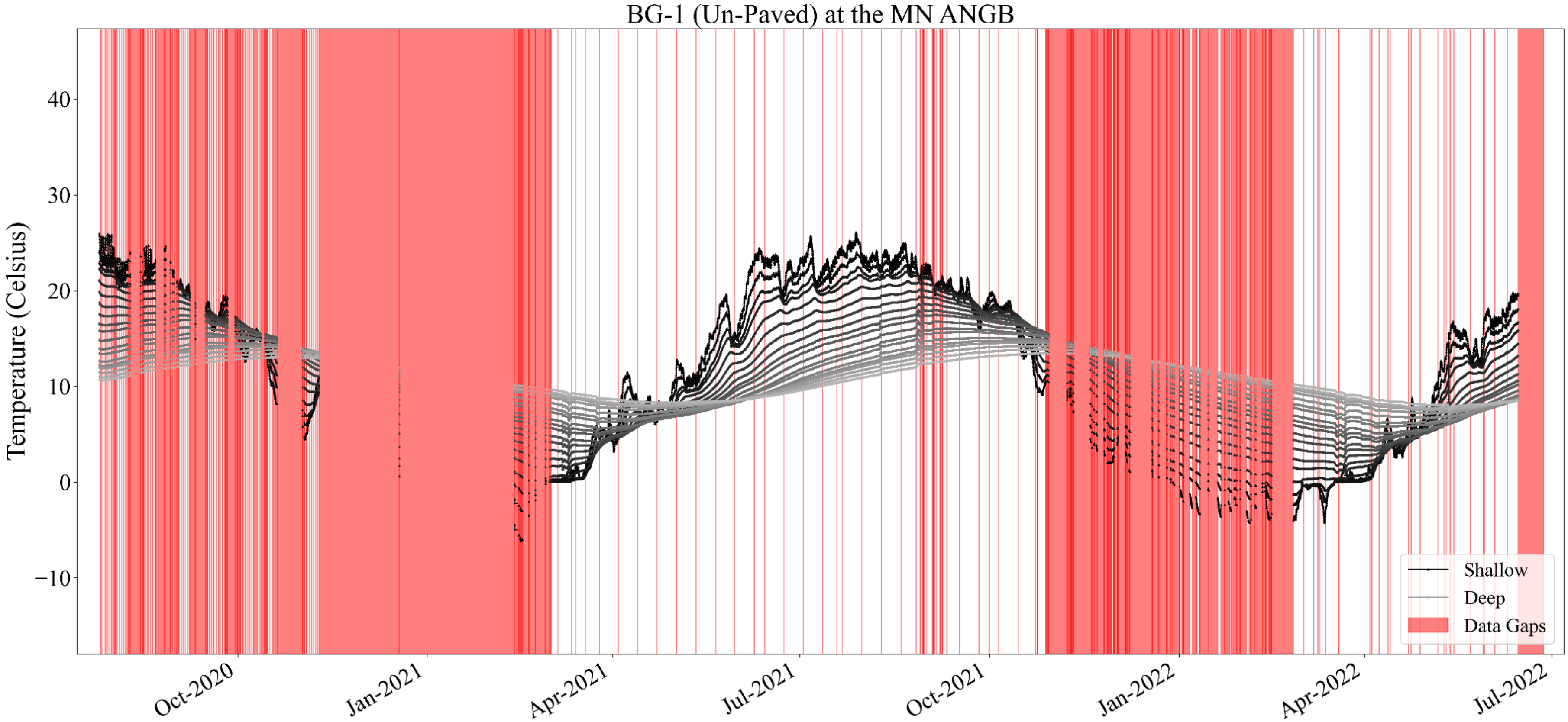
Figure 5.8. Temperature Data at the MN ANGB



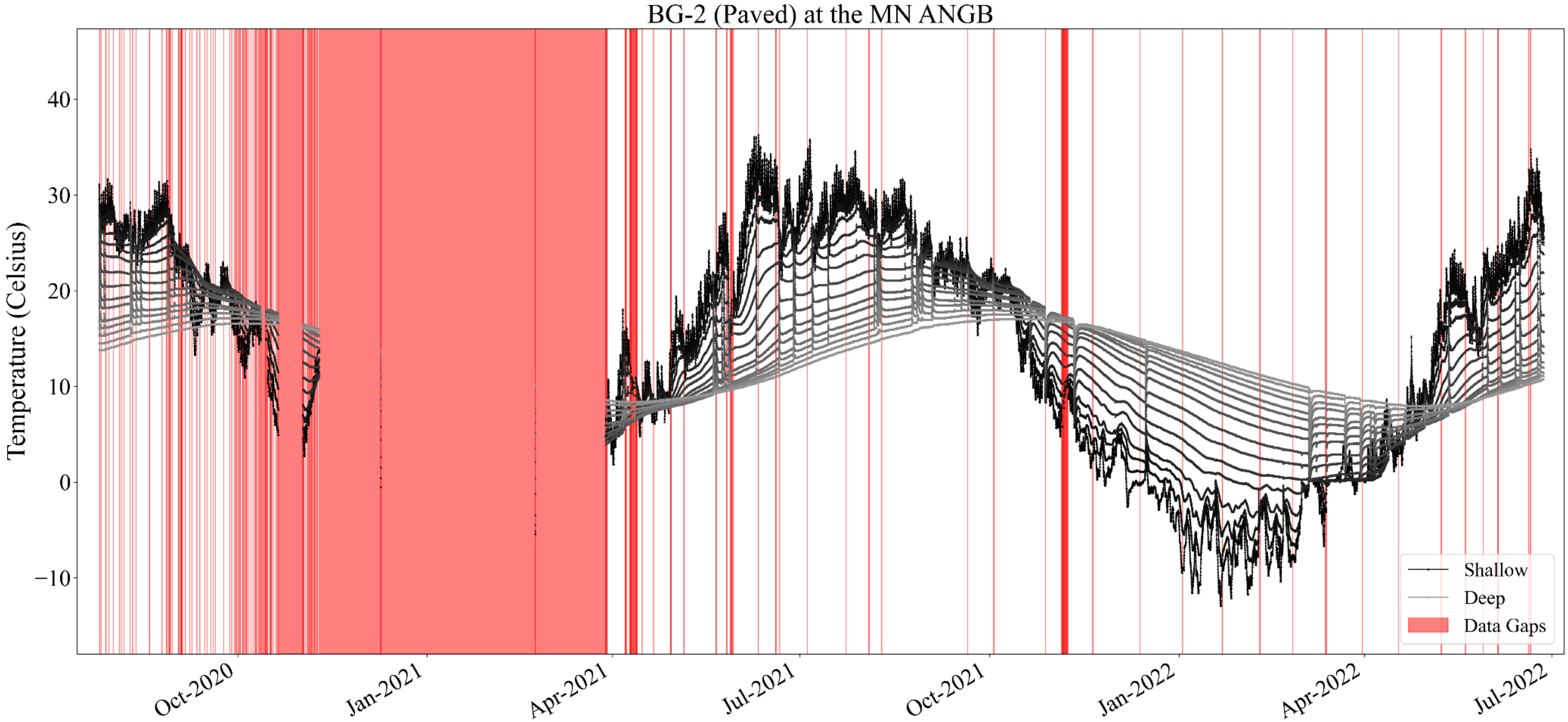
Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 14 ft bgs.



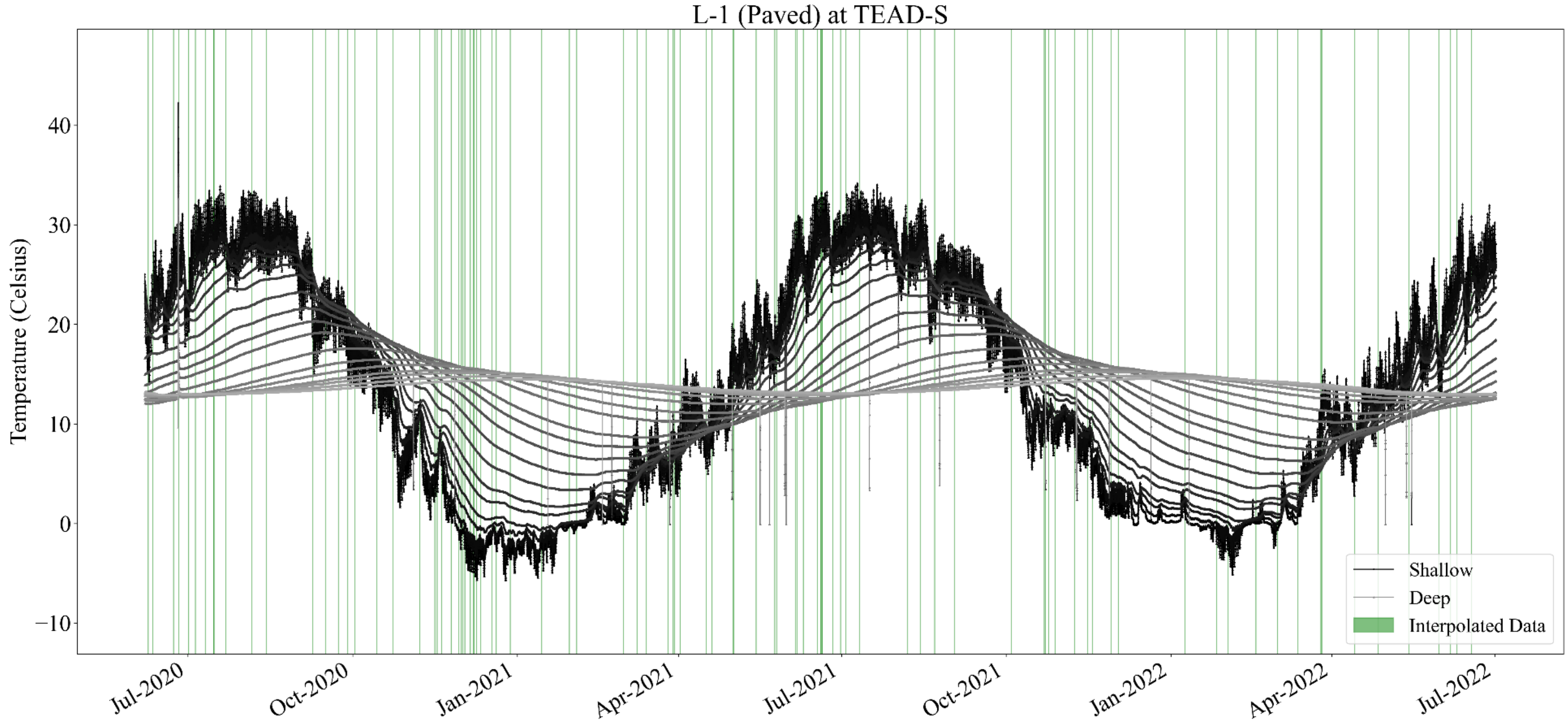
Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 14 ft bgs. This location did record any data past mid-January 2022, resulting in a data gap that could not be interpolated at this location.



Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 17 ft bgs. This location did record any data past mid-June 2022, resulting in a data gap that could not be interpolated at this location.

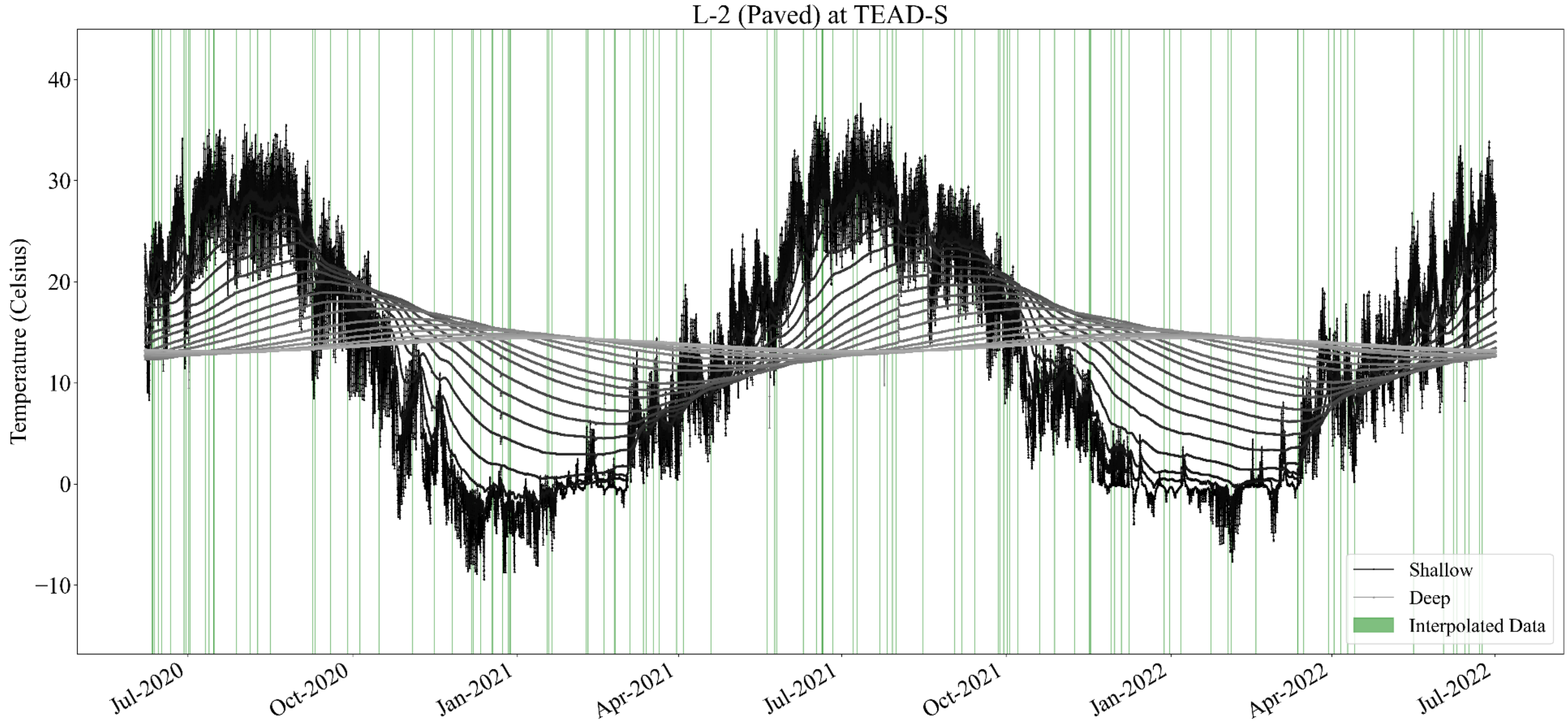


Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 14 ft bgs.

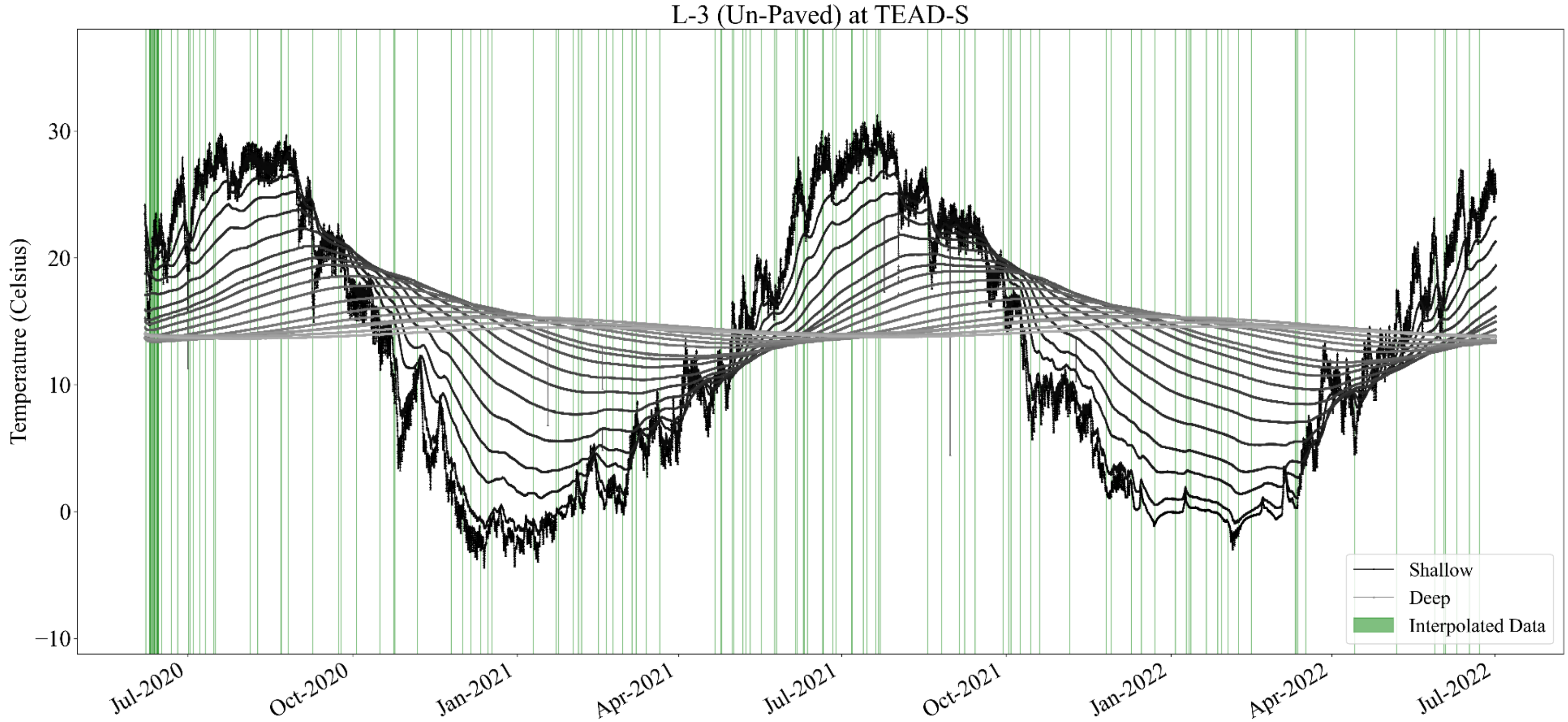


Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 24 ft bgs.

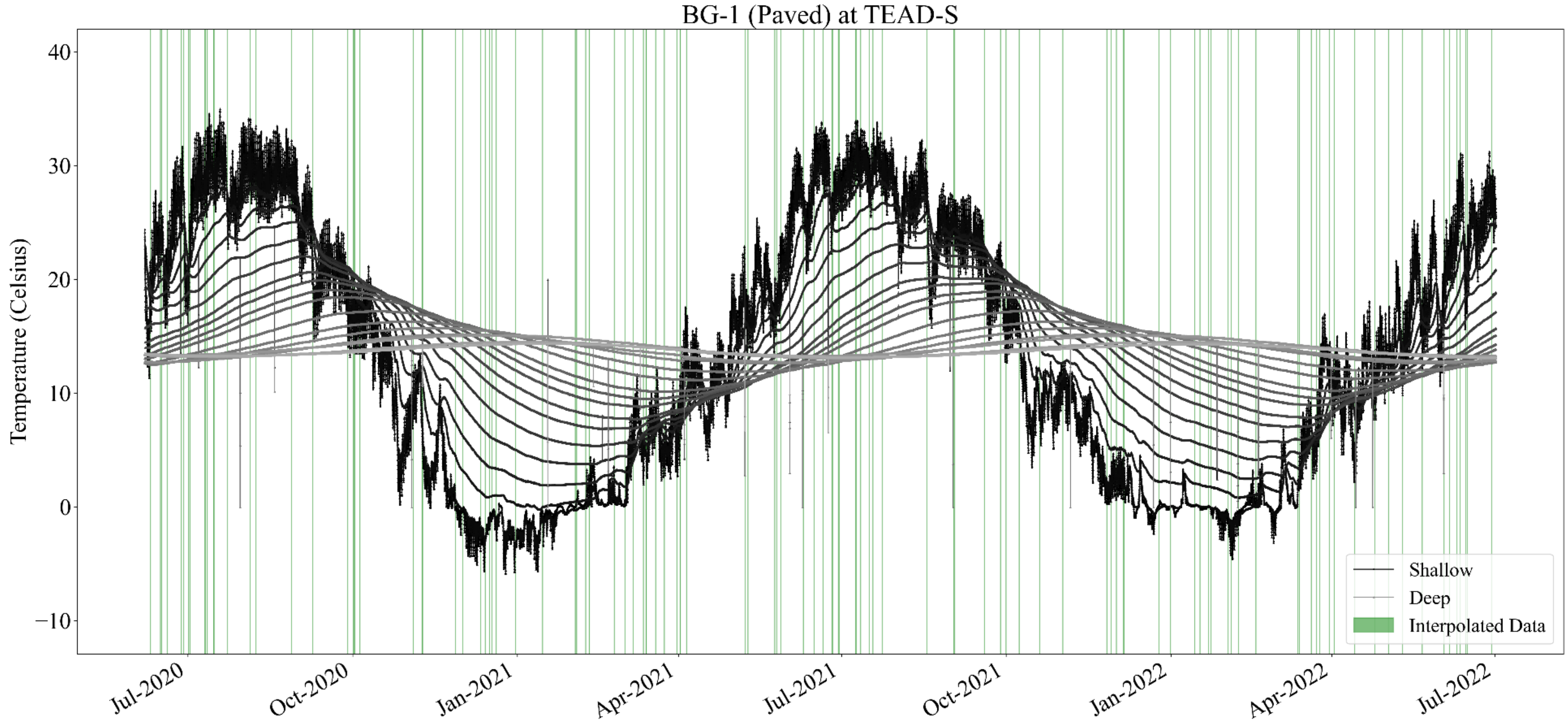
Figure 5.9. Interpolated Temperature Data at TEAD-S



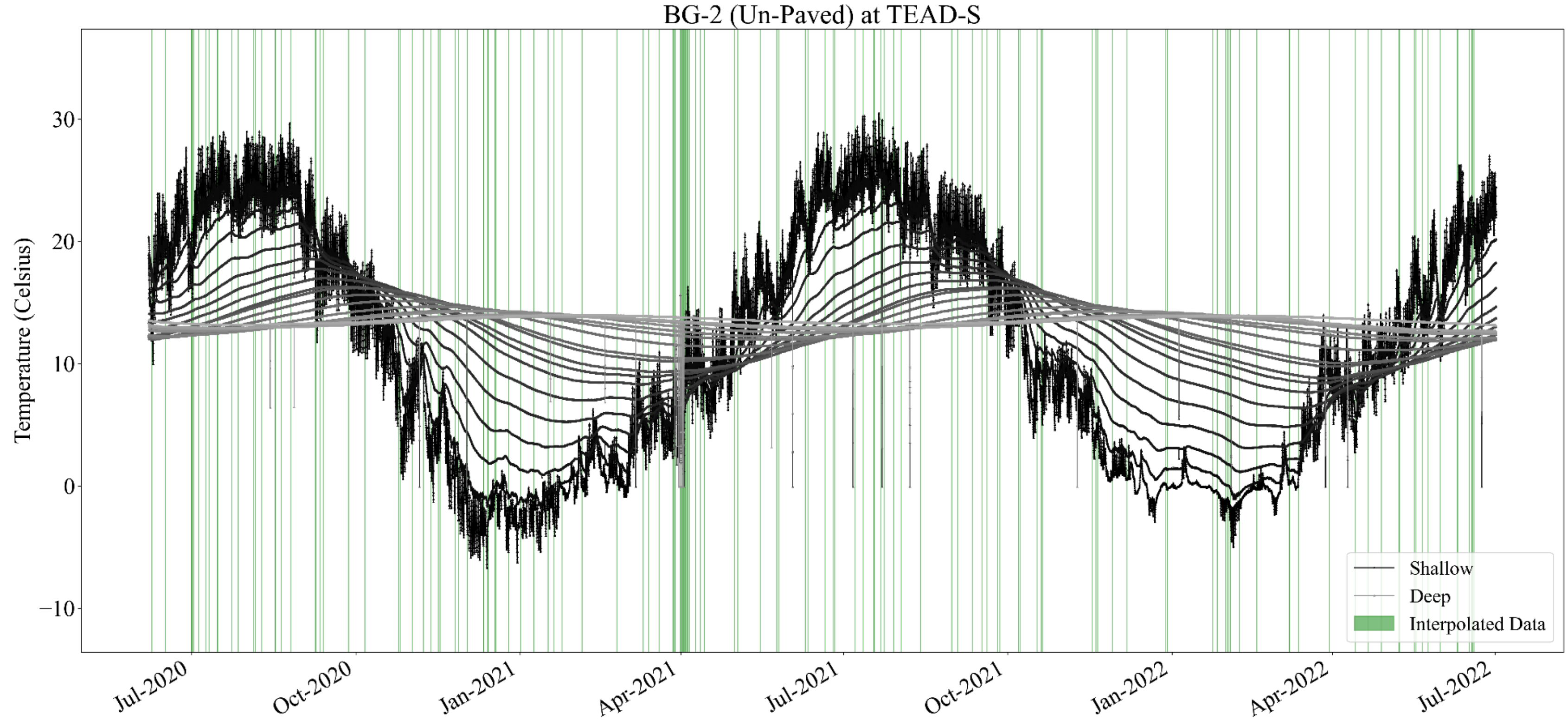
Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 24 ft bgs.



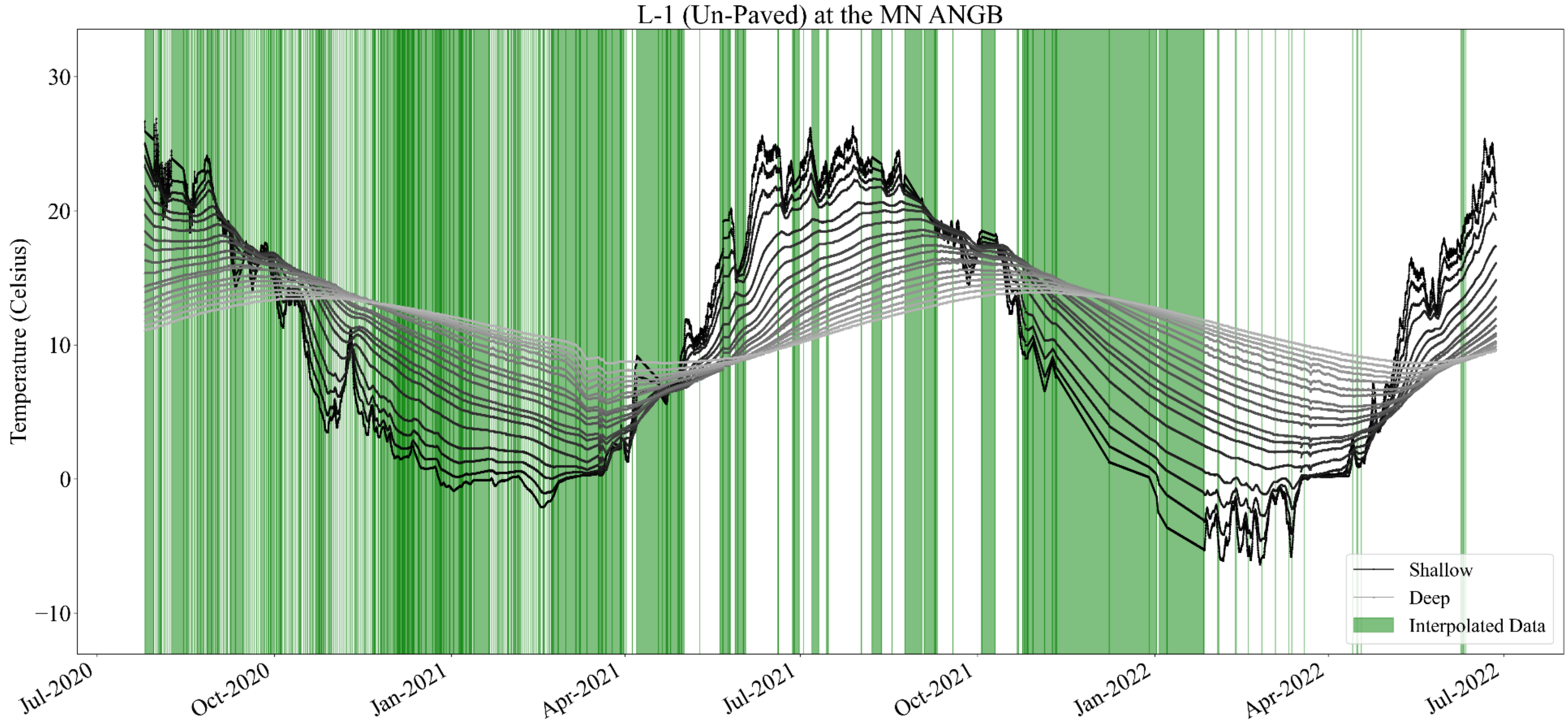
Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 24 ft bgs.



Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 24 ft bgs.

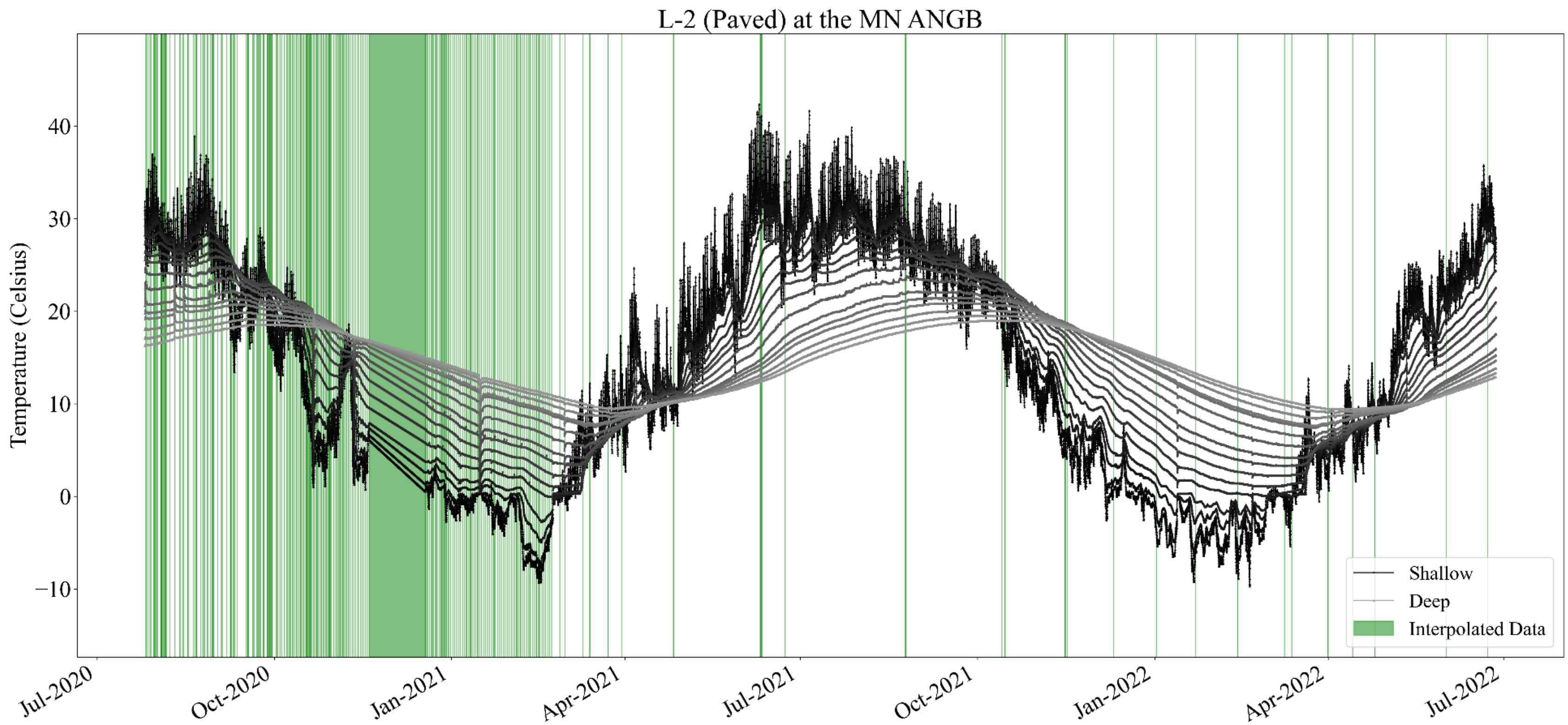


Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 24 ft bgs.

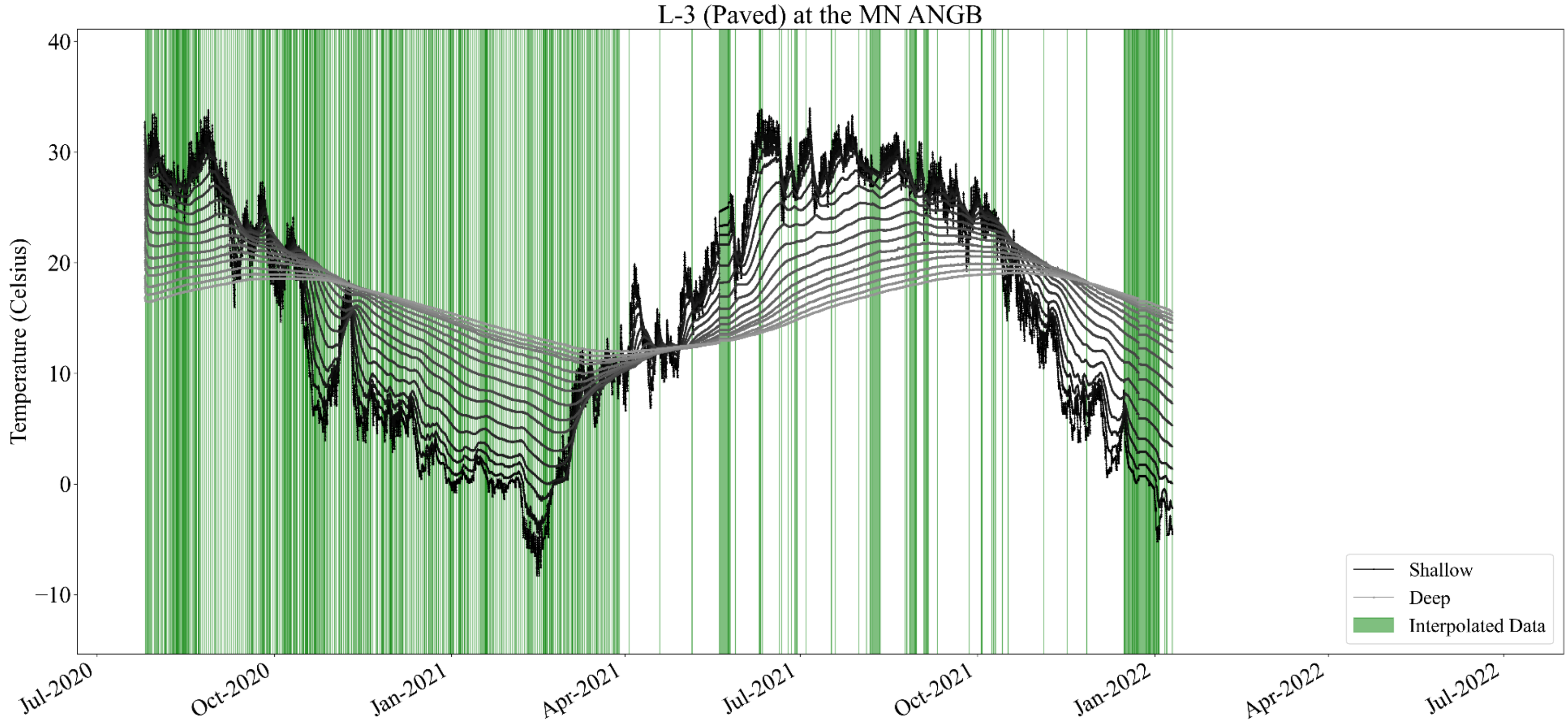


Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 17 ft bgs.

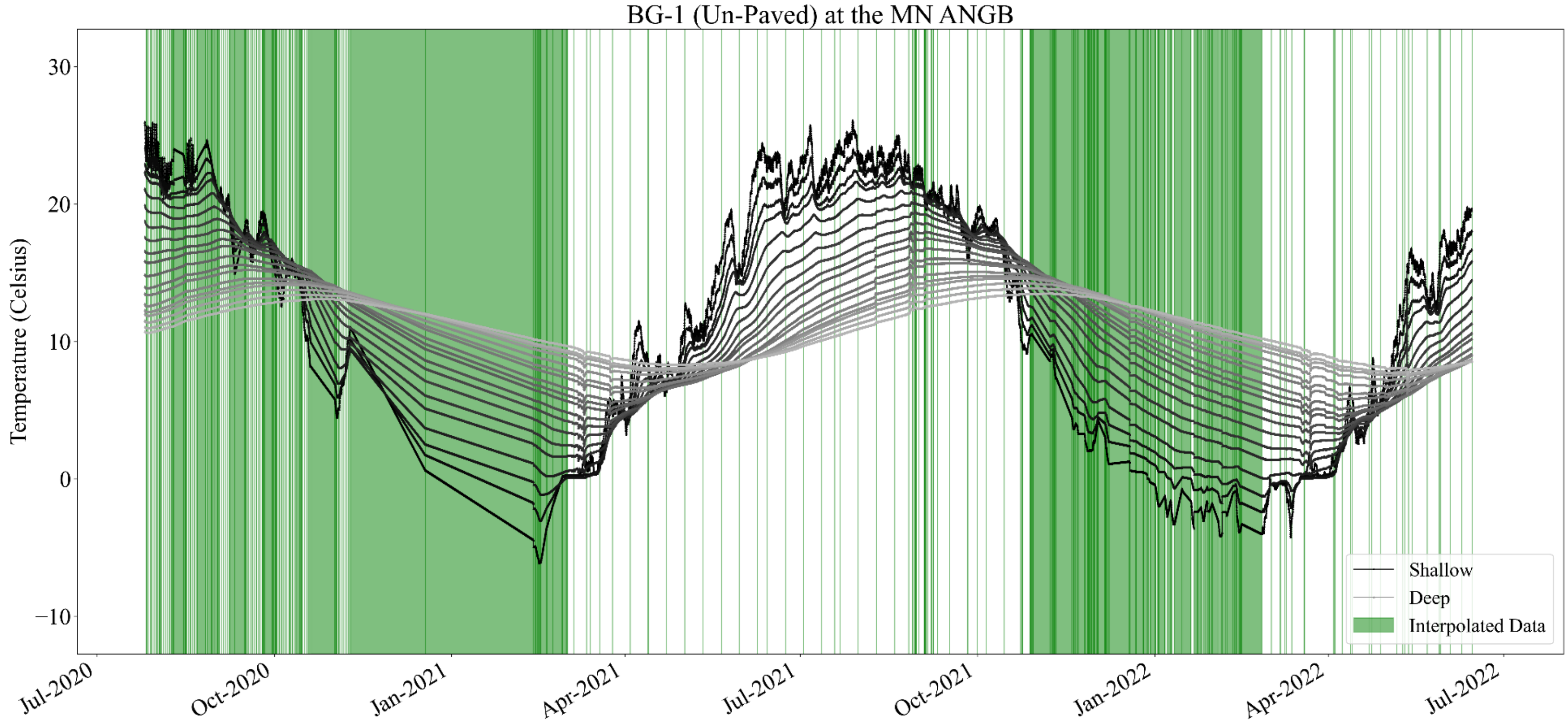
Figure 5.10. Interpolated Temperature Data at the MN ANGB



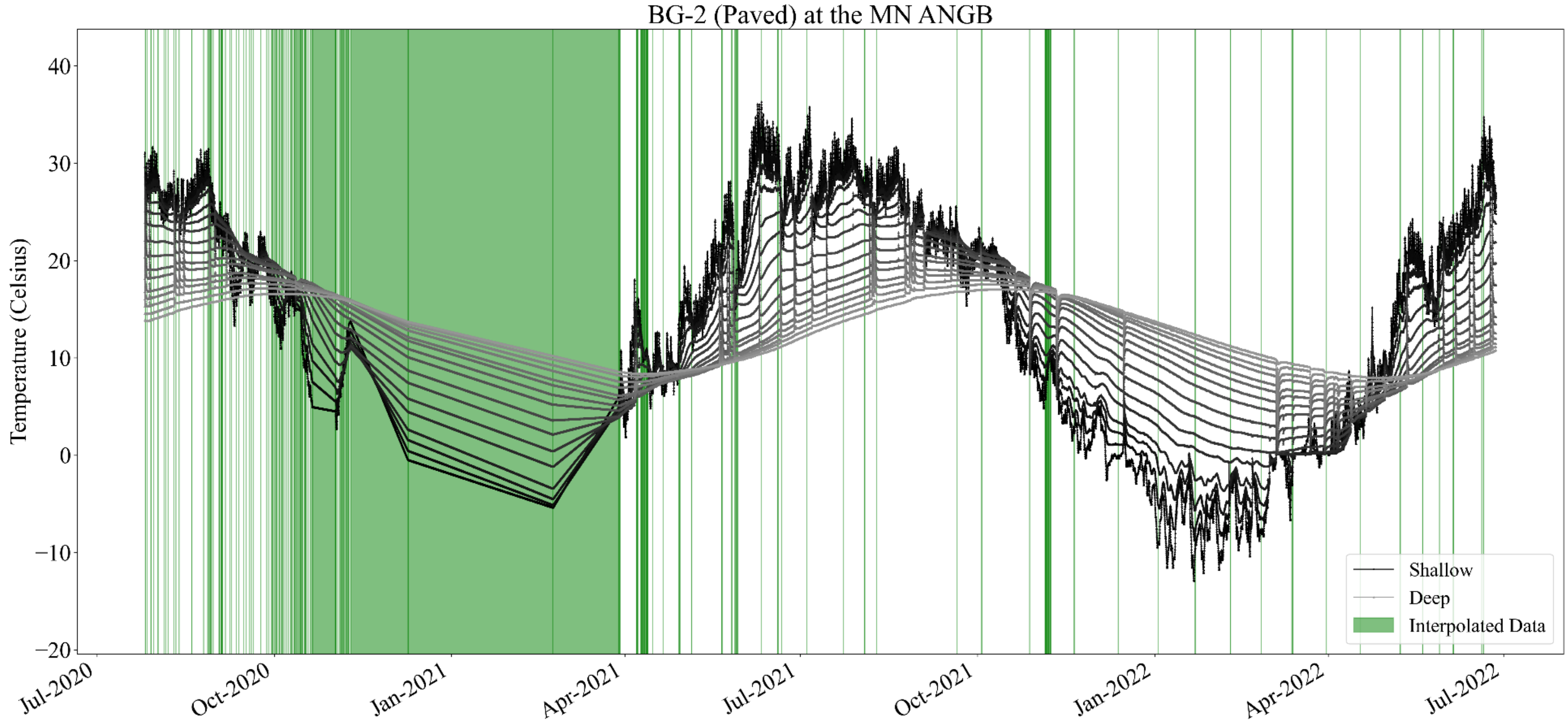
Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 14 ft bgs.



Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 14 ft bgs. This location did record any data past mid-January 2022, resulting in a data gap that could not be interpolated at this location.



Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 17 ft bgs. This location did record any data past mid-June 2022, resulting in a data gap that could not be interpolated at this location.



Note: Line shading grades from dark to light gray representing shallow to deep sensor locations, respectively, from 0.5 ft to 14 ft bgs.

5.7.4 NSZD Multiple Site Study

Site-wide NSZD rates were compiled from 40 petroleum LNAPL source zones in the United States, Canada, Europe, and Australia from researchers, project reports, and scientific papers, with NSZD rates measured by the gradient method, Carbon Traps, DCC, or temperature-based monitoring methods. At each site, the following data were compiled: i) general site location; ii) LNAPL fuel type; iii) measurement method, number of locations, and number of measurements per location; and iv) calculated site-wide average NSZD rate. The overall database consisted of 4,838 measurements across the 40 studies. Subsets of sites were used to evaluate: i) comparisons of rates using multiple methods at the same site; ii) temporal variability across seasons and multiple years at the same site; and iii) the impact of climatic temperature on measured NSZD rates (evaluated using average seasonal rates). Across the sites evaluated, there was not enough information available on site characteristics such as soil type, soil moisture, depth to LNAPL, LNAPL volume, or annual average site temperature to evaluate the effect of these site factors on measured NSZD rates.

Table 5.6 shows the average site-wide NSZD rates of all methods (in units of liters/hectare/year). The study methods, results, and conclusions have been documented in a scientific paper recently published in the journal Water Research. Additional citation information on this paper (Kulkarni et al. 2022b) is provided in Appendix F.

Table 5.6. Summary of Average Site-Wide NSZD Rates of All Methods

	Avg. Site-Wide NSZD Rate, All Methods, L/ha/yr *(gal/ac/yr)*
Minimum	650 (*70*)
10^{th} Percentile	1,590 *(170)*
25^{th} Percentile	2,810 *(300)*
Median	9,540 (*1,020*)
75^{th} Percentile	25,440 *(2,720)*
90^{th} Percentile	51,350 *(5,490)*
Maximum	152,000 *(16,250)*
Number of Sites	***40***

5.7.5 ORP Sensors

One potential advantage of the 2^{nd} generation temperature monitoring stations is that they also include sensors that record ORP at each location where temperature is recorded. Installation of the 2^{nd} generation temperature monitoring stations provided an opportunity to concurrently test ORP sensors, as described by Sale et al. (2021). ORP sensors measure the voltage differences between an Ag Ag-Cl reference electrode (Borin Manufacturing, STELTH® 2™) and multiple level dimensionally stable titanium sensing electrodes with a catalytic mixed metal coating (Corrpro Industries – Elgard™ Ribbon Mesh). ORP sensing electrodes are co-located with temperature sensors. Per standard ORP measurements, assuming a pH of 7, ORP values range from +606 mV, correlating to oxygen, and -624 mV, correlating to hydrogen, with intermediate values indicating intermediate redox couples.

At each demonstration site, ORP data were recorded for the same time periods and at the same locations and depths as the temperature data (see Tables 5.2 and 5.5). Figures 5.11 and 5.12 show the ORP data for TEAD-S and the MN ANGB, respectively, presented using proprietary "GAS Plots" (Gallo-Askarani-Sale plots) provided by the technology vendor S3NSE Technologies and CSU (non-proprietary plots of the ORP data are shown in Appendix B.1 and B.2). The color scale of GAS plots, depicting the visible light spectrum, document ORP conditions (see legend on figure). Warm colors (e.g., red and yellow) indicate oxidizing conditions, and cool colors (e.g., blue and violet) indicate reducing conditions.

Overall, the ORP plots illuminate ORP conditions in temporal cross-sections as a function of depth. The raw ORP data are provided in Appendix H.11 and H.12. The utility of the ORP data for understanding NSZD rates and processes is discussed in Section 6.4.3.

L-1 (Paved)

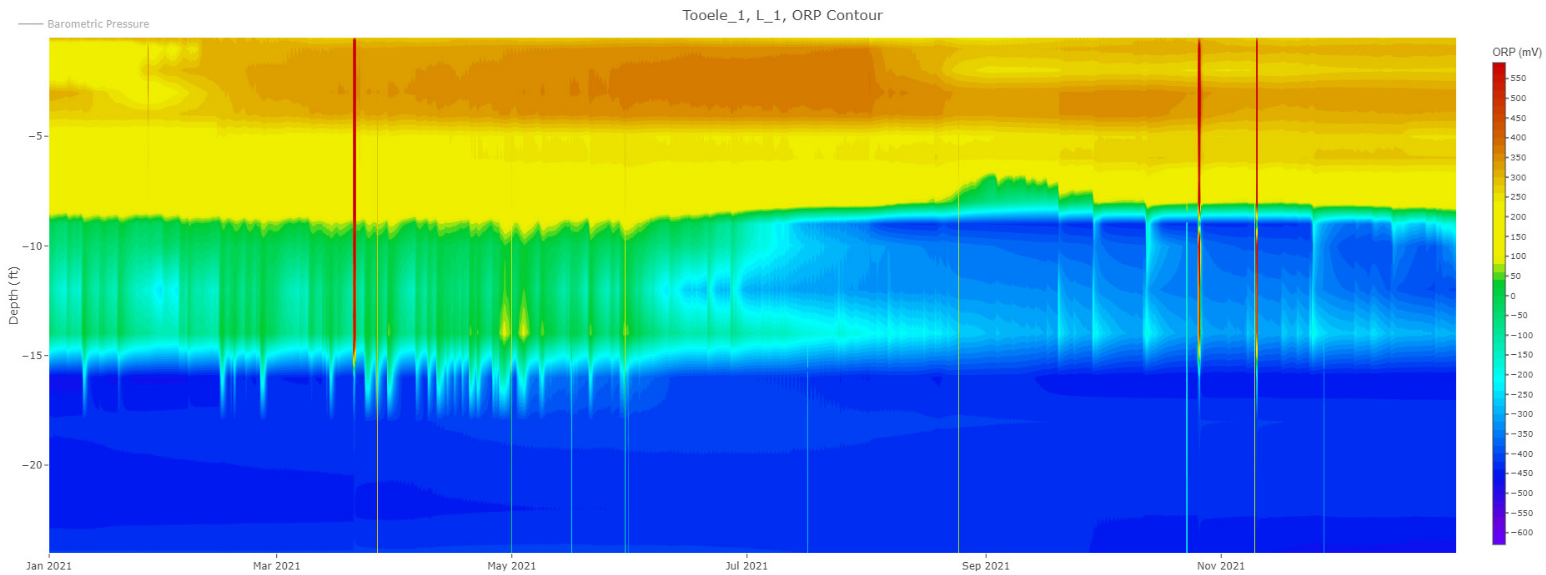
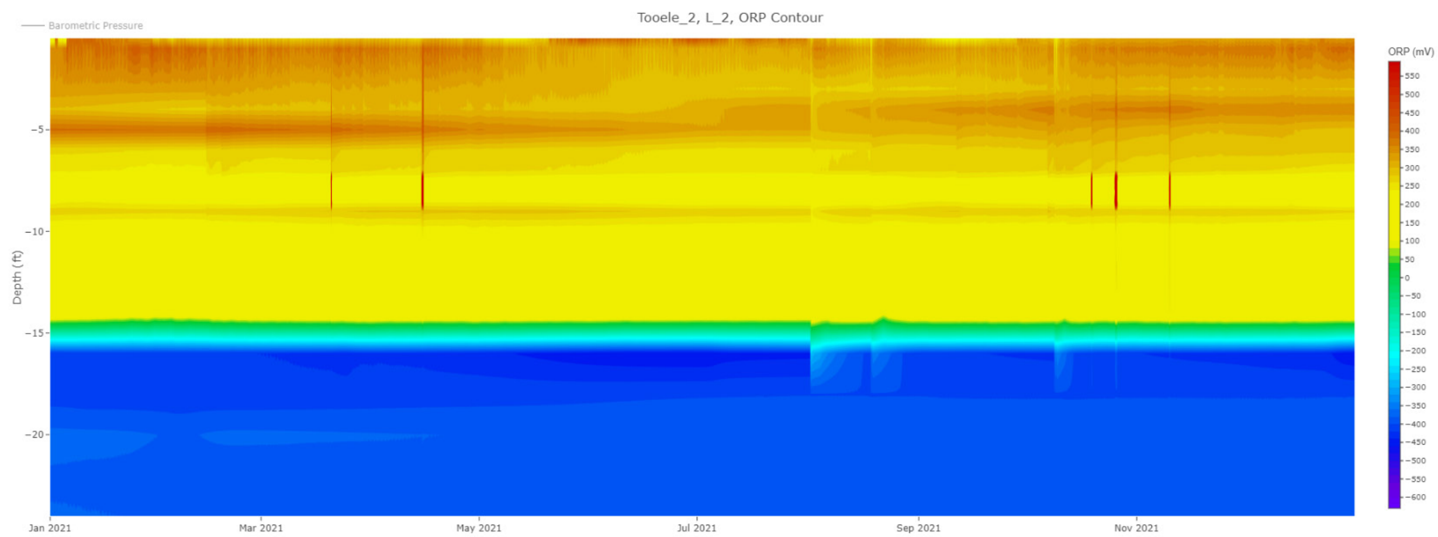
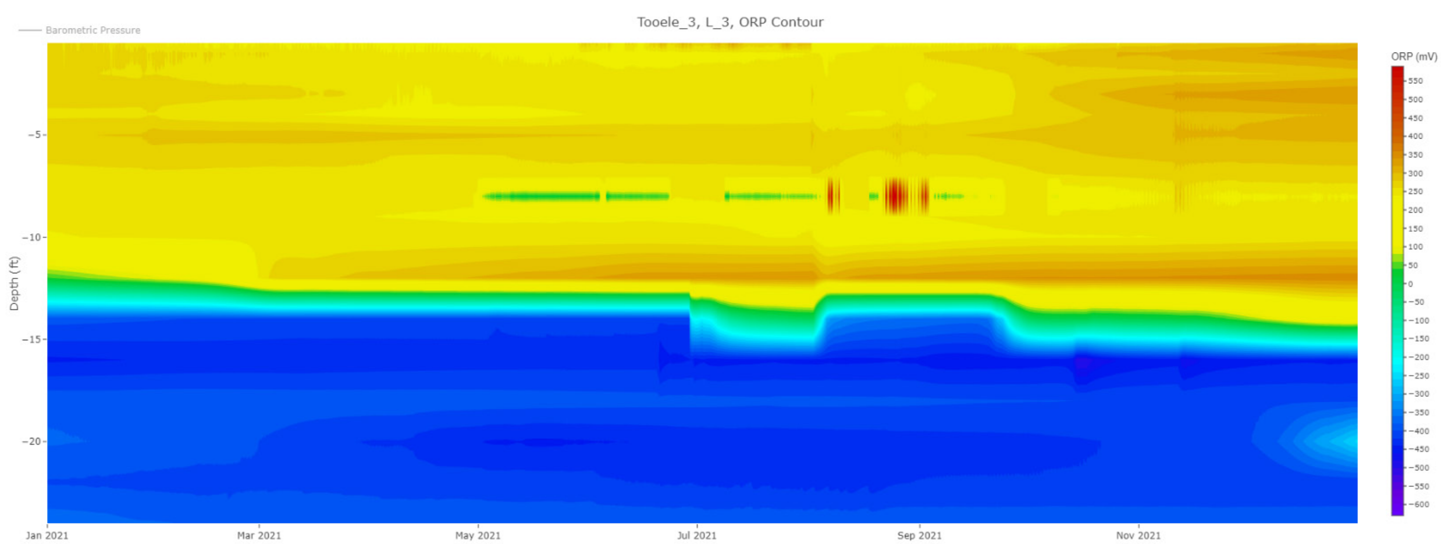


Figure 5.11. GAS Plots of ORP Data at TEAD-S

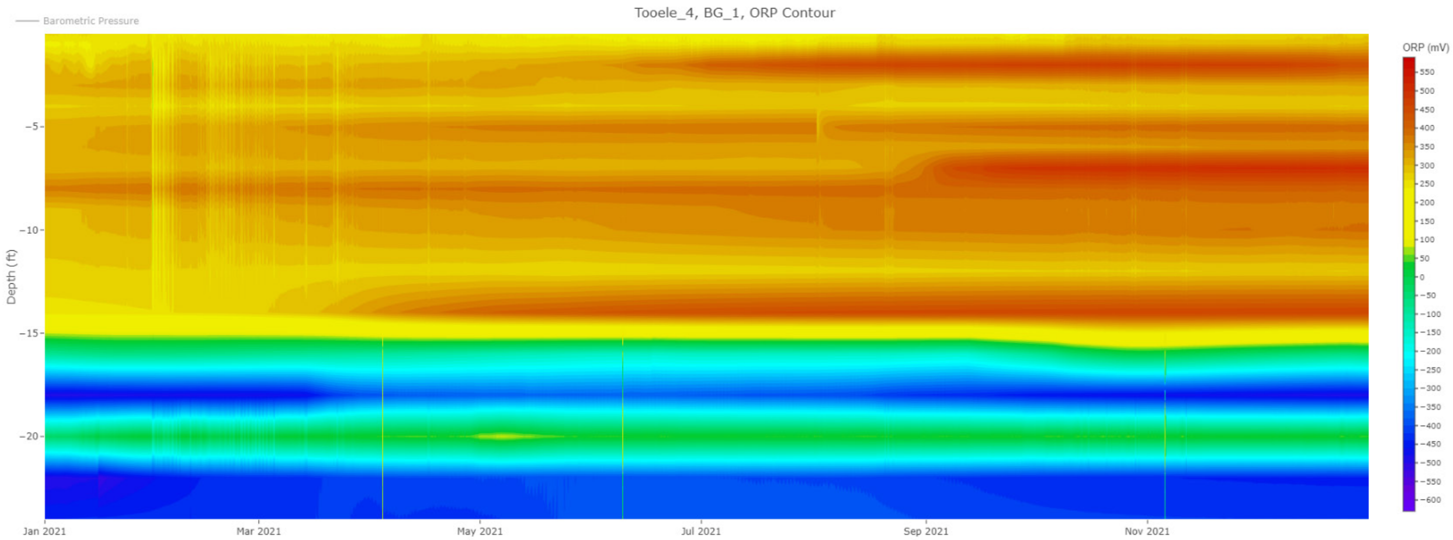
L-2 (Paved)



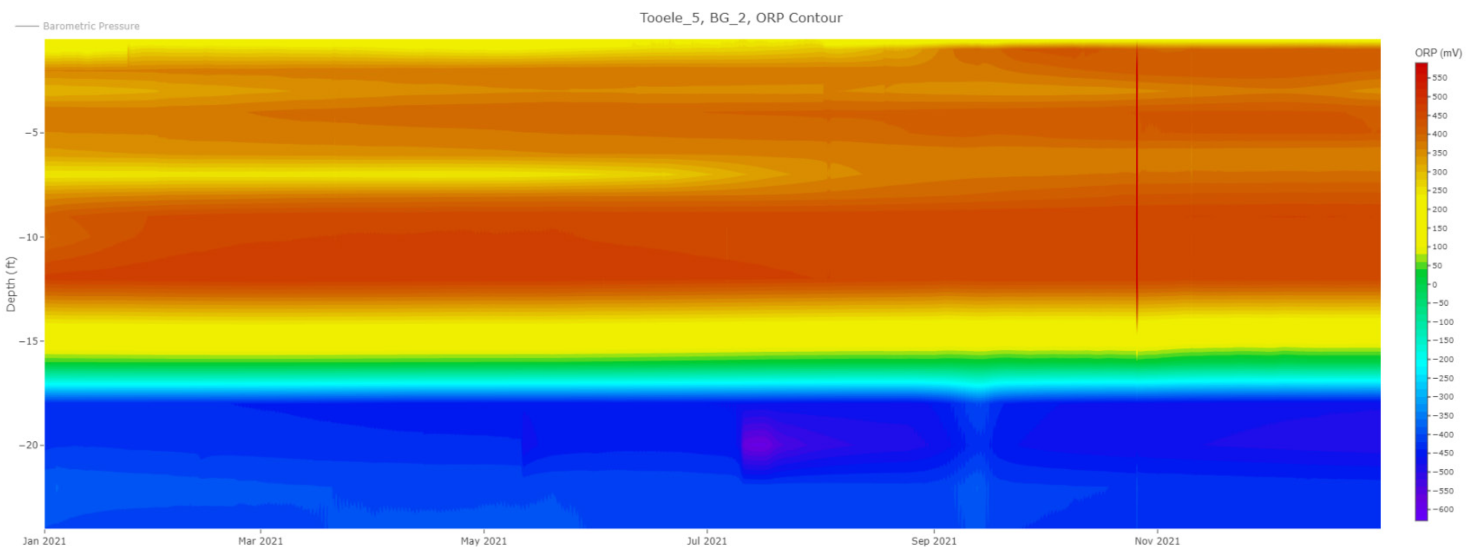
L-3 (Unpaved)



BG-1 (Paved)



BG-2 (Unpaved)



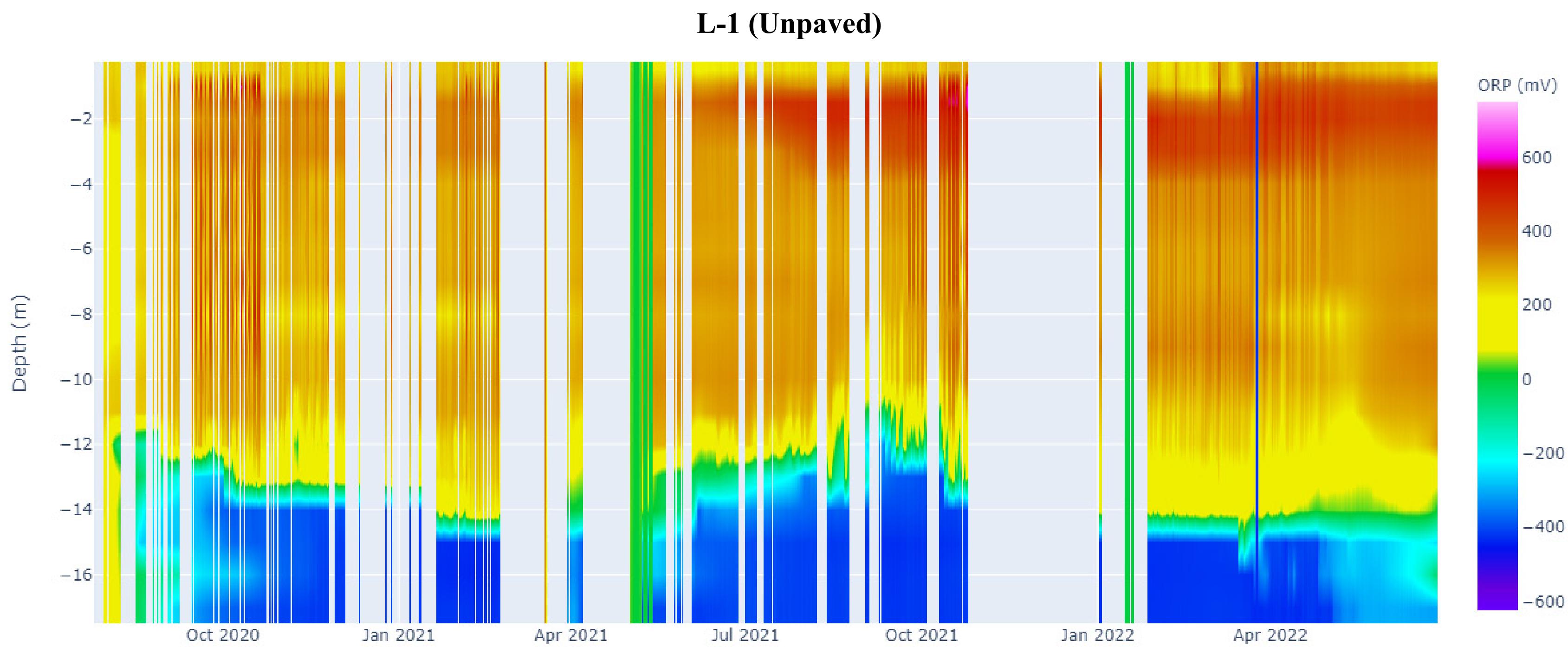
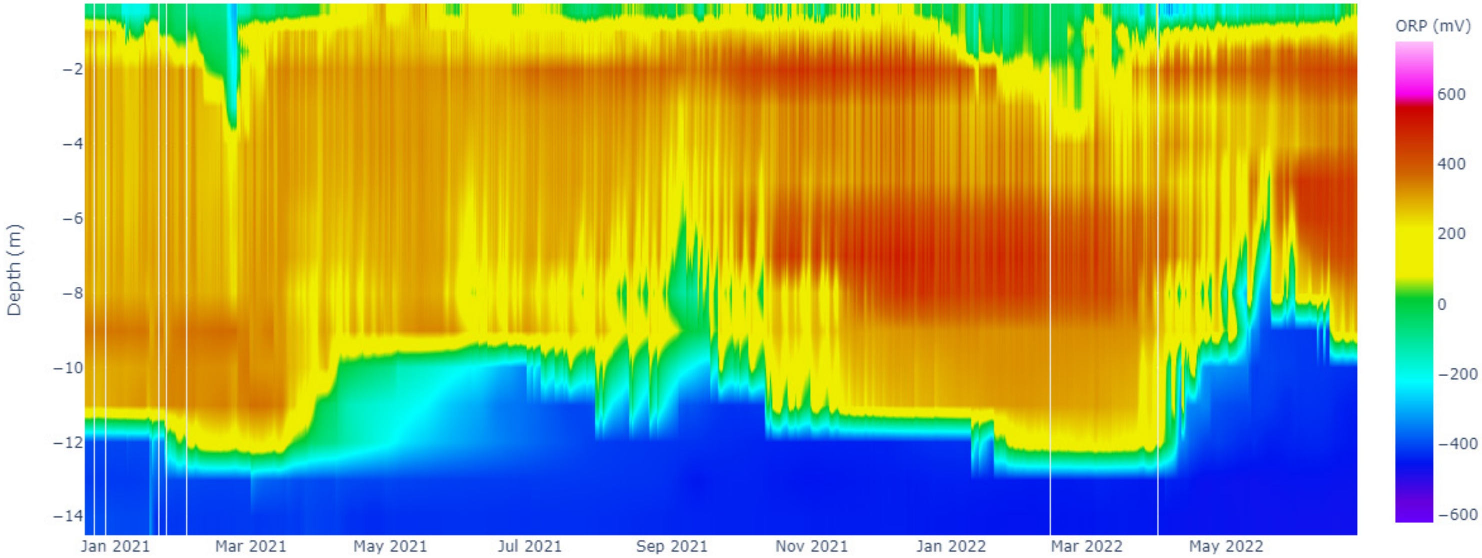
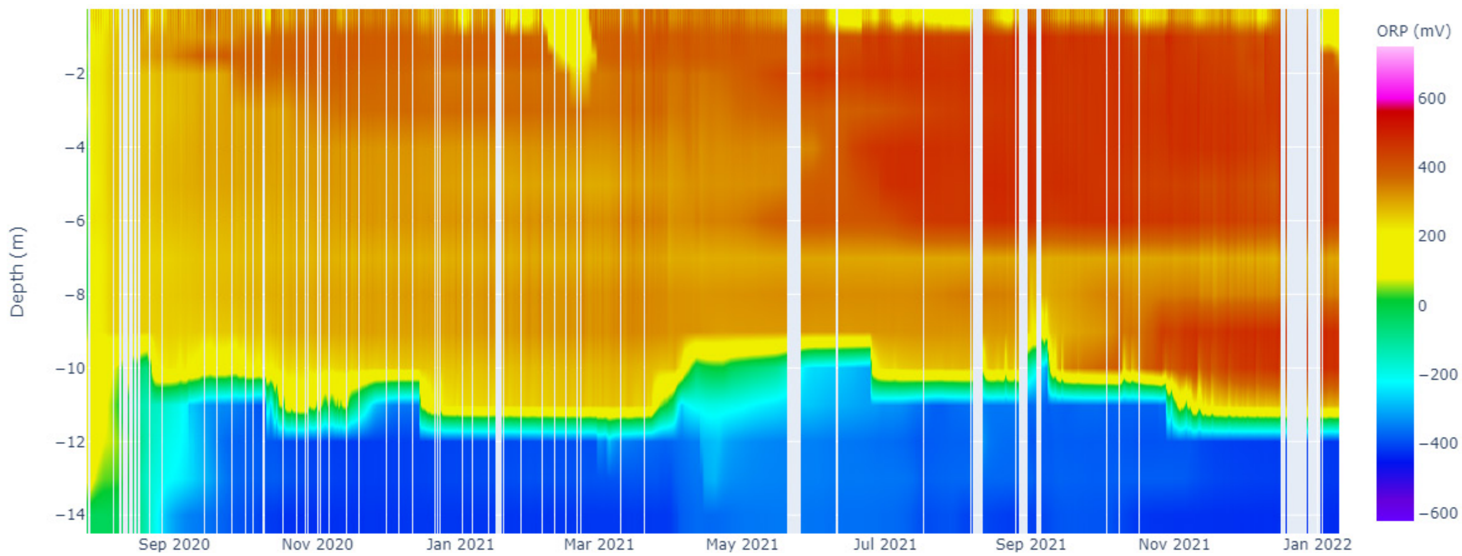


Figure 5.12. GAS Plot of ORP Data at the MN ANGB

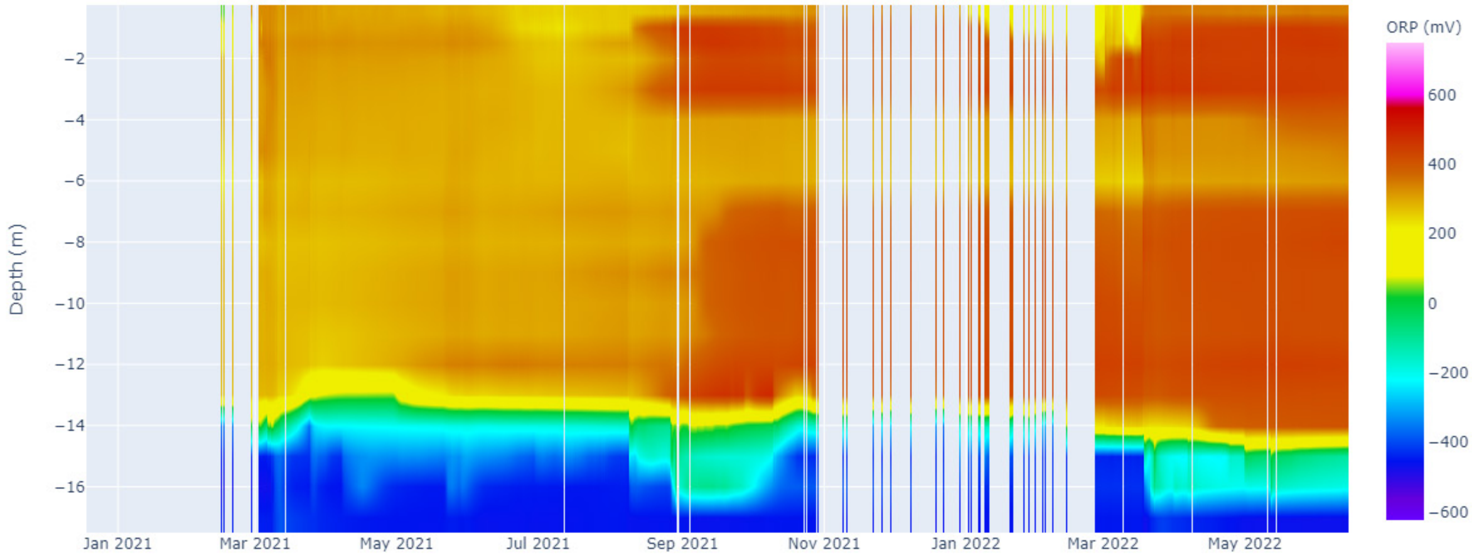
L-2 (Paved)



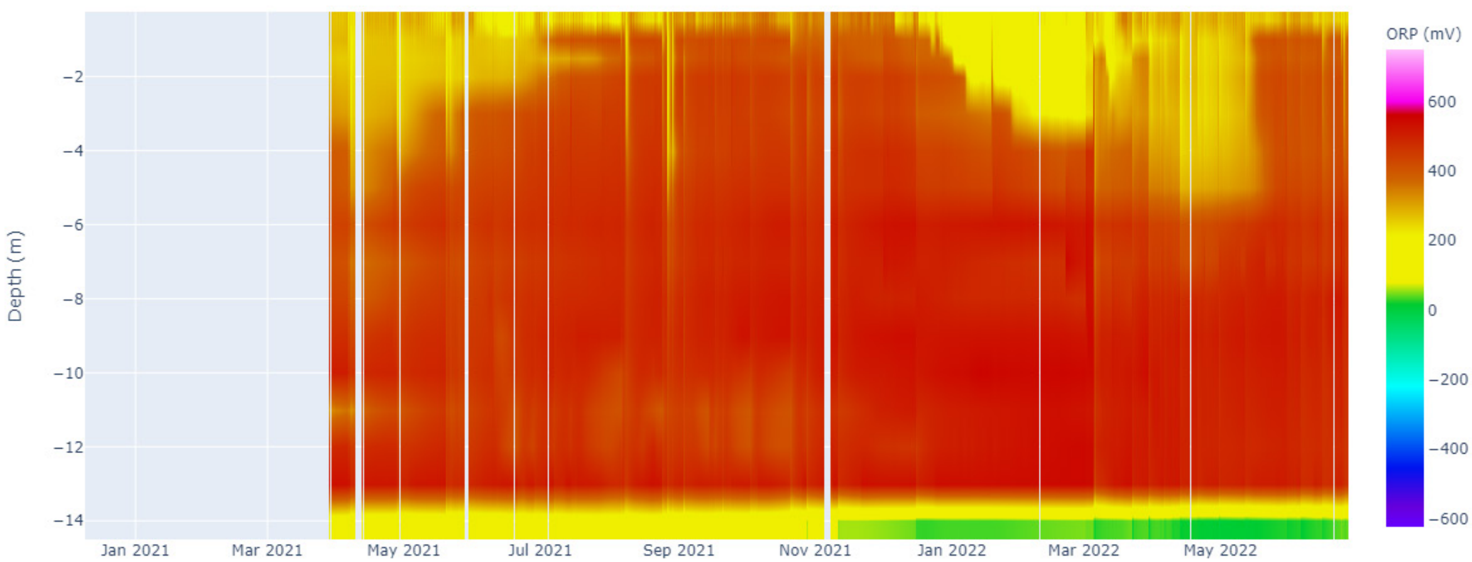
L-3 (Paved)



BG-1 (Unpaved)



BG-2 (Paved)



6.0 PERFORMANCE ASSESSMENT

Table 3.1 summarizes the six performance objectives, and an evaluation of these objectives is provided in Sections 6.1 to 6.6.

6.1 PERFORMANCE OBJECTIVE 1: COLLECTION OF A COMPLETE DATASET

Field demonstrations were conducted at two sites: TEAD-S and the MN ANGB. At each of the two demonstration sites, monitoring was conducted at three locations within the LNAPL source zone (2 paved, 1 unpaved) and at two background locations (1 paved, 1 unpaved) (see Figures 4.1 and 4.2). At each monitoring location, the data collection included i) oxygen, carbon dioxide, and methane; ii) Carbon Traps; and iii) temperature monitoring stations that recorded temperature, ORP, and water level data. The water level data are not required data and were not determined to be useful for understanding NSZD rates or processes and, therefore, are not discussed further.

As summarized in Table 3.1, the performance objective was to obtain temperature data for >95% of planned temperature measurement days and to obtain >90% of other planned alternative measurements.

6.1.1 Oxygen, Carbon Dioxide, and Methane

Although the Demonstration Plan called for only one round of soil gas measurements at each demonstration site, three rounds were collected at TEAD-S, and two rounds were collected at the MN ANGB. The number of soil gas sample collection points at each site is detailed in Table 5.1. Table 6.1 summarizes the soil gas data set obtained during the field demonstration. As discussed in Section 5.6.1, all methane results for MN ANGB were rejected due to anomalous readings.

Table 6.1. Summary of Soil Gas Samples Data Set Completeness at Each Demonstration Site

Site	Total Number of Sample Collection Points	Number of Planned Rounds of Sample Collection	Number of Rounds of Sample Collection	Total Possible Samples	Samples Collected and Analyzed
TEAD-S	41	1	3	123	123 (100%)
MN ANGB	41	1	2	82	82 (100%)

Results: Achieved. Data set completeness (100%) for oxygen and carbon dioxide exceeded the performance objective of 90% completeness for soil gas samples as an alternative method. The absence of reliable methane data at the MN ANGB (0% dataset completeness at the MN ANGB; 100% data set completeness at TEAD-S) did not adversely affect the use of the soil gas data to qualitatively evaluate NSZD, as discussed in Section 6.3.2.

6.1.2 Carbon Traps

One round of carbon flux measurements (i.e., Carbon Traps) was collected at each of the two demonstration sites. At each site, one Carbon Trap was deployed at each of the five sample locations for multiple weeks, for a total of 10 Carbon Traps. Valid carbon flux and NSZD rate results were obtained from each Carbon Trap.

Results: Achieved. Data set completeness (100%) exceeded the performance objective of 90% completeness for Carbon Trap samples as an alternative method.

6.1.3 Temperature Monitoring Stations

Each demonstration site had five temperature monitoring station locations. Each monitoring location consisted of 16-19 vertically-spaced temperature sensors (see Table 5.2 for sensor depths), resulting in a total of 176 temperature measurement points. At each measurement location, while sensor readings were recorded approximately every 60 minutes, the evaluation of NSZD rates utilized daily average temperatures. Therefore, data completeness is evaluated in terms of valid daily average sensor measurements. Except for the shallowest sensors, the variations in temperature and ORP within a single day were small compared to the longer-term variations. As a result, for any day with at least 12 hourly temperature measurements, the use of linear interpolation to estimate the missing temperature values almost certainly had very little effect on the daily average temperature value used in the NSZD rate evaluations. Thus, data completeness was evaluated in terms of days with at least 12 hourly measurements. Table 6.2 summarizes the data set completeness for the temperature monitoring sensors at each monitoring location. The number of records per day are shown in Figure 6.1 for TEAD-S and 6.2 for the MN ANGB, respectively.

Table 6.2. Summary of Temperature Monitoring Station Sensor Data Set Completeness

Temperature Monitoring Station Location	Number of days in monitoring period	Number of days with valid sensor data
TEAD-S		
L-1 (paved)	730	730 (100%)
L-2 (paved)	730	730 (100%)
L-3 (unpaved)	730	730 (100%)
BG-1 (paved)	730	730 (100%)
BG-2 (unpaved)	730	730 (100%)
MN ANGB		
L-1 (unpaved)	665	411 (62%)
L-2 (paved)	665	635 (95%)
L-3 (paved)	665	460 (69%)
BG-1 (unpaved)	665	398 (60%)
BG-2 (paved)	665	498 (75%)

Note: TEAD-S analysis period: 1 July 2020 through 30 June 2022. The MN ANGB analysis period: 1 September 2020 through 27 June 2022. Valid sensor data included days with at least 12 hourly temperature measurements.

As shown in Table 6.2, at the MN ANGB, valid sensor data were below the performance objective of 95% completeness at four of the five sensor locations. At this site, data were lost due to a number of different, partially unresolved issues with the wireless communication, the temperature monitoring station batteries and solar panels, and the datalogger software. Weather issues (e.g., the cold climate of Minnesota) did not appear to be the cause of the lost data. These issues and associated remedial efforts are discussed in more detail in Section 6.4.1. As discussed in Section 5.7.3, linear interpolation was used to estimate missing temperature values to calculate NSZD rates.

The likely impact of the error associated with the estimated temperature values on the calculated NSZD rates is discussed in Section 6.2.4, below.

6.1.4 Overall Performance Objective 1 Success Criteria and Results

Success Criteria: Obtain temperature measurements for >95% of planned measurement locations/days and >90% of planned alternative method measurements (Table 3.1)

Results: **Achieved at Site 1 (TEAD-S); Not Achieved at Site 2 (MN ANGB).** At TEAD-S, temperature data set completeness (100%) exceeded the performance objective of 95% completeness for planned measurement days. However, at the MN ANGB, the data set completeness at the site level (72%) was below the performance objective of 95%, and data set completeness was below 95% at four of five temperature monitoring locations. Since the performance objective was not met for temperature measurements at the MN ANGB, linear interpolation was used to estimate missing hourly measurements, and the likely effect of the data interpolation on calculated NSZD rates was assessed to determine whether failure to meet the performance objective meaningfully affected the validity of the NSZD results. These analyses are discussed further in Section 6.2.4.

6.2 PERFORMANCE OBJECTIVE 2: IMPROVED BACKGROUND CORRECTION FOR TEMPERATURE-BASED MONITORING OF NSZD

In order to quantify NSZD rates, the increase in soil temperature attributable to petroleum biodegradation must be separated from other factors that affect the soil temperature. The primary driver of shallow soil temperatures is solar insolation, which leads to seasonal variations in soil temperature (i.e., summer warming and winter cooling), although other anthropogenic sources such as pipelines may also need to be considered. For this demonstration, we have evaluated three methods for "background correction" (i.e., removing non-biodegradation-related heat sources):

1. ***Method 1 - Annual Average Temperature Data***: For this method, first described by Warren and Bekins (2015), NSZD rates are calculated at each location using the annual average (mean) temperature at each sensor depth. Averaging temperature data for a full year reduces the effect of seasonal variations. Theoretically, assuming no additional subsurface heat sources (such as NSZD), there is no net change in subsurface temperature over the course of a year at non-impacted locations. Thus any deviations from a vertical temperature profile at an impacted location can be utilized to derive NSZD rates, assuming that NSZD is the only source of additional heat. One limitation of this method is that the vertical temperature profile can be affected by deviations in temperature during the measurement year compared to long-term averages. For example, an unusually warm year would have a greater effect on the shallow sensors compared to the deeper sensors and would likely result in an underestimation of the actual NSZD rates for that year by flattening the temperature gradient upwards toward the ground surface. Another limitation of this method is that it does not allow for an evaluation of variations in NSZD rates within a single year.

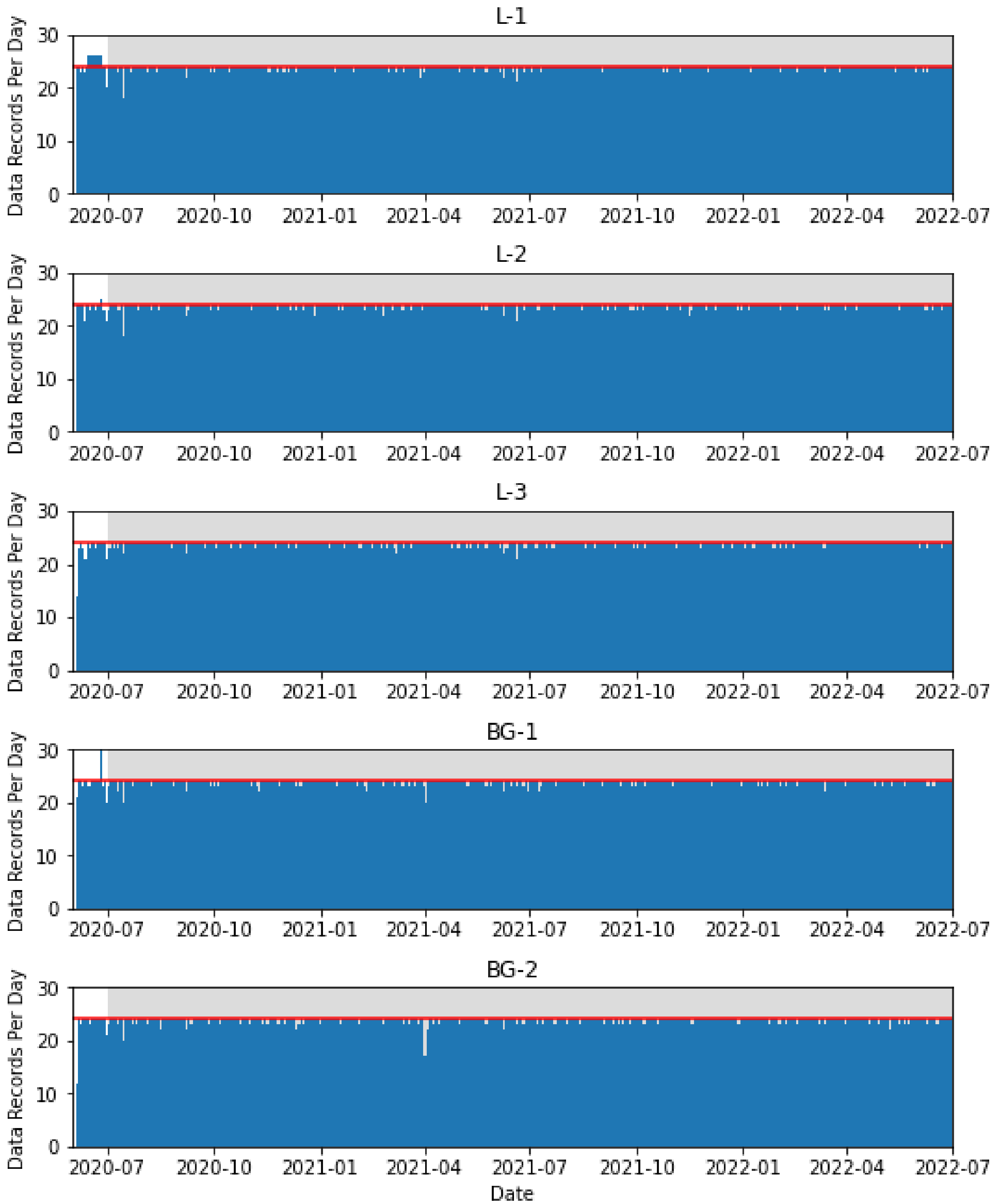


Figure 6.1. Maximum Number of Temperature Data Records Per Day at TEAD-S.

The entire data collection period beginning at installation is displayed; the light gray shading indicates the analysis period.

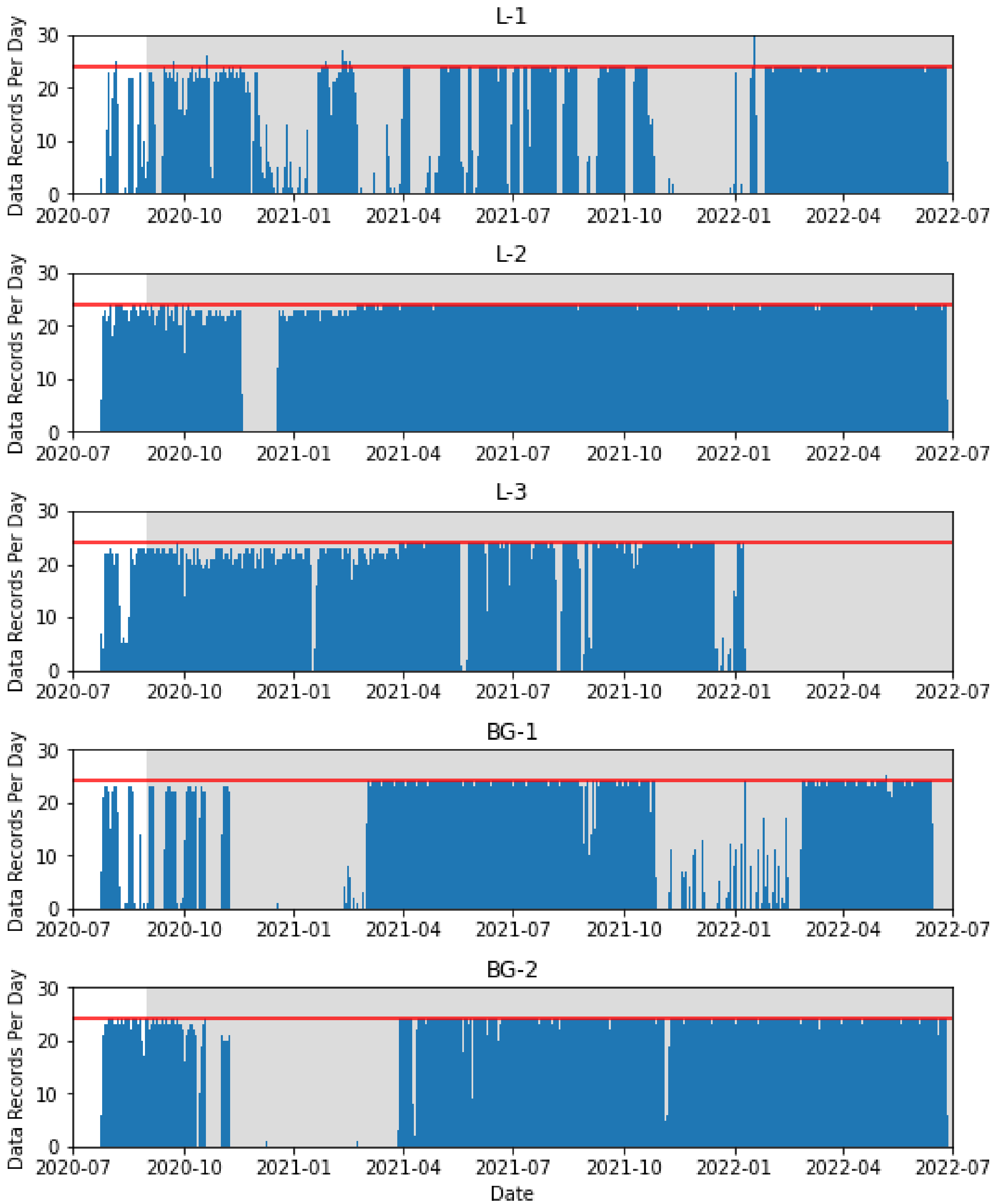


Figure 6.2. Maximum Number of Temperature Data Records Per Day at the MN ANGB.

The entire data collection period beginning at installation is displayed; the light gray shading indicates the analysis period.

2. ***Method 2 - Correction Using Background Location***: For this method, NSZD rates are calculated at each source area location based on the observed difference in temperature between a source area monitoring location and a background location with similar properties (e.g., lithology, surface cover, etc.) (e.g., Stockwell 2015; Sale et al. 2018). Daily NSZD rates can be computed, which allows for an evaluation of variations in NSZD rates within a single year. This method is based on the assumption that factors other than NSZD have the same effect on soil temperature at the source location and the background location. If this assumption is not valid, then the calculated NSZD rates may be larger or smaller than the true rates. Surface cover (e.g., bare dirt, vegetation, pavement, or shade) can affect both absolute soil temperature at shallow depths and the magnitude of seasonal temperature variation. As a result, differences in surface cover between the source location and background location can result in errors in the calculated NSZD rates. This project attempted to control for this variable by collecting background data at both paved and unpaved locations.
3. ***Method 3 - Single Stick Method***: For this method, an algorithm is used to estimate the heat flux at the ground surface (attributed to seasonal variations) and the heat flux at a subsurface point (attributed to NSZD) required to account for the observed daily change in vertical temperature profile at each monitoring location (Karimi Askarani and Sale 2020). This method allows for an evaluation of variations in NSZD rates within a single year. The Single Stick method needs around two months of data to condition the algorithm. As a result, the Single Stick method does not yield NSZD rates for the first two months of monitoring at each location.

All three methods rely on a continuous array of daily values and cannot be applied robustly to datasets with significant data gaps unless a method is used to estimate missing temperature values. The presence of external heat sources or errors in estimating the thermal properties of the soil could result in over or under estimation in NSZD rates.

For the annual average method, NSZD rates were calculated on an annual average dataset consisting of 365 continuous days, with one annual average temperature per depth. For the Single Stick and background-corrected datasets, an NSZD rate was calculated for each date in the analyzed dataset. To compare the annual average method NSZD rates, calculated over the course of a year, with the Single Stick and background-corrected rates, calculated for each day, an annual average NSZD rate was calculated for both the Single Stick and background-corrected rates from the daily NSZD rates.

Since more than one year of temperature data were collected at each site, annual average rates for each method were calculated for each continuous 365-day period within the dataset, and the median NSZD value is reported. The "uncertainty" in the rates is shown as the 25^{th} and 75^{th} percentile values of the calculated annual average NSZD rates. For example, at TEAD-S, where the dataset ran from 1 July 2020 to 30 June 2022, there are 365 unique "one-year" datasets analyzed, and the summary statistics (i.e., 25^{th} percentile, median, 75^{th} percentile) were derived from these 365 annual datasets.

The input parameters needed to compute the NSZD rates from the soil temperature data are summarized in Table 6.3.

Table 6.3. Input Parameter Values Used to Calculate Annual Average and Background Corrected NSZD Rates from Soil Temperature Data

Parameter	Value	Basis
TEAD-S		
Specific heat capacity of soil	1,139 J/kg-K	Busby (2015), Clay, Sand, Sandy Loams, but generally less than 40% silt
Soil bulk density	1,320 kg/m^3	Busby (2015), Clay, Sand, Sandy Loams, but generally less than 40% silt
Depth to water	15 ft bgs (All locations)	Representative site data
Thermal Conductivity	BG-1: 0.58 W/m-K BG-2: 0.60 W/m-K L-1: 0.72 W/m-K L-2: 0.57 W/m-K L-3: 0.49 W/m-K	Methodology in Kulkarni et al. 2022a
MN ANGB		
Specific heat capacity of soil	1,039 J/kg-K	Busby (2015), Loam to sand
Soil bulk density	1,470 kg/m^3	Busby (2015), Loam to sand
Depth to water	10 ft bgs (BG-2, L-2, L-3); 15 ft bgs (BG-1, L-1)	Representative site data
Thermal Conductivity	BG-1: 1.74 W/m-K BG-2: 1.29 W/m-K L-1: 1.86 W/m-K L-2: 1.28 W/m-K L-3: 0.92 W/m-K	Methodology in Kulkarni et al. 2022a

One of the key input parameters in the estimation of NSZD rates is the thermal conductivity of the subsurface. The thermal conductivity can vary both spatially and temporally, due to factors such as the variable soil moisture content. While prior approaches have utilized literature values based on site conditions or one-time point measurements on ex situ core with a small spatial support (e.g., several cubic inches), this study applied a new method to quantify depth-discrete thermal conductivities. As described in Kulkarni et al. (2022a), daily subsurface temperature data over a full year provide seasonal amplitude differences that can be used to calculate a thermal diffusivity, which is then used to estimate a site-specific thermal conductivity over that time period. As such, the temperature data collected during the demonstration period can be utilized to provide a spatial and temporal average soil thermal conductivity at the site.

The thermal conductivity of the soil at each Temperature Monitoring Station was estimated based on the approach described in Kulkarni et al. (2022a). The thermal conductivity of each vertical interval between sensors in the unsaturated zone was calculated at each location for each continuous 365-day window in the temperature dataset. Following the recommendations of Kulkarni et al. (2022a), and a review of the thermal conductivity profiles, for each 365-day window, the mean thermal conductivity was calculated across the intervals for unsaturated soil depths greater than 3 ft (1 m) bgs and shallower than where the amplitude of temperature fluctuations decreased below 0.5 deg C. Since more than one year of temperature data were collected at each site, the median thermal conductivity value was calculated across the range of continuous 365-day periods within the dataset at each location. This median thermal conductivity value across the unsaturated zone of interest (see Table 6.3) was utilized for the annual average and background-corrected methods.

This calculation approach required estimates of the specific heat capacity and bulk density of the soil (see Table 6.3), which were taken from Busby (2015) based on the predominant USCS soil type for each boring log at the demonstration sites (see Appendix D for boring logs).

Prior to analysis, the time series of temperatures over time were reviewed at both demonstration sites to ensure reasonable and consistent temperatures and general correspondence of changes over time between locations and depths. The collected data were deemed of sufficient quality for further analyses of NSZD rates. Background-corrected profiles were computed and evaluated to determine typical and representative depths of the heat signal from NSZD processes (i.e., a peak in background-corrected temperature that corresponds to the depth of aerobic methane oxidation). For both the Annual Average Temperature Data Method (Method 1) and the Correction Using Background Correction Method (Method 2), at TEAD-S, the upward heat flux was computed based on the difference in temperatures at depths of 0.5 and 7 ft bgs, and the downward heat flux was computed based on the difference in temperatures at depths of 9 and 12 ft bgs. At the MN ANGB site, the upward heat flux was computed based on the difference in temperatures at depths of 1 and 2 ft bgs, and the downward heat flux was computed based on the difference in temperatures at depths of 5 and 10 ft bgs.

NSZD results are presented as annual averages to minimize the impact of short-term deviations, and short-term (i.e., daily) NSZD rates are also provided below (e.g., see Figures 6.5 and 6.6). In addition, 25^{th} to 75^{th} percentile annual average NSZD rates are presented to further evaluate uncertainty in the calculated NSZD rates.

6.2.1 6.2.1 Evaluation of NSZD Rates Based on Annual Average Temperature Method

For this demonstration, the Method 1 annual average temperature method is used as the reference method for the evaluation of other methods to determine NSZD rates. The annual average temperature method is used as the reference because it is least likely to be affected by factors unrelated to NSZD. However, the annual average method requires a full year of temperature data and cannot be used to evaluate variations in NSZD rates over time periods of less than one year. Therefore, validation of the Method 2 background location method and/or the Method 3 Single Stick method may support a more detailed evaluation of the temperature data with respect to variations in NSZD rates over time.

Qualitative Evaluation of NSZD Based on Annual Average Temperatures: The average annual temperature profiles for the five monitoring locations at each of the two demonstration sites are provided in Figures 6.3 (TEAD-S) and 6.4 (MN ANGB) for the annual period 1 January 2021-31 December 2021. Visual comparison of the temperature profiles between the background locations and source area locations provides a qualitative indication of NSZD.

At TEAD-S, there is a clear difference in the profiles between the unpaved background location (BG-2) and the unpaved source area location (L-3) (Figure 6.3), with temperatures consistently higher at the source area location compared to background (2.0˚C to 2.4˚C higher over the depth interval of 7 ft to 10 ft bgs). At the unpaved source area location (L-3), the vertical temperature profile has a "shark fin" shape (i.e., a maximum temperature at an intermediate depth (i.e., 8 ft bgs), with lower temperatures above and below this depth) that indicates a heat source (likely attributable to methane oxidation) at this depth interval.

No such temperature maxima is observed at the background location (BG-2); rather, temperatures generally increase with depth to the bottom of the profile, with the increasing trend most pronounced in the shallow (approximately 0 to 7 feet bgs) zone. The vertical temperature profile for L-3 has a similar pronounced increasing trend in the shallow zone. These similar shallow trends of temperatures increasing with depth are likely caused by year-to-year variations in annual air temperatures, thus causing a net heating in the subsurface during this 365-day window.

In contrast to the unpaved locations, the vertical temperature profiles at the TEAD-S paved locations (L-1, L-2, and BG-1) show very little difference between the background location and the two source area locations. In addition, there is no obvious local maxima at either of the two source area locations. These results suggest little or no NSZD at the two paved source area locations. In summary, the vertical temperature profiles for TEAD-S indicate the occurrence of NSZD at the unpaved source area location but not the two paved source area locations, as seen with the 2021 data.

At the MN ANGB, the vertical temperature profiles at the unpaved locations (L-1 and BG-1) show very little difference between the background location and the source area location. In addition, there is no visible local maxima at either location. These results suggest little or no NSZD at the unpaved background and source area locations. However, field observations several weeks after installation indicated the presence of LNAPL at both the background (BG-1) and impacted (L-1) locations in the unpaved area. A “hydrocarbon” odor and a layer of free product were observed on the water table at both these locations while gauging water levels a few weeks after installation. In addition, the Carbon Trap results for these locations indicated that some, albeit relatively low, NSZD is occurring at both of these locations (i.e., 72-129 gal/acre/year; see Table 5.4). Thus, at the MN ANGB, the unpaved background location BG-1 is not likely to be a true non-impacted background location.

In contrast, there is a clear difference in the profiles between the MN ANGB paved background location (BG-2) and the two paved source area locations (L-2 and L-3), with temperatures consistently higher at the source area locations compared to background. In addition, at the two paved source area locations, the vertical temperature profiles show local maxima in a window around 2 to 6 ft bgs.

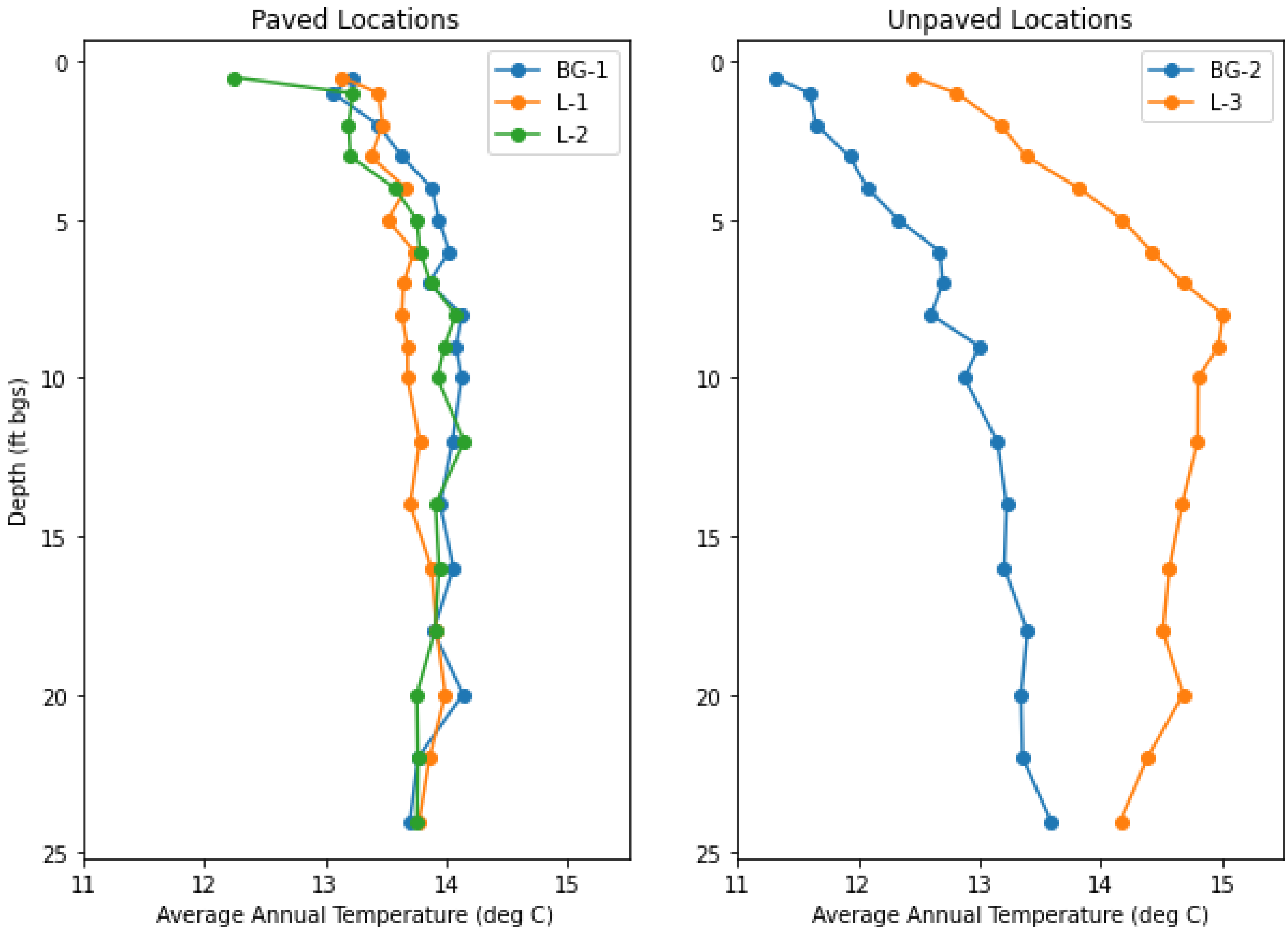


Figure 6.3. Mean Annual Vertical Temperature Profiles: January to December 2021 – TEAD-S

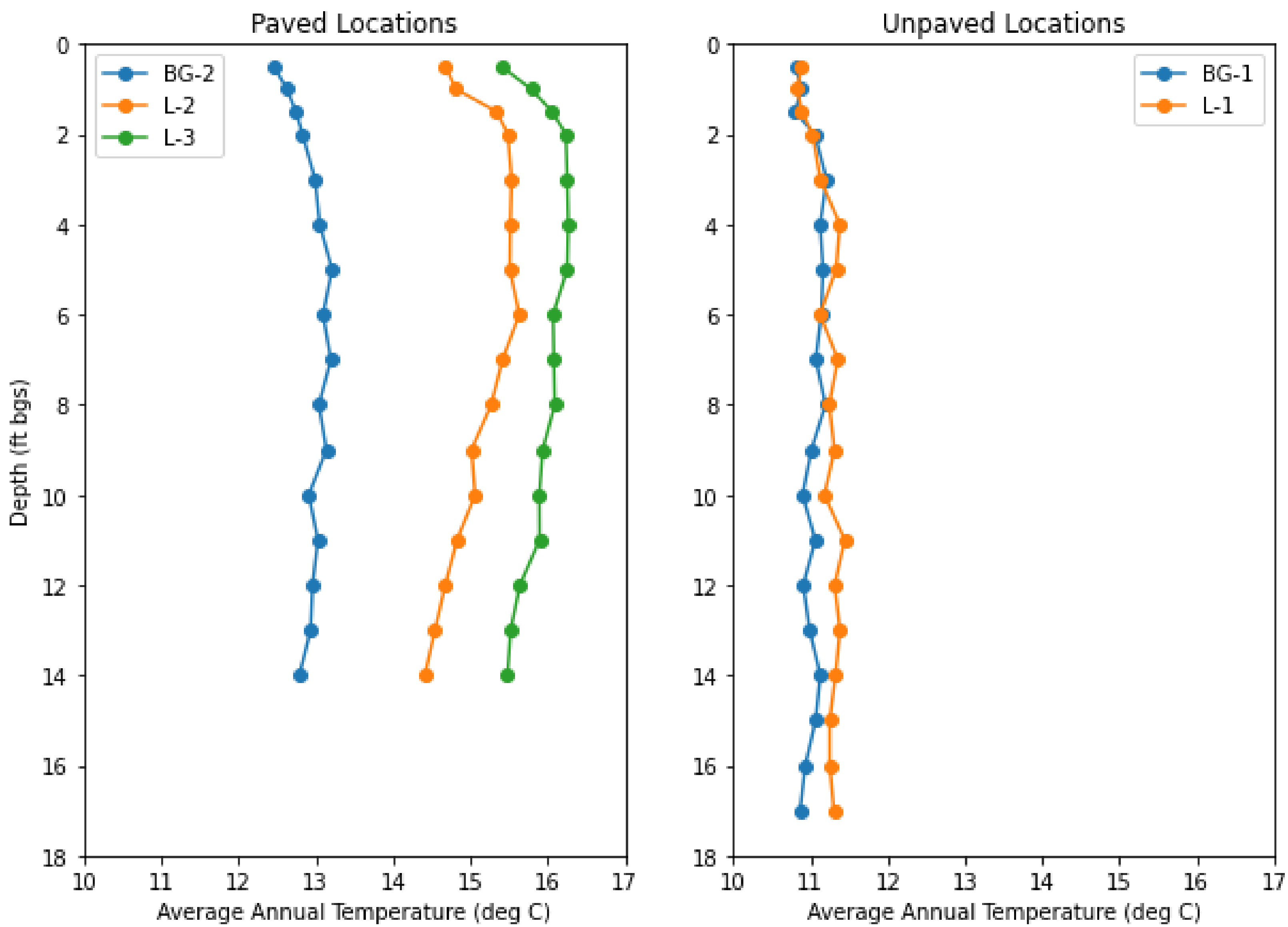


Figure 6.4. Mean Annual Vertical Temperature Profiles: January to December 2021 – MN ANGB

NSZD Rates Based on Annual Average Temperatures: The annual average temperature method can be used to calculate an absolute NSZD rate at each individual monitoring location (i.e., each source location and each background location). At each background location, the absolute NSZD rate is typically expected to be zero. The observation of a non-zero NSZD rate at a background location could indicate either i) factors other than NSZD that affect the vertical temperature profile and/or ii) the unexpected occurrence of NSZD (i.e., the unexpected presence of LNAPL at the background location). Factors other than NSZD, such as lateral heat transport in groundwater or year-to-year variations in annual average ground surface temperature, can result in non-zero vertical annual average temperature gradients, that, in turn, result in non-zero calculated NSZD rates. When these factors occur at a site, they are expected to have similar effects on the calculated NSZD rates at both background and source area monitoring locations.

As a result, for source area locations, it is important to consider both *absolute* NSZD rates (i.e., the NSZD rates calculated considering only the annual average temperature data at the single location) and the *net* NSZD rates (i.e., the difference between the absolute NSZD rate at the source location and the NSZD rate at the matched background location). If NSZD is not occurring at the background location, then the net NSZD rate is the best estimate of the true NSZD rate at the source area location because it controls for the apparent NSZD rate associated with factors unrelated to NSZD. Table 6.4 provides the absolute NSZD rates for each monitoring location, and Table 6.5 provides the net NSZD rates for each source area monitoring location.

At TEAD-S, average annual NSZD rates are non-zero at each of the background and impacted locations (see Table 6.4). Multiple lines of evidence, including PID readings during installation, soil gas measurements, and Carbon Trap measurements each support the absence of NSZD at these two background locations. Consequently, the “NSZD rates” at these locations are likely indicative of other factors that may be present, such as changes in solar insolation over time, rather than the biodegradation of petroleum hydrocarbons in the subsurface.

After calculating the net annual average NSZD rates, apparent NSZD rates at the paved location L-1 were negative, indicating the absence of measurable and quantifiable NSZD rates at this location, and consistent with the lack of a clear local maxima profile seen on the vertical temperature profiles (see Figure 6.3). At the paved location, L-2, and unpaved location, L-3, where local maxima are observed on the vertical temperature profile (see Figure 6.3), the NSZD rates are measurable but low (170-300 gallons/acre/year).

At the MN ANGB, the annual average temperature method also indicates measurable and quantifiable NSZD rates at both background locations (see Figure 6.4). Here, multiple lines of evidence, including field observations during sensor installation, Carbon Trap results, and soil gas profiles, point to the potential presence of petroleum hydrocarbons and active NSZD processes at both background locations. Thus, while installed in areas originally thought to be background locations based on prior investigation activities, these locations are likely not true background locations. As a result, the true NSZD rates at the impacted locations likely lie between the absolute NSZD rates shown in Table 6.4 and the net rates shown in Table 6.5.

6.2.2 Comparison of Methods to Calculate NSZD Rates Using Temperature Data

Although the total monitoring period at each demonstration site was a minimum of 18 months, the primary comparison of NSZD rates calculated using the three methods was conducted by using 12-month (1 year) windows of temperature data across the periods of data analyses.

For the Method 1 annual average and Method 2 background-correction methods, the periods of data analyses were 1 July 2020 – 30 June 2022 at TEAD-S and 1 September 2020 – 27 June 2022 at the MN ANGB. Due to the requirement for a pre-conditioning period before the Method 3 Single Stick data analysis algorithm can be used, the period of NSZD analysis was shorter for the Single Stick method by several months. The full datasets are used to evaluate temporal variations in NSZD rates.

Similar to the Method 1 annual average temperature method, the Method 3 Single Stick method can be used to calculate an absolute NSZD rate at each individual monitoring location (i.e., each source location and each background location). However, the correction using the Method 2 background location approach can only be used to calculate a net NSZD rate (i.e., the difference in NSZD rates between the impacted location and the background location) at the impacted locations. Table 6.4 provides the absolute NSZD rates calculated for each monitoring location and Table 6.5 provides the net NSZD rates for each source area monitoring location.

Table 6.4. Comparison of Absolute NSZD Rates (gal/acre/yr)

Temperature Monitoring Station Location	Method 1 - Annual Temperature Method	Method 3 - Single Stick Method
TEAD-S		
L-1 (paved)	150 [120-200]	370 [320-420]
L-2 (paved)	420 [380-450]	1,150 [1,130-1,180]
L-3 (unpaved)	640 [610-690]	1,080 [1,030-1,170]
BG-1 (paved)	250 [210-280]	-200 [-220 to -140]
BG-2 (unpaved)	370 [340-400]	270 [240-290]
MN ANGB		
L-1 (unpaved)	1,220 [1,100-1,350]	730 [720-730]
L-2 (paved)	2,710 [2,570-3,040]	3,180 [3,160-3,300]
L-3 (paved)	1,440 [1,390-1,500]	2,910 [2,790-3,020]
BG-1 (unpaved)*	570* [380-1,160]	-120* [-280-20]
BG-2 (paved)	610 [460-1,050]	100 [50-220]

Note: Results reported as median [25th percentile-75th percentile] of results computed for each continuous 365-day window of measurements within the dataset. Results rounded to the nearest 10.
* LNAPL observed in monitoring well at this background location

Table 6.5. Comparison of Net NSZD Rates (gal/acre/yr)

Temperature Monitoring Station Location	Method 1 - Annual Temperature Method	Method 2 - Correction Using Background Location Method	Method 3 - Single Stick Method
TEAD-S			
L-1 (paved)	-90 [-120 to -40]	-140 [-180 to -100]	570 [460-640]
L-2 (paved)	170 [170-190]	180 [170-190]	1,320 [1,270-1,400]
L-3 (unpaved)	300 [260-310]	360 [330-380]	800 [780-890]
MN ANGB			
L-1 (unpaved)	630* [140-780]	610* [60-740]	850* [700-1,000]
L-2 (paved)	2,060 [2,000-2,110]	2,060 [2,010-2,110]	3,090 [3,060-3,110]
L-3 (paved)	850 [460-940]	1,020 [770-1,040]	2,810 [2,550-2,970]

Note: Results reported as median [25th percentile-75th percentile] of results computed for each continuous 365-day window of measurements within the dataset. Results rounded to the nearest 10.
* LNAPL observed in monitoring well at this background location.

Overall, the net NSZD rates calculated by the Method 1 annual average method and Method 2 background correction method are similar at both TEAD-S and the MN ANGB and vary within a factor of 2 (see Table 6.5). By comparison, the Method 3 Single Stick method consistently shows higher NSZD rates on both an absolute and net basis at TEAD-S and somewhat higher NSZD rates at the MN ANGB. (Note that the Method 2 background correction method allows for the calculation of net NSZD rates but not absolute NSZD rates.) The variation in NSZD rates within a method (i.e., the range) was generally smaller than the difference in NSZD rates between the different methods. This suggests that the Method 3 Single Stick method may result in higher computed NSZD rates compared to the two other temperature-based NSZD calculation methods (Table 6.5).

Evaluation of Daily NSZD Rates: The key advantage of the Method 2 background correction method and the Method 3 Single Stick method over the Method 1 annual average method is that the first two methods support a calculation of NSZD rates for time periods as short as a single day, whereas the Method 1 annual average method can only be used to calculate the NSZD rate for full-year time periods. The evaluation of NSZD rates for time periods less than a full year can provide an improved understanding of NSZD processes over time. For example, a comparison of NSZD rates in summer vs. winter can provide information on how changes in soil temperature affect NSZD rates.

Figures 6.5 and 6.6 illustrate the daily NSZD rates calculated by the Method 2 background correction method (net NSZD rates) and Method 3 Single Stick method (absolute NSZD rates) at each of the three impacted sites at TEAD-S and the MN ANGB, respectively. Although the daily rates at both TEAD-S and the MN ANGB are highly variable and may not be reliable for estimating short-term NSZD rates (daily to weekly), they do provide a qualitative estimate of monthly and seasonal variations in NSZD rates. This presentation of time-averaged values is consistent with the published literature documenting NSZD rates determined using the temperature-based methods. These publications present time-averaged NSZD rates using an averaging time of months or longer (e.g., Warren and Bekins 2015; Karimi Askarani et al. 2018; Karimi Askarani and Sale 2020; Kulkarni et al. 2020).

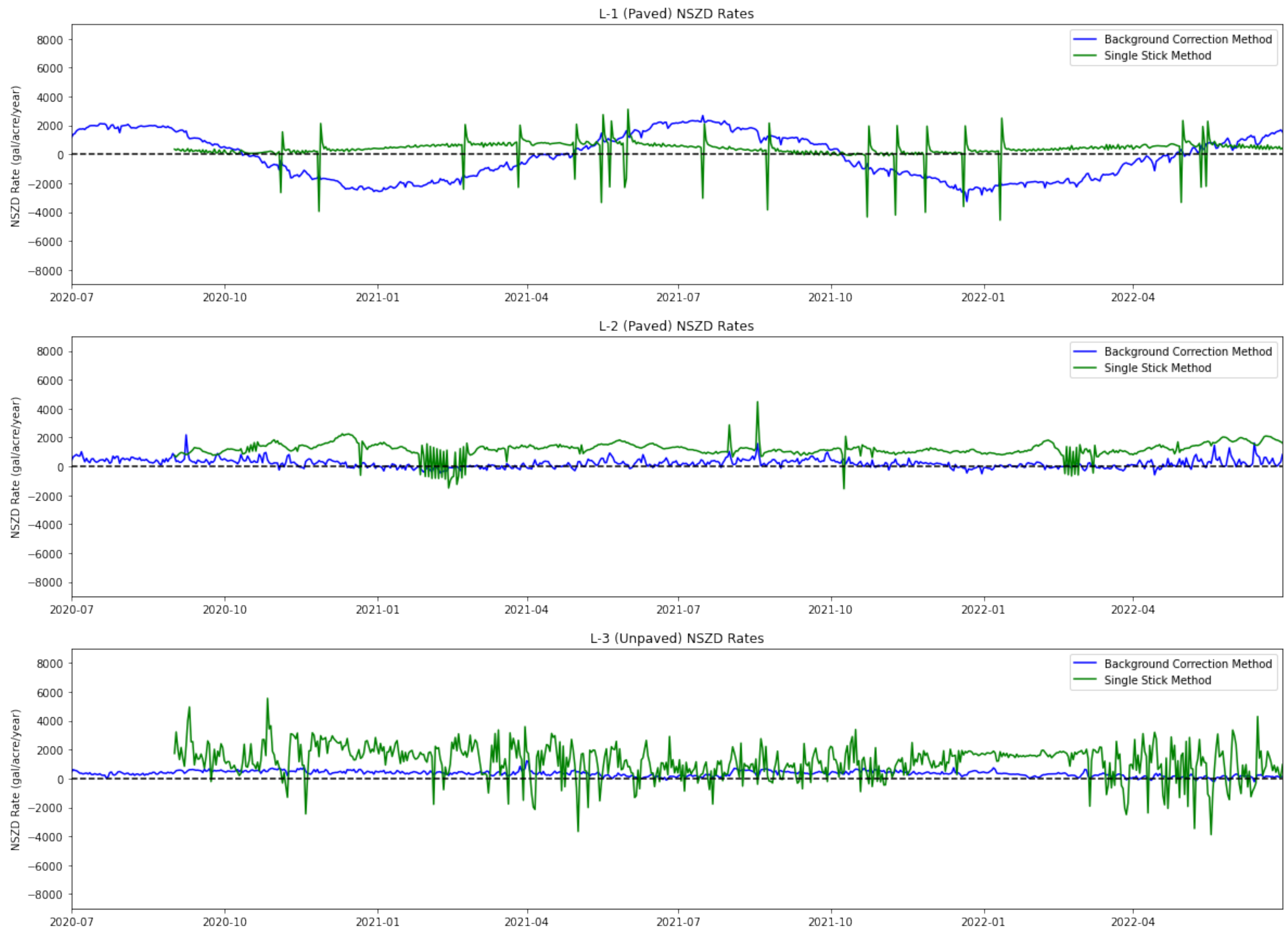


Figure 6.5. Comparison of Method 2 Background Corrected Method and Method 3 Single Stick Method Over Time at TEAD-S.

Figure 6.6. Comparison of Method 2 Background Corrected Method and Method 3 Single Stick Method Over Time at the MN ANGB.

6.2.3 Performance Objective 2 Success Criteria and Results

Success Criteria: Attainment of more stable background-corrected temperature gradients and NSZD rates compared to 1st generation methods. More accurate short-term (weekly to monthly) NSZD rates compared to 1st generation methods (Table 3.1).

The three methods were evaluated for general characteristics and a resolution of the Success Criteria.

Result: Stability. The stability of each of the three methods was evaluated by assessing how calculated NSZD rates changed over time for the three methods. Given the substantial data gaps at the MN ANGB, and issues with computing daily NSZD values that were deemed accurate over short time periods, the stability of each method were not compared against each other over short time periods. Comparison of the 25th to 75th percentile ranges with the median NSZD values for each of the three methods demonstrates that annual NSZD rates computed during different time windows are within a factor of 2x and thus are reasonably stable over time at an annual time scale. However, the data do not support further evaluation of whether certain methods may be more stable than others at this annual time scale.

Result: Accuracy. Given the data issues, the accuracy of the NSZD rates were instead evaluated by comparison to the Method 1 average annual temperature method from a full year of monitoring data. As discussed above, the annual average method does not require an explicit background correction to account for seasonal ground surface heating and cooling (i.e., the summer heating and winter cooling theoretically cancel out in the annual average). However, the accuracy of the annual average method can still be affected by the occurrence of unusually warm or cool weather during the measurement year. As a result, the evaluation of method accuracy by comparison to the annual average temperature method is semi-quantitative. Overall, the Method 2 background corrected method yielded NSZD rates closer to the Method 1 annual average method than the Method 3 Single Stick method. The Method 3 Single Stick method resulted in higher NSZD values than the other two methods at both demonstration sites, with larger differences at TEAD-S than at the MN ANGB.

Section 6.2.4 presents an evaluation of the impact of the missing data on the accuracy of the temperature-based NSZD measurements. Overall, uncertainty in NSZD rates associated with the estimation of temperature values to fill the gaps in the measured temperature dataset is likely to be modest at 30% or less.

***Overall Performance Objective 2 Results*: Not Achieved.** Method 2, the background corrected method, yielded NSZD rates similar to Method 1, the annual average method. Relative to Method 1, Method 3, the Single Stick method, resulted in consistently higher NSZD values at both demonstration sites. However, as discussed in Section 6.3 below, the agreement in NSZD rates between the individual temperature-based methods and the other non-temperature alternative methods to estimate NSZD rates was more variable. Overall, additional field demonstration would be needed to determine which temperature-based method yields the most accurate estimates of NSZD rates across a large number of sites.

6.2.4 Impact of Data Interpolation on Calculated NSZD Rates

As discussed in Section 6.1.3, equipment issues resulted in significant gaps in the temperature data set for the MN ANGB. These data gaps were filled by linear interpolation, as described in Section 5.7.3. In order to evaluate the effect of this data interpolation on the calculated NSZD rates, identical data gaps were imposed on the data set from TEAD-S, and the same linear data interpolation method was used to fill those gaps. This interpolated data set for TEAD-S is provided in Appendix H.6. The comparison of NSZD rates for the original and interpolated data sets for TEAD-S are provided in Table 6.6. This evaluation was not applied for the Single Stick method, and thus the impact of the data gaps at the MN ANGB cannot be quantified for the Single Stick method.

Table 6.6. Comparison of NSZD Rates (gal/acre/yr): Original vs Interpolated Data Sets for TEAD-S

Temperature Monitoring Station Location	Annual Average Temperature Method 1			Background Temperature Method 2		
	Original Dataset (gal/acre/year)	Interpolated Dataset (gal/acre/year)	Relative Percent Difference	Original Dataset (gal/acre/year)	Interpolated Dataset (gal/acre/year)	Relative Percent Difference
BG-1 (Paved)	250 [210-280]	190 [150-250]	27%	NC	NC	NC
L-1 (Paved)	150 [120-200]	180 [140-260]	18%	-140 [-180 to -100]	-40 [-160 to 90]	110%
L-2 (Paved)	420 [380-450]	380 [350-420]	10%	180 [170-190]	190 [180-210]	4%
BG-2 (Unpaved)	370 [340-400]	380 [350-440]	3%	NC	NC	NC
L-3 (Unpaved)	640 [610-690]	640 [610-690]	0%	360 [330-380]	350 [320-360]	8%

Note: 1. Percent differences calculated as the relative percent difference.
2. NC = net NSZD rate cannot be calculated with Method 2

For the NSZD rates calculated using the annual average method, the differences in NSZD rates between the original TEAD-S dataset and the TEAD-S dataset with artificial gaps filled by linear interpolation were generally small (i.e., less than 30%) for each of the five locations. For the background-correction method, the relative percent differences are generally small (approximately 5%) for two of the three locations, with only L-1 showing a large difference. However, it should be noted that this location had relatively small negative NSZD rates, and thus the large relative percent difference may not be a significant issue.

Figure 6.7 shows the daily NSZD rates at the impacted locations using the original TEAD-S dataset and the data gaps interpolated dataset for Method 2. As can be seen, the daily NSZD rates are generally consistent between the two datasets (although the rates are more variable for the interpolated datasets), lending further credence that a linear interpolation routine to address data gaps is likely to result in relatively small errors for background temperature correction Method 2.

Overall, this analysis indicates that the error or uncertainty in NSZD rates at the MN ANGB associated with the estimation of temperature values to fill the gaps in measured temperature dataset is likely to be modest. The error is likely to be 30% or less at most locations for the annual average or background correction methods.

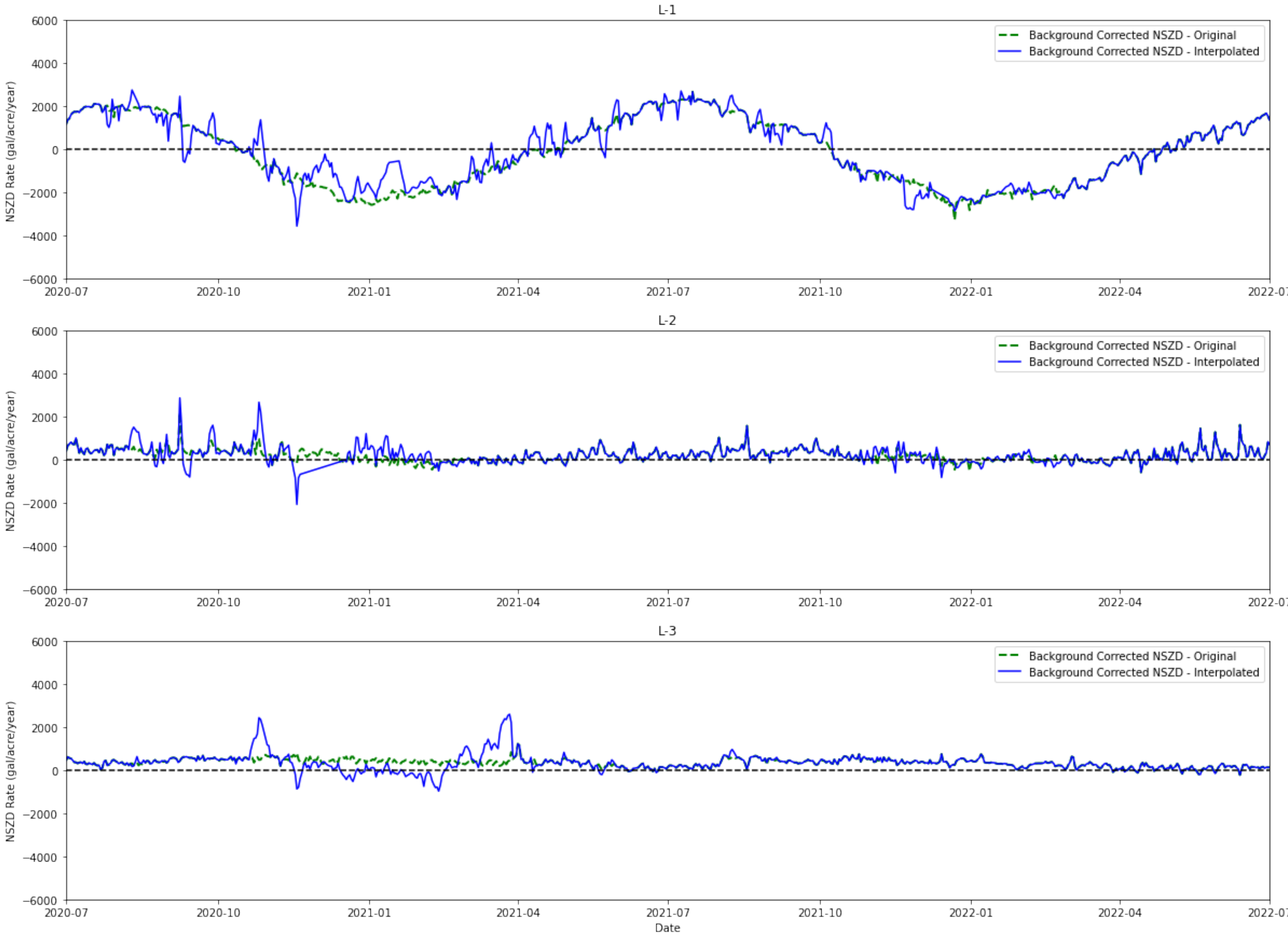


Figure 6.7. Comparison of the Background-corrected NSZD Rates Over Time for the Original TEAD-S Dataset and the Data Gaps Interpolated Dataset.

(TEAD-S data with MN ANGB data gaps imposed at each location and then linearly interpolated)

6.3 PERFORMANCE OBJECTIVE 3: COMPARISON BETWEEN NSZD RATES FROM TEMPERATURE-BASED MONITORING AND OTHER NSZD METHODS

As explained in Section 3.3, a limited set of alternative measurements were collected at each of the two demonstration sites to evaluate whether the methods yielded roughly comparable results at these sites (see Table 6.7).

6.3.1 Quantitative Evaluation of NSZD Rates Determined Using Carbon Trap Method

The Carbon Trap method was utilized for one sampling event at each of the two demonstration sites (Table 6.7). The NSZD rates measured by the Carbon Trap method were within a factor of 2x of the NSZD rates determined using the annual average temperature method for three of the six source area locations, with larger differences observed at the other three locations. This magnitude of difference is comparable to that observed at other sites (see also the results of the multi-site study described in Section 6.6). The Carbon Trap method yielded higher NSZD rates at two of the six locations (TEAD-S L-1 and TEAD-S L-3) and lower NSZD rates at the other four locations, indicating an absence of significant bias between the two measurement methods. At each of the four background locations, the Carbon Trap method yielded lower NSZD rates compared to the annual average temperature method. It should be noted that Carbon Traps only provide a short-term snapshot at one time period, and the resultant NSZD rates may not be representative of an entire year.

6.3.2 Qualitative Evidence of NSZD Based on Soil Gas Gradients

At each monitoring location, soil gas gradients were used to provide qualitative evaluations of NSZD. Decreasing oxygen and increasing carbon dioxide and methane with depth is evidence of NSZD. At each monitoring location, the evidence of NSZD was evaluated as follows:

- ***No Evidence of NSZD***: Consistently high oxygen and low carbon dioxide at all measurement depths during all sampling events. For example, at background locations BG-1 and BG-2 at TEAD-S (see Figure 5.5), there is no decrease of O_2 with depth or increase in CH_4 and CO_2 with depth, indicating that there is no expression of NSZD processes in the soil gas profile.
- ***Weak Evidence of NSZD***: Consistently high oxygen and low carbon dioxide at all measurement depths during most sampling events, with decreasing oxygen or increasing carbon dioxide with depth during at least one event.
- ***Medium Evidence of NSZD***: Decreasing oxygen and increasing carbon dioxide with depth during most sampling events, but some inconsistency across sampling events.
- ***Strong Evidence of NSZD***: Decreasing oxygen and increasing carbon dioxide with depth during each sampling event. For example, as shown on Figure 5.5, impacted location L-1 at TEAD-S had consistently decreasing oxygen with depth and increasing CO_2 and CH_4 with depth during each sampling event, consistent with the expected theoretical soil vapor profile for hydrocarbon biodegradation.

Using these criteria applied to Figures 5.5 and 5.6, the two background locations at TEAD-S showed no evidence of NSZD, and both background locations at the MN ANGB exhibited weak evidence of NSZD. In addition, five of the six source area locations showed medium or strong evidence of NSZD (all except L-1 at the MN ANGB).

Table 6.7. Comparison of NSZD Rates for Temperature-Based and Carbon Trap Methods, and Qualitative Evidence of NSZD Based on Soil Gas Gradients

Temperature Monitoring Station Location	NSZD Rate by Method 1 - Annual Temperature Method (gal/acre/year)	NSZD Rate by Method 2 - Background Location Method (gal/acre/year)	NSZD Rate by Method 3 - Single Stick Method (gal/acre/year)	NSZD Rate by Carbon Trap Method (gal/acre/year)	Evidence of NSZD Based on Soil Gas Gradients
TEAD-S					
L-1 (paved)	150 [120-200]	-140 [-180 to -100]	370 [320-420]	295	Strong
L-2 (paved)	420 [380-450]	170 [170-190]	1,150 [1,130-1,180]	84	Medium
L-3 (unpaved)	640 [610-690]	360 [330-380]	1,080 [1,030-1,170]	1,105	Medium
BG-1 (paved)	250 [210-280]	NC	-200 [-220 to -140]	Not Detectable	No Evidence of NSZD
BG-2 (unpaved)	370 [340-400]	NC	270 [240-290]	Not Detectable	No Evidence of NSZD
MN ANGB					
L-1 (unpaved)	1,220 [1,100-1,350]	610* [60-740]	730 [720-730]	72	Weak
L-2 (paved)	2,710 [2,570-3,040]	2,060 [2,010-2,110]	3,180 [3,160-3,300]	1,856	Medium
L-3 (paved)	1,440 [1,390-1,500]	1,020 [770-1,040]	2,910 [2,790-3,020]	404	Medium
BG-1 (unpaved)*	570* [380-1,160]	NC	-120* [-280-20]	129	Weak
BG-2 (paved)	610 [460-1,050]	NC	100 [50-220]	37	Weak

Note: Temperature-based NSZD results reported as median [25^{th} percentile-75^{th} percentile] of results computed for each continuous 365-day window of measurements within the dataset. Results rounded to the nearest 10.
* LNAPL observed in monitoring well at this intended background location
NC – net NSZD rate cannot be calculated with Method 2

Evidence of NSZD was present at both background locations at the MN ANGB (BG-1 and BG-2). Additional field observations after installation indicated the presence of LNAPL at BG-1. A "hydrocarbon" odor and a layer of free product were observed on the water table at this location while gauging water levels a few weeks after installation. In addition, the Carbon Trap results for this location indicated some, albeit relatively minimal, NSZD is occurring (129 gal/acre/year). While BG-2 had a detected but relatively minimal Carbon Trap measurement of 37 gal/acre/yr and weak evidence of NSZD based on the soil gas profile, LNAPL was not observed at this location, and PID readings from the soil boring were relatively low (<5 parts per million (ppm)).

As described in Section 5.4, each measurement location included both a dedicated soil vapor monitoring point comprised of four vertically-spaced soil gas collection points, as well as a temperature monitoring station with vertically-spaced soil gas collection points. The comparability of results between these two locations was used to determine whether valid soil gas samples could be collected from temperature monitoring stations rather than having to install dedicated soil vapor monitoring points. As mentioned in Section 5.4, the dedicated soil vapor monitoring points at depth were set in layers of sand and separated from the adjacent soil vapor point by a layer of bentonite, whereas there were no bentonite layers separating the soil vapor points in the temperature monitoring boreholes, as the vapor points were zip-tied to the PVC casing during construction. As shown in Figures 5.5 and 5.6 in Section 5.7.1, at each location, the vertical gas gradients were similar at both the soil gas collection points and the temperature monitoring stations. These results indicate that valid soil gas samples can be collected using soil gas collection points installed on the temperature monitoring stations even with a simplified well construction approach. Such an approach would reduce installation costs at future sites and provide a relatively inexpensive secondary line of evidence that NSZD is occurring based on the qualitative assessment of the soil gas vertical profile.

6.3.3 Performance Objective 3 Success Criteria and Results

As discussed in Sections 6.3.1 and 6.3.2, above, the purpose of the alternate NSZD methods was to provide a qualitative evaluation of consistency with the temperature methods rather than a quantitative comparison.

***Criteria*:** Comparability of NSZD rates for temperature method and alternative methods. Agreement between methods within a factor of 2X (or evidence that temperature-based monitoring methods are more accurate based on, for example, lower spatial and temporal variability) (Table 3.1).

Results: Mostly Achieved. Across the six source area locations at the two demonstration sites, the NSZD rates measured using the Carbon Trap method were generally consistent with the annual average temperature method, with no overall bias observed between the two methods, even though the differences in values at some locations exceeded the success criteria of 2X. The soil gas gradient method indicated evidence of NSZD at five of the six source area locations and no or weak evidence of NSZD at each of the four background locations.

6.4 PERFORMANCE OBJECTIVE 4: DEMONSTRATION OF 2^{ND} GENERATION EQUIPMENT AND METHODS FOR TEMPERATURE-BASED MONITORING OF NSZD

The 2^{nd} generation temperature sensors support continuous temperature measurement at up to 20 vertical depths at each location, compared with eight depths for 1^{st} generation sensors (e.g., Kulkarni et al. 2020), thus providing a more detailed vertical temperature profile than the 1^{st} generation sensors. The higher vertical resolution temperature data from digital temperature sensors compared with the conventional thermocouples in 1^{st} generation equipment support the application of alternative computational methods to separate biologically-generated NSZD heat from seasonal heating and cooling (i.e., improved background correction). Compared with project team experience at other sites with the 1^{st} generation sensors, simplified wiring supported by the 2^{nd} generation sensors made installation of equipment substantially faster and easier than 1^{st} generation equipment at the demonstration sites.

A demonstration of increased data density and lower cost was completed by comparing the data density and cost for the two demonstration sites against the historical performance and cost for the 1^{st} generation equipment because the performance of the 1^{st} generation equipment has been documented at a number of temperature monitoring sites (e.g., Kulkarni et al. 2020). The accuracy and resolution of the 2^{nd} generation equipment are based on manufacturer specifications (see Appendix C.1).

6.4.1 Equipment Reliability and Data Acquisition

At TEAD-S, the 2^{nd} generation equipment collected and recorded over 99% of the expected temperature measurements, thus demonstrating appropriate reliability. However, as shown in Table 6.2 (Section 6.1.3), the temperature and ORP data collection was far less reliable at the MN ANGB. Across the five monitoring stations, only 60% to 95% of days had at least 12 hours of temperature measurements recorded. As shown in Figure 5.8, most of the monitoring stations had time periods of days to weeks when no temperature data were successfully recorded. Because the monitoring stations use cellular technology to transmit the data to a remote monitoring dashboard, the data gaps were noted early in the demonstration period, and the demonstration team worked with the technology vendor (S3NSE Technologies) to resolve the issues. In consultation with S3NSE Technologies, it was determined that the loss of data was attributable to at least three factors: i) inadequate power provided by the monitoring station solar panels and batteries, ii) intermittent failure of the monitoring stations to connect to cell towers to transmit data, and iii) failure of the monitoring software to successfully record and store a complete dataset locally on a memory card when data connectivity with the dashboard was not feasible.

During the demonstration period, S3NSE Technologies implemented the following measures at the MN ANGB to improve data collection and transmittal:

September 2020: Modified system code to reduce power consumption.

November 2020: Modified system code to improve cellular connection.

December 2020: Installed new batteries at three locations and new memory cards at two locations. Replaced cellular boards at 3 monitoring stations.

February 2021: Installed new batteries and memory cards at all five locations.

March 2021: Installed new antenna to improve cellular connection and updated data loggers to record data locally when not transmitted to remote location.

January 2022: Monitoring Station L-1 returned to S3NSE for repair then reinstalled at the site.

February 2022: Monitoring Stations L-3 and BG-1 returned to S3NSE for repair and then reinstalled at the site. (Data collection at L-2 and BG-2 were deemed sufficient at that time such that these locations were not returned for repair; see Figure 6.2).

Although some of the corrective measures appear to provide at least some improvement in data collection at the MN ANGB, S3NSE was not able to fully resolve the equipment or software issues over the course of the approximately 23-month demonstration period at the MN ANGB.

6.4.2 Utility of More Detailed Temperature Dataset

One expected benefit of the 2nd generation equipment was the attainment of more detailed vertical temperature profiles at each measurement location. For this demonstration, each temperature monitoring station contained 16 to 19 vertically-spaced temperature sensors, compared to a maximum of eight vertically-spaced sensors typically included in a 1st generation temperature monitoring station. The more detailed vertical temperature profile was expected to provide a more accurate characterization of the heat generation associated with NSZD and, thus, a more accurate NSZD rate.

In order to evaluate the utility of the more detailed vertical temperature profiles, an alternate temperature dataset representative of 1st generation equipment was created for each temperature monitoring station at TEAD-S consisting of the temperature data from eight of the sensors at that temperature monitoring station. Due to the substantial data gaps at some of the MN ANGB sensor locations, this dataset was not evaluated further for this performance objective. The eight sensors were selected by retaining data from every 2nd to 3rd temperature sensor on the temperature monitoring station in order to maintain relatively uniform vertical spacing typical of 1st generation equipment. Two different sensor depth profiles were selected and analyzed and compared to the 18 sensors on the full sensor string (0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18, 20 ft bgs): i) an "odd" sensor string (1, 3, 5, 7, 9, 12, 16, 20 ft bgs), and ii) an "even" sensor string (0.5, 2, 4, 6, 8, 10, 14, 18 ft bgs). NSZD rates were then calculated using the same procedures and methods used for the original dataset, and the NSZD rates obtained from the "1st generation" and "2nd generation" datasets were compared (see Figures 6.8, 6.9, and 6.10).

In general, while there was some agreement among all three sensor selections (e.g., BG-1 and L-1 using the Single Stick method), there were notable differences between the results depending on what sensor depth profiles were selected, and there appeared to be no apparent bias using one sensor profile compared to the other. The range of differences between sensor depth profiles, however, were typically less than between different NSZD calculation methods, implying that the methodology chosen has a larger impact on the calculated NSZD rates than the number of temperature sensors. It is hypothesized that more temperature sensors result in more accurate results, but the results from the datasets collected for this study do not allow for a more conclusive determination.

The daily NSZD rates calculated for each of the three sensor depth profiles (all, even, odd) by the Method 3 Single Stick method and Method 2 background-corrected method are shown in Appendix H. It is notable that at four of the locations using the Method 3 Single Stick method, the results for one of the 8-sensor profiles were numerically unstable (i.e., the calculated NSZD values oscillated between very low and very high values; see Appendix B.4), and numerical instability occurred for both the "even" and "odd" depth profiles, with no apparent ability to predict which depth configuration would result in daily NSZD rates that are reasonable. Thus, for application of the Method 3 Single Stick method, there appears to be a clear advantage to using the 2nd generation sensors that collect at least twice as many vertical temperatures along the vertical profile at these two demonstration sites. In contrast, for the background correction method, each of the three temporal profiles are similar, and thus the impact of using the 2nd generation equipment appears to be less for this methodology.

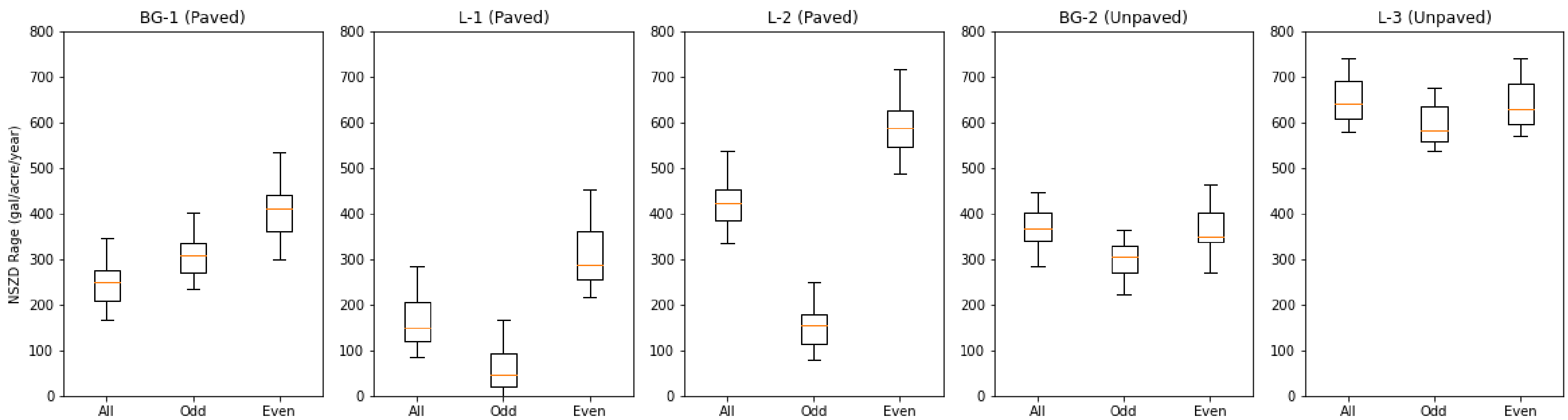


Figure 6.8. Comparison of NSZD Rates at TEAD-S for the Method 1 Annual Average Method for the Complete Dataset ("All"), the "Odd" Sensor Strings (1, 3, 5, 7, 9, 12, 16, 20 ft bgs), and the "Even" Sensor Strings (0.5, 2, 4, 6, 8, 10, 14, 18 ft bgs).

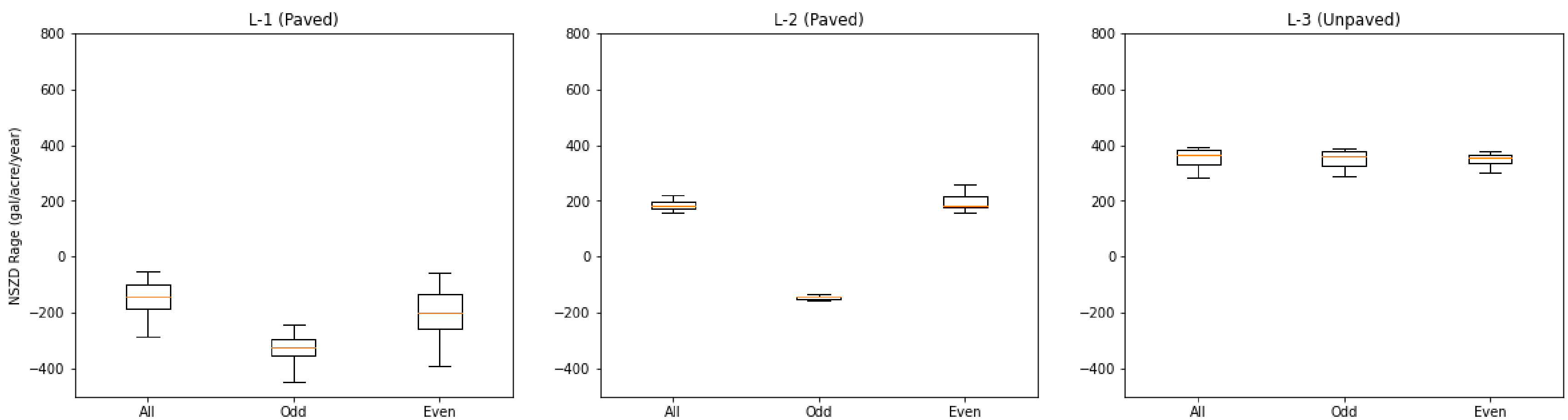


Figure 6.9. Comparison of NSZD Rates at TEAD-S for the Method 2 Background Correction Method for the Complete Dataset ("All"), the "Odd" Sensor Strings (1, 3, 5, 7, 9, 12, 16, 20 ft bgs), and the "Even" Sensor Strings (0.5, 2, 4, 6, 8, 10, 14, 18 ft bgs).

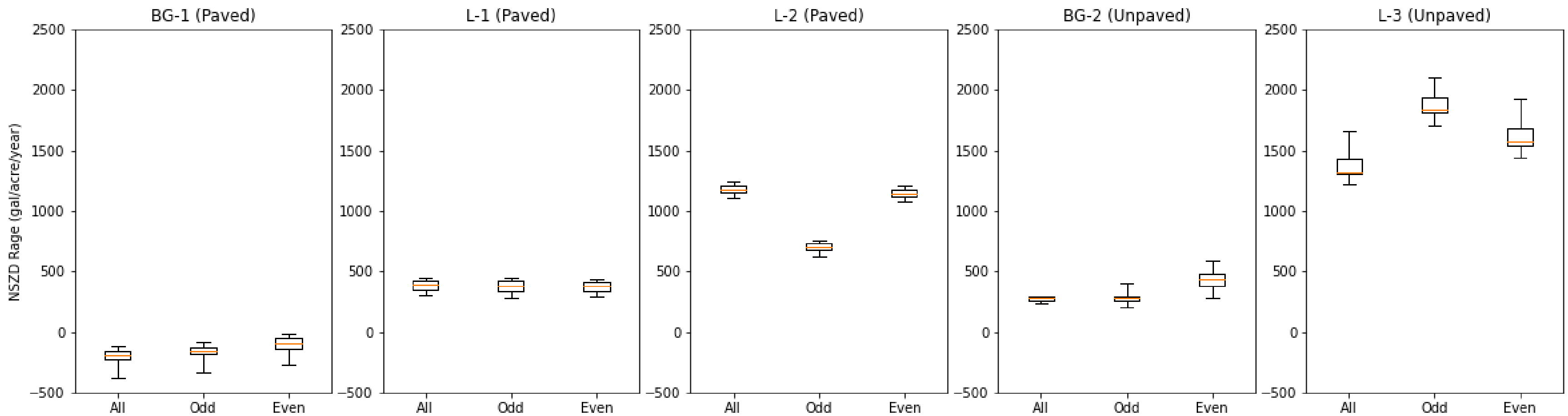


Figure 6.10. Comparison of NSZD Rates at TEAD-S for the Method 3 Single Stick Method for the Complete Dataset ("All"), the "Odd" Sensor Strings (1, 3, 5, 7, 9, 12, 16, 20 ft bgs), and the "Even" Sensor Strings (0.5, 2, 4, 6, 8, 10, 14, 18 ft bgs)

6.4.3 Utility of Additional Data Provided by 2nd Generation Equipment

In addition to a higher vertical density of temperature sensors, each 2nd generation temperature monitoring station included 16 to 19 vertically-spaced ORP sensors.

As shown in Section 5.7.5 and Figures 5.11 and 5.12, ORP data were collected at each location at TEAD-S and the MN ANGB during the demonstration period concurrently with temperature data collection. Overall, the GAS plots illuminate ORP conditions in temporal cross-sections as a function of depth (see Figures 5.11 and 5.12).

In general, each location shows oxic conditions near grade, reflecting atmospheric oxygen entering the vadose zone via advection and diffusion. At the source area locations, at depths near and below the water table, blue colors representing reducing conditions suggest ongoing attenuation of hydrocarbons (oxidation) via sulfate reduction and/or methanogenesis.

At background location BG-2 at the MN ANGB, oxidizing conditions throughout the profile are consistent with other field observations indicating that this location is largely unimpacted by petroleum and indicate naturally oxidizing aquifer conditions. At background location BG-1 at the MN ANGB, reducing conditions at depth suggest the presence of hydrocarbons, which are causing the naturally oxidizing aquifer to become reduced. At background locations BG-1 and BG-2 at TEAD-S, blue colors at depth indicate anaerobic conditions. Other site conditions (i.e., historical site observations, field observations during sensor installation, soil gas profile data, and Carbon Trap data) indicate these background locations are not impacted by hydrocarbons; therefore, the ORP data indicate naturally reducing aquifer conditions at TEAD-S.

Overall, the ORP data provide information on aquifer conditions and an additional qualitative line of evidence of NSZD at minimal cost.

6.4.4 Cost Comparison

Recent cost data from S3NSE Technologies lists a price of $6,000 per location for up to 20 temperature and ORP sensors, or approximately $300 per sensor point. In comparison, representative cost data to construct a 1st generation system with 8 temperature sensors is approximately $7,500 per location, or approximately $925 per sensor point. The costs per temperature monitoring station are thus 20% cheaper with the 2nd generation equipment. Thus, the 2nd generation equipment provides clear cost advantages in terms of total system costs, per sensor point costs, as well as the number of sensors available.

6.4.5 6.4.5 Performance Objective 4 Success Criteria and Results

The primary goals for the 2nd generation equipment were i) equal or greater reliability compared to 1st generation equipment, ii) attainment of at least 50% more temperature depth intervals at each location (i.e., at least 12 depth intervals), and iii) a 20% or greater reduction in equipment costs. A secondary goal was attainment of additional types of data (i.e., soil gas sample ports and ORP measurements) not available from the 1st generation equipment.

***Criteria*:** Lower costs compared to 1st generation equipment. More detailed vertical temperature dataset compared to 1st generation equipment.

Results*: *Mostly Achieved. At one of the two demonstration sites (i.e., MN ANGB), the 2^{nd} generation equipment failed to record temperature data at times throughout the demonstration period, resulting in data gaps and an incomplete temperature record. The equipment vendor, S3NSE Technologies, was unable to fully resolve the issues despite numerous attempts over the course of the demonstration. At both sites, the 2^{nd} generation equipment was able to record temperatures at more than twice as many depths (>50%) as the 1^{st} generation equipment, which produced a more detailed vertical temperature profile. As discussed in Section 6.4.2, additional temperature data at these two demonstration sites improved the performance of the Method 3 Single Stick method, whereas the impact of using the 2^{nd} generation equipment appears to be less for the Method 1 annual average and Method 2 background-correction methods. The gas analyses from the 2^{nd} generation equipment soil gas sample ports were comparable to the result obtained from adjacent stand-alone soil gas sample points, and the ORP data provided secondary evidence for the qualitative evaluation of NSZD at each site.

The sensor accuracy of the 2^{nd} generation temperature sensors (±0.5° C accuracy) is less than the accuracy of the thermocouples used in the 1^{st} generation equipment (±0.1° C accuracy). Although we were unable to resolve the impact of using lower-accuracy temperature sensors as part of this demonstration, we hypothesize that resolving low NSZD rates may be more challenging with the lower-accuracy sensors, and future practitioners should attempt to utilize higher accuracy sensors on the 2^{nd} generation platform as the sensor technology improves.

The 2^{nd} generation equipment provides clear cost advantages in terms of per sensor point costs, as well as the number of sensors available (Section 6.4.4).

In summary, if the equipment vendor is able to fully resolve the equipment reliability issues described under Performance Objective 1 (Section 6.1.3), the 2^{nd} generation equipment provides a clear improvement over the 1^{st} generation equipment.

6.5 PERFORMANCE OBJECTIVE 5: DOCUMENTATION OF NSZD BELOW PAVED SURFACES

In addition to providing one-time snapshots rather than continuous monitoring, the alternative methods for quantification of NSZD (i.e., CO_2 flux and the gradient method) have potential issues when applied below paved surfaces because the presence of pavement disrupts the 1-D diffusion of oxygen and carbon dioxide in the vadose zone (e.g., Smith et al. 2021). While the overall vertical profile should be useful for a qualitative evaluation of the occurrence of NSZD, the violation of the 1-D diffusion assumption and the potential for channelization of vapor flow through openings in the pavement introduce additional uncertainty into the quantification of NSZD rates with these methods. Various approaches to account for this issue with Carbon Traps have been suggested by E-Flux (e.g., the approach used by Smith et al. 2021), and one recent approach currently under development by E-Flux is an "in situ microcosm" approach. Given these issues, the demonstration of the temperature-based methods below paved surfaces may expand the range of sites where NSZD rates can be quantified.

Two performance objectives were evaluated here to document NSZD below paved surfaces: (1) the temperature gradient measurements for LNAPL source areas below pavement; and (2) supporting data of methane, carbon dioxide, and oxygen concentrations consistent with biodegradation (i.e., oxygen decreases with depth, carbon dioxide and methane increase with depth).

6.5.1 Performance Objective 5 Success Criteria and Results

Criteria: Temperature profile consistent with NSZD. Methane/carbon dioxide/oxygen distribution consistent with NSZD.

Results: ***Mostly Achieved.*** At TEAD-S, while the soil gas profiles (see Section 5.7.1; Figure 5.5; Section 6.3.2) are consistent with the expected profiles and demonstrate the occurrence of NSZD below paved surfaces, the Method 1 average annual vertical temperature profiles at the paved locations at TEAD-S did not correspond to the average annual vertical temperature profiles expected for NSZD processes (i.e., no clear evidence of elevated soil temperatures in the subsurface at the impacted locations compared to the non-impacted background location). Likewise, the Method 2 background-corrected NSZD results were low (or negative), suggesting little to no NSZD, and the Carbon Trap results indicated low NSZD rates at the paved locations. In contrast, the Method 3 Single Stick method indicated measurable NSZD results notably higher than the rates indicated by the other methods. In summary, the weight of evidence suggests NSZD in paved areas at the first demonstration site, TEAD-S, but the NSZD rates appear to be lower than those at the unpaved location.

At the MN ANGB, in contrast, the two paved locations, L-2 and L-3, did show average annual vertical temperature profiles consistent with NSZD, and the calculated NSZD rates based on temperature-based monitoring methods and Carbon Traps at these locations supports the occurrence of NSZD beneath paved surfaces.

In addition, Smith et al. (2021) demonstrated the use of temperature-based methods beneath paved sites at a retail fuel station in Europe. Thus, the general theory and results from other published studies (e.g., Smith et al. 2021) provide further evidence that temperature-based methods are suitable for quantification of NSZD rates beneath paved surfaces, although additional field verification may be desirable to support the limited data to date.

6.6 PERFORMANCE OBJECTIVE 6: COMPILATION OF NSZD RATES ACROSS NSZD MONITORING SITES

This project demonstration included a data mining component to characterize rates of NSZD measured across a wide range of petroleum-contaminated sites. The goals of the data mining study were to i) characterize the range of site-wide average NSZD rates measured across a wide range of sites, ii) evaluate the impact of fuel type on NSZD rates, iii) evaluate the comparability of different methods to measure NSZD rates, and iv) characterize how NSZD rates vary at individual sites over a time-scale of a few months to a few years. For this purpose, data were compiled from 40 sites where NSZD rates had been measured using one or more measurement methods.

6.6.1 Summary of Findings

At all 40 sites, the following data were compiled: i) general site location; ii) LNAPL fuel type; iii) measurement method, number of locations, and number of measurements per location; and iv) calculated sitewide average NSZD rate and the associated measurement method (i.e., Gradient Method, Carbon Traps, Dynamic Closed Chamber (DCC), or Thermal Monitoring). The resulting dataset showed average sitewide NSZD rates that ranged from 650 to 152,000 L/ha/yr (70 to 16,250 gallons per acre per year (gal/acre/yr)), with a median value of 9,540 L/ha/yr (1,020 gal/acre/yr).

No clear bias was observed between the four NSZD rate measurement methods. When comparing the different NSZD measurement methods applied to the same sites, the site-average NSZD rates differed by a median factor (i.e., ratio of faster rate to slower rate) of 2.1 times. Despite the variability from measurement method, seasons and time-scales, at the majority of sites, a reasonable estimate of the long-term NSZD rate (e.g., within a factor of 2 or 3) can be achieved by: i) a single measurement method employed at 3-7 locations per site; and ii) spanning at least two semi-annual (fall and spring) or four seasonal measurements per location.

Additionally, based on a limited dataset of four sites, NSZD rates were typically higher during the summer and fall (when subsurface temperatures are highest) compared to winter and spring (when subsurface temperatures are lowest), which suggests that biodegradation rates are enhanced by low-level increases in temperature, also discussed in various literature studies (Kulkarni et al. 2022b). As such, increasing the mean annual soil temperature with engineered methods could potentially increase the biodegradation rate at a site. Although NSZD rates vary across sites and over time at an individual site, the fuel type does not appear to be the primary factor explaining the observed differences in NSZD rates.

The findings of this study have recently been published in the journal Water Research. Additional citation information on this paper (Kulkarni et al. 2022b) is provided in Appendix F.

6.6.2 Performance Objective 6 Success Criteria and Results

***Criteria*:** Documentation of the typical range of NSZD rates across sites and identification of site factors predictive of higher or lower NSZD rates.

Results: Achieved. The range of NSZD rates observed across the 40 sites evaluated is summarized in Table 5.6. In addition, Kulkarni et al. (2022b; see Appendix F) show an absence of any observable relationship between LNAPL fuel type and NSZD rates. The study also found no bias between NSZD rate measurements methods included in the study (i.e., carbon flux, soil gas gradients, or heat flux) either within sites or across sites. Across the sites evaluated, there was not enough information available regarding site characteristics such as soil type, soil moisture, depth to LNAPL, LNAPL volume, or site annual average air temperature to evaluate the effect of these site factors on measured NSZD rates.

7.0 COST ASSESSMENT

The costs of implementing the field demonstration program were tracked and used to estimate the expected cost of implementing temperature-based NSZD monitoring at a specific project site.

7.1 COST MODEL

The key elements of the demonstration that are required to implement the temperature-based method to document and quantify NSZD included project planning and preparation, hardware procurement, field program implementation, and data evaluation and reporting (see Table 7.1). For the cost model, costs associated with the supplemental demonstration activities used to validate the temperature-based NSZD method are not included. These include the installation and sampling of Carbon Traps and soil vapor monitoring points.

Table 7.1. Cost Model for Field Demonstration

Cost Element	Data Tracked	Examples
Project planning and preparation	Labor hours	Senior Project Scientist/Engineer, Project Scientist/Engineer
Hardware procurement	Equipment costs	S3NSE Technologies Inc.
Field Program Implementation	Labor hours	Senior Project Scientist/Engineer, Project Scientist/Engineer
	Equipment Rental, Supplies, Shipping	Standard sampling equipment rental, operating costs, consumables
Data evaluation and reporting	Labor Hours	Senior Project Scientist/Engineer, Project Scientist/Engineer

The following costs are fundamental to a life-cycle cost evaluation but were not tracked as a part of this report, as they are standard, well-established technologies widely available to the environmental remediation community, and for which costs may vary widely depending on location and other site-specific considerations (e.g., state or local laws and regulations).

- Drilling costs to install the boreholes;
- Costs associated with concrete or asphalt coring/cutting;
- Management, characterization, treatment, and disposal of investigation-derived waste, such as soil cuttings and decontamination water; and
- Plugging and abandonment of the monitoring locations upon completion of the monitoring.

7.1.1 Cost Element: Project Planning and Preparation

Project planning for the two field demonstration sites included reviewing existing site data, obtaining site access, and developing work plans for the installation of the temperature monitoring hardware. The costs associated with this cost element were derived from labor costs and are summarized in Table 7.2.

Table 7.2. Cost Model for Project Planning and Implementation

Cost Element	Data to be Tracked	Representative Unit Cost	Representative Unit
Project Planning and Implementation	Labor hours: Senior Project Scientist/Engineer	8-16	Hours per site
	Labor hours: Project Scientist/Engineer	24-40	Hours per site

7.1.2 Cost Element: Hardware Procurement

The costs for procuring the temperature-based NSZD hardware (temperature sensors, datalogger, cellular modem) are one of the key drivers for the cost model. In addition, ongoing data services provided by S3NSE Technologies are provided on an annual subscription model by S3NSE.

7.1.3 Cost Element: Field Program

Costs for the field program included labor hours associated with the installation of the temperature monitoring stations, as well as expenses associated with field supplies (e.g., PID, etc.) and shipping.

Table 7.3. Cost Model for Field Program Implementation

Cost Element	Data to be Tracked	Representative Unit Cost	Representative Unit
Field Program Implementation	Labor hours: Senior Project Scientist/Engineer	1-2	Hours
	Labor hours: Project Scientist/Engineer	8-10	Hours
	Supplies	$50	Dollars per day
	Equipment Rental, Supplies, Shipping	$220	Dollars per day

7.1.4 Cost Element: Data Evaluation and Reporting

Following the installation, the temperature-based NSZD technology requires routine monitoring to ensure that the system and data collection functions as expected. Also, after sufficient data collection and on a periodic schedule, the data need to be analyzed and the NSZD rates computed. Key elements include data review and validation, data analysis, and documentation of the results and overall findings. The primary cost element, therefore, is labor. Typical time required for data compilation and review, data analysis, and reporting is summarized in Table 7.4. This labor hours estimate covers the time required for data QA evaluation and calculation of NSZD rates. The hours estimate does not include time for project reporting beyond the basic determination of NSZD rates, such as an evaluation of how NSZD may fit within an overall remediation strategy for the site.

Table 7.4. Cost Model for Data Evaluation and Reporting

Cost Element	Data to be Tracked	Representative Unit Cost	Representative Unit
Data Evaluation and Reporting	Labor hours: Senior Project Scientist/Engineer	8	Hours per site
	Labor hours: Project Scientist/Engineer	16	Hours per site

7.2 COST DRIVERS

There are two primary cost drivers of the temperature-based NSZD technology:

- Cost of monitoring hardware and long-term monitoring;
- Costs associated with drilling the borehole locations and management of investigation-derived wastes.

The monitoring hardware and long-term monitoring costs will be independent of location. The costs for installation of the monitoring equipment may vary widely depending on the site and will likely be the largest variable cost in a full cost accounting model. For example, installation at a remote facility would be expected to lead to higher costs than one located near a major metropolis due to larger mobilization costs. Likewise, a site with source zones requiring extensive treatment or disposal costs due to the nature of the source material (e.g., comingled plumes or the presence of other co-contaminants) would be expected to cost more than a site with just a light hydrocarbon such as gasoline or diesel.

7.3 COST ANALYSIS

Table 7.5. Estimated Cost for Installation of 5 2nd Generation Temperature Monitoring Stations at 1 Site

Cost Element	Cost Element	Units	Cost Per Unit	Estimated Cost
1. Project planning and preparation	Senior Project Scientist/Engineer,	8 hours	$200	$1,600
	Project Scientist/Engineer	24 hours	$125	$3,000
2. Hardware procurement	Temperature Monitoring Stations	5 units per site	$8,000	$40,000
3. Field Program Implementation	Labor hours: Senior Project Scientist/Engineer	4 hours	$200	$800
	Labor hours: Project Scientist/Engineer	40 hours	$125	$5,000
	Drilling Subcontractor	1 per site	$20,000	$20,000
	Supplies	1 per site	$50	$50
	Equipment Rental, Supplies, Shipping	4 days	$220	$880
4. Data evaluation and reporting	Senior Project Scientist/Engineer,	8 hours	$200	$1,600
	Project Scientist/Engineer	16 hours	$125	$2,000
			TOTAL	**$74,930**

Table 7.5 shows the estimated costs for installing temperature monitoring stations at a representative field site. It is assumed that five temperature monitoring stations are installed at relatively shallow depth (less than 20-25 feet below ground surface), that installation takes 4 10-hour days, and that the site is local (i.e., no travel expenses, lodging, per diem, etc.).

Overall, the capital cost would be approximately $75,000 for a continuous NSZD monitoring system for five locations. Assuming similar costs for project planning and preparation, data evaluation and reporting, and field program implementation (excluding the cost of the drilling subcontractor and equipment rental), the total cost for implementing five Carbon Traps for a one-time sampling event is $24,000. Each additional annual sampling event with Carbon Traps would be expected to cost approximately $13,300 (assuming 2 days of field work for installation and retrieval). If additional NSZD data is required to resolve intra-annual or seasonal effects (e.g., semi-annual or quarterly sampling), then the per-year costs would increase for each required event.

For a one-time NSZD study, the Carbon Trap technology would be less expensive than the temperature-based NSZD method. But for long-term annual monitoring of NSZD, where NSZD measurements are desired every year (or more frequently), the breakeven point would be at about the six-year point (or sooner). The advantage to long-term continuous NSZD monitoring using the temperature method is that it could potentially be used as a substitute for groundwater monitoring at some sites, greatly reducing long term monitoring costs.

Table 7.6. Comparison of Estimated Cost for Carbon Traps and Temperature-Based Monitoring at 1 Site Over Time

	1-Year Total Cost	5-Year Total Cost	10-Year Total Cost
Carbon Traps	$24,000	$77,000	$144,000
Temperature-Based NSZD	$75,000	$89,000	$107,000

Note: Costs rounded to the nearest $1,000

8.0 IMPLEMENTATION ISSUES

There are no widespread barriers to the implementation of temperature-based NSZD methods. Further guidance on NSZD methods, and the temperature-based (thermal or biogenic heat) method specifically, is available in various guidance documents, including API (2017), ITRC (2018), CRCCare (2018), and CL:AIRE (2019). In addition, temperature-based methods and their application are described in the recently published ASTM guidance document E3361-22: *Standard Guide for Estimating Natural Attenuation Rates for Non-Aqueous Phase Liquids in the Subsurface*.

To our knowledge, there are no current regulations or permits that are required to implement the technology as a monitoring technology, although site-specific application and use of the NSZD data should be considered within the larger site conceptual model and in consultation with any applicable State or Federal regulators. While reluctance to implement natural remedies that rely on NSZD remains among some regulators, other regulatory bodies have included the qualitative evaluation of NSZD when considering whether site closure is acceptable even with LNAPL remaining in-place (e.g., VA 2012; WV 2019). The continual advancement of guidance documents such as ITRC (2018) and ASTM E3361-22 (2022) provides the fundamental scientific basis for NSZD and accepted measurement methods. A continuing body of evidence reviewed during this project, including that collected at the two demonstration sites, indicates that NSZD has been measured at all sites in the literature (Kulkarni et al. 2022b; Appendix F).

The 2nd generation monitoring sensors and communication equipment can be procured from S3NSE Technologies as newly commercialized, custom-built equipment. Colorado State University Research Foundation (CSURF) currently owns the patent (Sale et al. 2015; US Patent No. 10,094,719) for devices and methods for measuring the thermal flux and estimating the NSZD rate, which GSI has exclusively sublicensed. Please contact GSI for further information on implementing temperature-based NSZD methods.

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APPENDIX A POINTS OF CONTACT

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APPENDIX B SUPPORTING FIGURES

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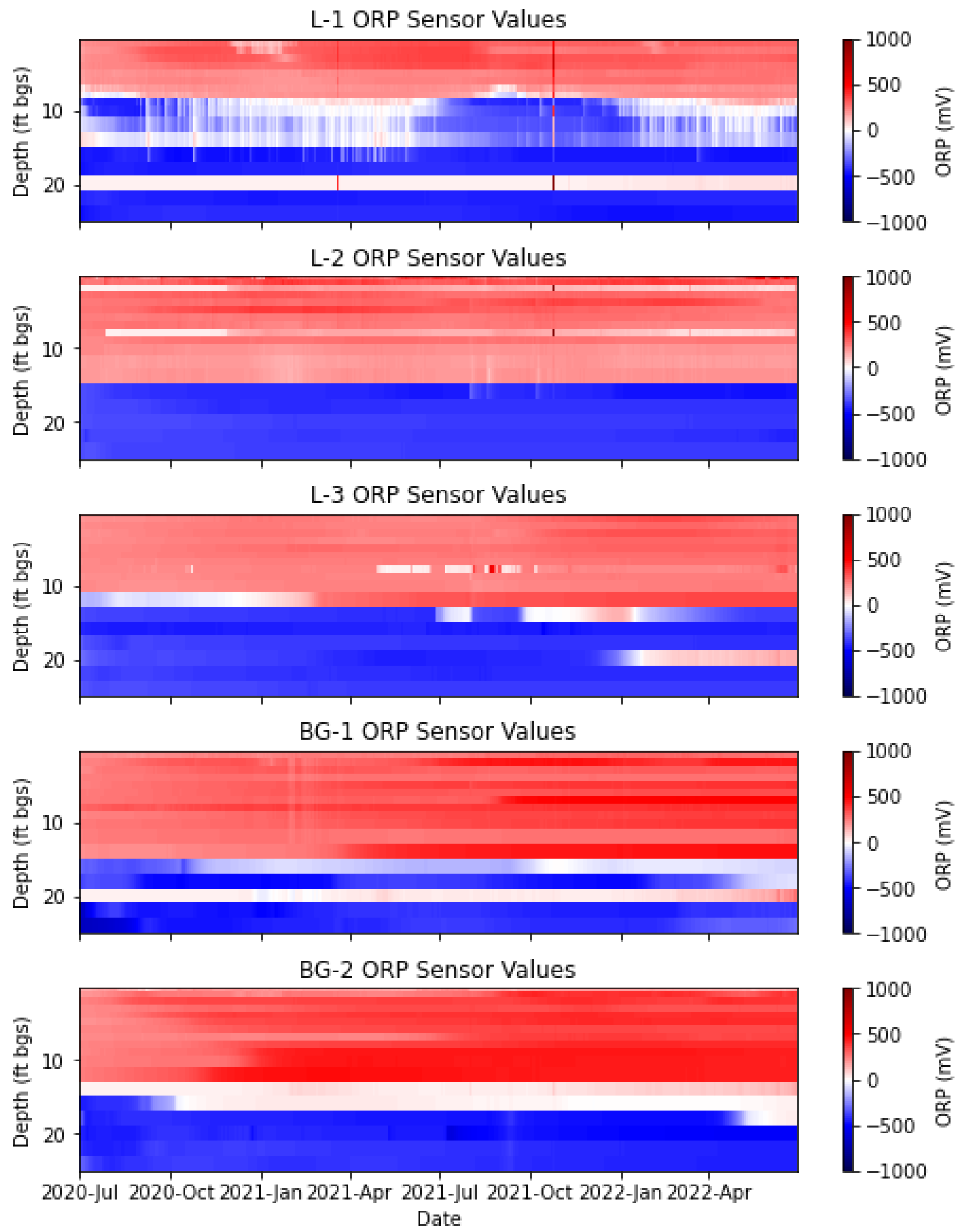

Figure B.1. ORP Data at TEAD-S (non-proprietary visualization)

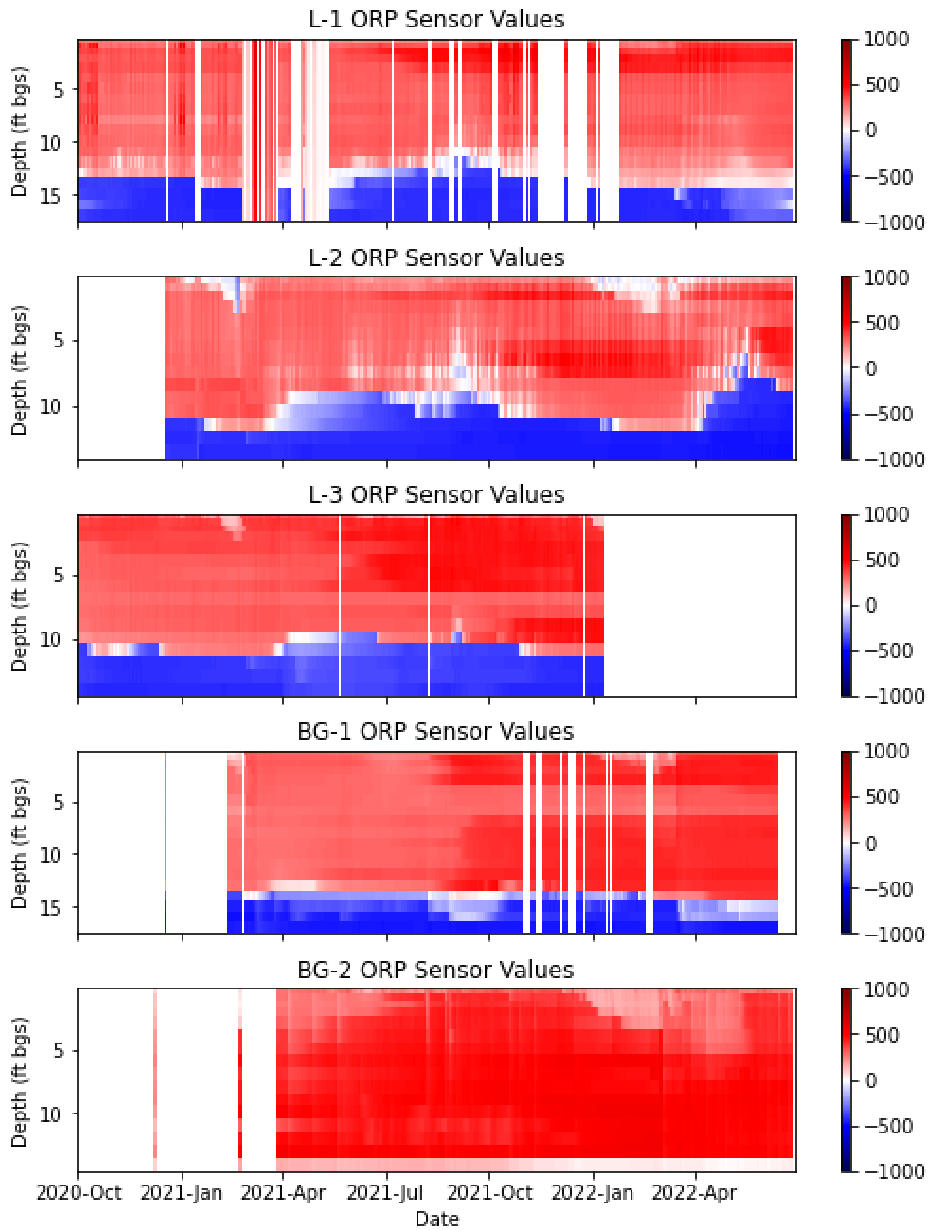

Figure B.2. ORP Data at the MN ANGB (non-proprietary visualization)

Figure B.3. Comparison of Daily NSZD Rates at TEAD-S for the Method 2 Background Correction Method for the Complete Dataset ("all"), the "Odd" Sensor Strings (1, 3, 5, 7, 9, 12, 16, 20 ft bgs), and the "Even: Sensor Strings (0.5, 2, 4, 6, 8, 10, 14, 18 ft bgs).

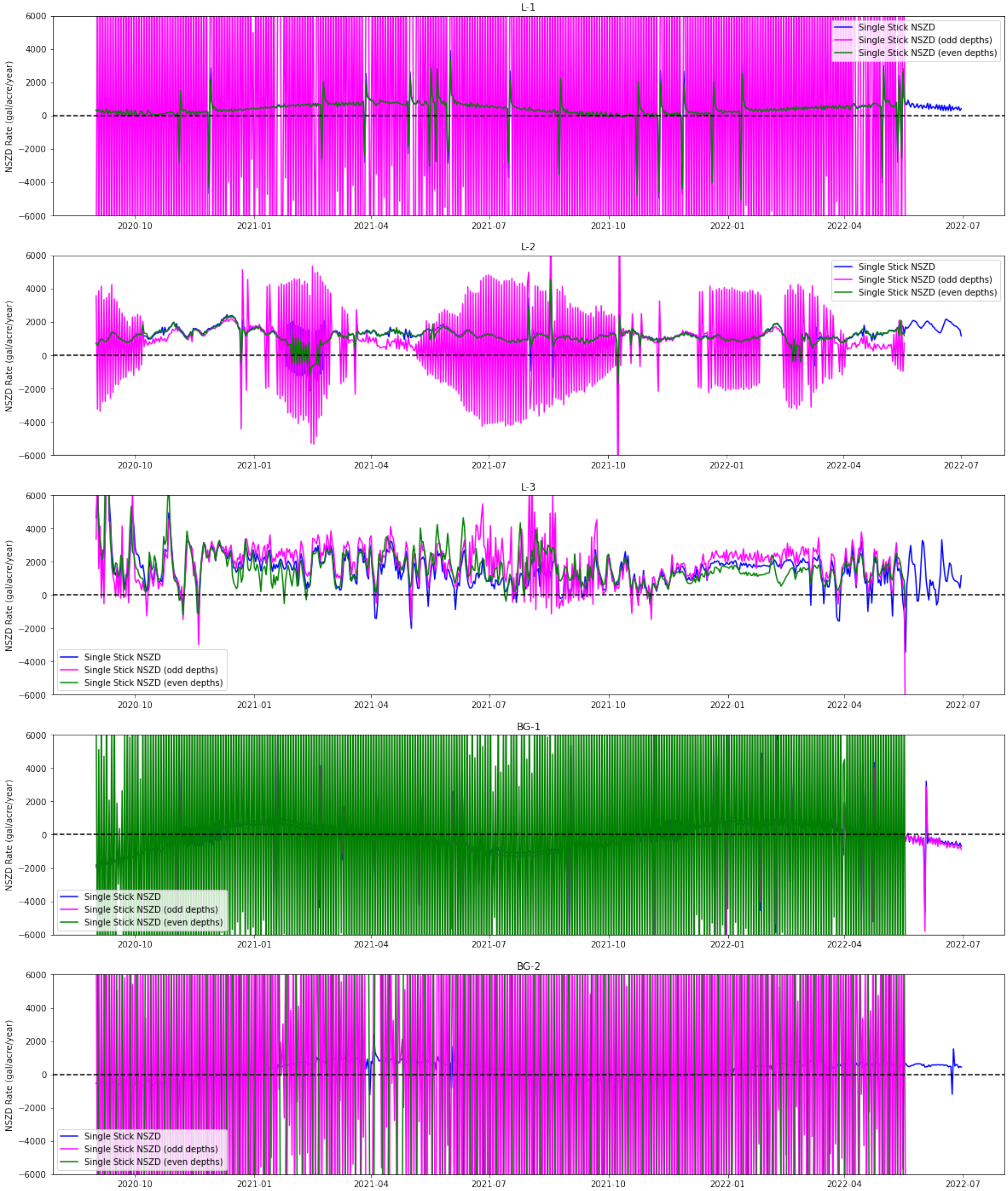

Figure B.4. Comparison of daily NSZD rates at TEAD-S for the Method 3 Single Stick method for the complete dataset ("all"), the "odd" sensor strings (1, 3, 5, 7, 9, 12, 16, 20 ft bgs), and the "even: sensor strings (0.5, 2, 4, 6, 8, 10, 14, 18 ft bgs).

APPENDIX C DATA COLLECTION QUALITY ASSURANCE

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APPENDIX C.1 DATA COLLECTION QUALITY ASSURANCE

APPENDIX C.2 SOIL GAS CALIBRATION DOCUMENTATION

APPENDIX C.1: DATA COLLECTION QUALITY ASSURANCE
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1.0 INTRODUCTION

This appendix summarizes the quality and validity of data used for temperature-based NSZD quantitative and qualitative assessments. The data collection period began during the summer of 2020 and lasted for approximately 23 to 26 months at TEAD-S and the MN ANGB. The data types for this demonstration involved subsurface temperatures, soil gas measurements, ORP measurements, water levels, and Carbon Trap flux rates. Key areas considered in this assessment included data completeness, equipment and sensor calibration, precision, and accuracy.

2.0 QUALITY ASSURANCE CONSIDERATIONS

Due to the nature of the data used in this project equipment, calibration with respect to both precision and accuracy are the largest factors in data quality and assurance. Thus, the following section will cover the calibration processes and procedures that were followed to prepare for data collection during the demonstration period. Soil and groundwater analytical data were not required or collected during this project.

3.0 EQUIPMENT CALIBRATION AND DATA COLLECTION PROCEDURES

Prior to the collection and measurement of data, field equipment was properly calibrated and checked to perform both accurate and precise measurements. Data measurements and collection underwent calibration and thorough testing prior to field use. All calibration testing occurred within a laboratory or office.

3.1 Carbon Traps

- One round of carbon flux measurements was conducted at each of the two demonstration sites, for a total of 10 Carbon Traps installed, five at each site. GSI field staff installed the Carbon Traps in the field, and the calibration, analytical analyses, and reporting were performed by E-Flux LLC, a Colorado-based company that sells these devices commercially. Carbon flux and NSZD rate results were obtained from each Carbon Trap. Further details on data analysis and quality assurance/quality control (QA/QC) can be found in the E-Flux laboratory reports provided in Appendix H.1 and H.2.
- No independent GSI calibrations were performed for the Carbon Traps. Special care was used to ensure that installation was performed according to E-Flux installation guidelines. A travel blank was included for each demonstration site.

3.2 Temperature Sensors

- Temperature sensors were calibrated and checked by the manufacturer to conform to ±0.5° C accuracy from -10° C to 85° C. S3NSE Technologies then performed an agreement test at room temperature and stated that the results indicated that the measurements from each sensor fell within ±0.2° C, which verified that all sensors were within the manufacturer-specified temperature accuracy allowance. Following the data sheet of DS180B20 temperature sensors used in the 2nd generation equipment used during this demonstration, temperature measurements under a 1000-hour stress test at +125 C drifted by +/- 0.2 C (note that this temperature is well above ambient environmental conditions). The printed circuit board (PCB) was manufactured by S3NSE Technologies and contains an LTE modem.

3.3 ORP

- ORP sensors were constructed and produced by S3NSE Technologies. Calibration and quality assurance were also performed by S3NSE to conform to ±1mV accuracy. The vendor, S3NSE Technologies, stated that since the primary components of ORP sensors are i) a dimensionally stable sensing electrode made by tantalum-iridium mixed metal oxides, and ii) a reference electrode with a minimum design life of 30 years (Hydrocarbon Proof (HCP), STELTH 1), the performance degradation of ORP sensors are negligible. The sensors feed the voltages sensed to an onboard 18-bit analog-to-digital converter (ADC). The printed circuit board (PCB) is manufactured by S3NSE Technologies and contains an LTE modem.

3.4 Water Levels

- Three pressure transducers at each site were installed near the bottom of the casing, within the screen. Water levels were gauged within a few days of well installation and again approximately 1 month afterward. These measurements were used to calibrate the transducers. However, after further review of this data over the demonstration period, transducer water levels at TEAD-S do not appear realistic or consistent with precipitation data. Precipitation data at TEAD-S were obtained via the Weather Underground (2022a) weather station approximately 7 miles northwest in Rush Valley, UT. Transducer water levels at the MN ANGB are reasonable, mostly consistent with local precipitation data, and could represent actual conditions. The local weather station is approximately 2 miles northeast (Weather Underground, 2022b). However, only two of the three sites are reporting reasonable values, and only BG-1 is continuous over the demonstration period length. Therefore, the water level data were rejected as unreliable, and as their performance was not an explicit objective of the demonstration, they were not considered further.

3.5 Soil Gas

- Soil vapor ports were installed at five locations each at both demonstration sites. Soil gas values were measured during three separate data collection efforts at TEAD-S and two separate data collection efforts at the MN ANGB over the course of the demonstration period. Data were collected for each sampling event via a GEM 2000/5000 series landfill gas meter. The gas meter was rented through an environmental supplier and calibrated before the soil gas sampling event by the equipment supplier (see Appendix C.2, Soil Gas Calibration Documentation, for the calibration reports). A charcoal filter was used to check the accuracy of high methane sample port readings. At the MN ANGB, very high methane and implausible methane readings were recorded at some locations (e.g., 100% methane at locations with detectable concentrations of oxygen and carbon dioxide), suggesting that the charcoal filter was not removing petroleum hydrocarbons from the sample stream. Based on these observations, the methane readings for the MN ANGB were rejected as unreliable and likely biased high.

4.0 SUMMARY

Overall, with the exception of the methane readings at the MN ANGB, the quality of data collected were deemed adequate for the purposes of this project.

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APPENDIX C: DATA COLLECTION QUALITY ASSURANCE
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Appendix C.2 Soil Gas Calibration Documentation

Manufaturer	Landtec	am	Aaron McMenomey
Model	GEM 2000	dpm	Dan Massingill
S/N	10555107	jc	Jason Carroll
O2 reading	0.0	jj	Judd Johnson
CH4 reading	50.1	kam	Kent A. Mitchell
CO2 reaqding	35.2	rcs	Roberto C. Silva
H2S Pod		tab	Tim A. Beyer
Tech	KAM		

Ajax Environmental
10801 Hammerly Blvd., Suite 148
Houston, TX 77043
713-789-4149

Calibration Gas used is traceable to N.I.S.T.		
MFG: GasCo	Lot#: 305-401790363-1	Expiration Date: 04/10/2022

Certification of Calibration

Manufacturer: Landtec **Model:** GEM 2000 **S/N:** 10555107

Calibration Gas:	**Reading After Calibration**
Oxygen: 0.0%	**0.0 % O_2**
Methane: 50%/Vol	**50.1 % CH_4**
Carbon Dioxide: 35%/Volume	**35.2 % CO_2**

Calibrated by: Kent A. Mitchell

Signature: ______________________

Date completed: June 19, 2020

Manufaturer	Landtec	am	Aaron McMenomey
Model	GEM 2000	dpm	Dan Massingill
S/N	A7101	jc	Jason Carroll
O2 reading	0.0	jj	Judd Johnson
CH4 reading	50.0	kam	Kent A. Mitchell
CO2 reaqding	35.1	rcs	Roberto C. Silva
H2S Pod		tab	Tim A. Beyer
Tech	KAM		

Ajax Environmental
10801 Hammerly Blvd., Suite 148
Houston, TX 77043
713-789-4149

Calibration Gas used is traceable to N.I.S.T.
MFG: GasCo Lot#: 305-401790363-1 Expiration Date: 04/10/2022

Certification of Calibration

Manufacturer: Landtec **Model:** GEM 2000 **S/N:** A7101

Calibration Gas:	**Reading After Calibration**
Oxygen: 0.0%	**0.0 % O2**
Methane: 50%/Vol	**50 % CH4**
Carbon Dioxide: 35%/Volume	**35.1 % CO2**

Calibrated by: Kent A. Mitchell

Signature: ____________________

Date completed: April 1, 2021

Manufaturer	Landtec	am	Aaron McMenomey
Model	GEM 2000	dpm	Dan Massingill
S/N	A7104	jc	Jason Carroll
O2 reading	0.0	jj	Judd Johnson
CH4 reading	50.1	kam	Kent A. Mitchell
CO2 reaqding	35.0	rcs	Roberto C. Silva
H2S Pod		tab	Tim A. Beyer
Tech	KAM		

Ajax Environmental
10801 Hammerly Blvd., Suite 148
Houston, TX 77043
713-789-4149

Calibration Gas used is traceable to N.I.S.T.
MFG: GasCo Lot#: 305-401790363-1 Expiration Date: 04/10/2022

Certification of Calibration

Manufacturer: Landtec **Model:** GEM 2000 **S/N:** A7104

Calibration Gas:	Reading After Calibration
Oxygen: 0.0%	**0.0 % O_2**
Methane: 50%/Vol	**50.1 % CH_4**
Carbon Dioxide: 35%/Volume	**35.0 % CO_2**

Calibrated by: Kent A. Mitchell

Signature: ____________________

Date completed: March 31, 2022

Ajax Environmental
10801 Hammerly Blvd., Suite 148
Houston, TX 77043
713-789-4149

Calibration Gas used is traceable to N.I.S.T.
MFG: GasCo Lot#: 305-401790363-1 Expiration Date: 04/10/2022

Post Rental Bump Report

Manufacturer: Landtec **Model:** GEM 2000 **S/N:** A7104

Calibration Gas:	Reading After Calibration
Oxygen: 0.0%	0.0 % O2
Methane: 50%/Vol	50.6 % CH4
Carbon Dioxide: 35%/Volume	35.4 % CO2

Calibrated by: Kent A. Mitchell

Signature: Kent A. Mitchell

Date completed: April 6, 2022

FIELD ENVIRONMENTAL INSTRUMENTS, INC.
www.fieldenvironmental.com

301 Brushton Ave
Suite A
Pittsburgh, PA 15221
Toll Free (800) 393-4009
Local (412) 436-2600
Fax (412) 436-2616

Landtec Landfill Meter Calibration Certificate

	Reading %	Acceptable Range
Fresh Air Oxygen	20.9	(20.65% - 21.15%)

	Lot #	Expiration
Cal Standard	19-6832	7/22/2023

	Reading %	Acceptable Range
Methane 50%	50.0	(51% - 49%)
Carbon Dioxide 35%	35.0	(34% - 36%)

	Lot #	Expiration
Cal Standard	18-6634	1/24/2021

	Reading %	Acceptable Range
Carbon Monoxide 50 ppm	50.0	(51 - 49)
Hydrogen Sulfide		(24 - 26)

Model	GEM-2000+
S/N	GM13982
Barcode	U67557X
Order #	434374

Calibrated By: Jeremy Sloan

Date of Calibration: 08/18/20

All calibrations performed by Field Environmental Instruments conform to manufacturer's specifications.
All calibration gas used is traceable to NIST. Additional documentation is available upon request.

FIELD ENVIRONMENTAL INSTRUMENTS, INC.
www.fieldenvironmental.com

301 Brushton Ave
Suite A
Pittsburgh, PA 15221
Toll Free (800) 393-4009
Local (412) 436-2600
Fax (412) 436-2616

Landtec Landfill Meter Calibration Certificate

Fresh Air	Reading %	Acceptable Range
Oxygen	20.9	(20.65% - 21.15%)

	Lot #	Expiration
Cal Standard	19-6936	9/17/2023

	Reading %	Acceptable Range
Methane 15%	15.0	(14.7% - 15.3%)
Carbon Dioxide 15%	15.0	(14.5% - 15.5%)

	Lot #	Expiration
Cal Standard	na	na

	Reading %	Acceptable Range
Carbon Monoxide 50 ppm	na	(51 - 49)
Hydrogen Sulfide 25ppm	na	(24 - 26)

Model	GEM-2000
S/N	GM12221/10
Barcode	u60083x
Order #	452380

Calibrated By: Ashrene Mohammed

Date of Calibration: 03/30/21

All calibrations performed by Field Environmental Instruments conform to manufacturer's specifications.
All calibration gas used is traceable to NIST. Additional documentation is available upon request.

APPENDIX D BORING LOGS

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Appendix D.1 TEAD-S Boring Logs
Appendix D.2 MN ANGB Boring Logs

APPENDIX D: BORING LOGS
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Appendix D.1 TEAD-S Boring Logs

GSI ENVIRONMENTAL

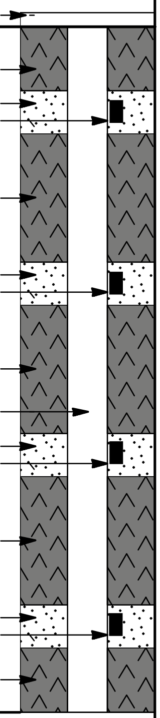
GSI Environmental Inc.
2211 Norfolk St. Suite 1000
Houston, TX 77098
Telephone: 713-522-6300

Log of Soil Boring & Well Construction: BG-1 Soil Vapor Monitoring Location

CLIENT ESTCP
GSI JOB NUMBER 5186
DATE STARTED 4 Jun. 2020 **COMPLETED** 4 Jun. 2020
DRILLING CONTRACTOR Cascade Drilling
DRILLING METHOD Mini-Sonic
DRILLING EQUIPMENT Mini-Sonic
GROUND SURFACE Concrete

PROJECT NAME ER19-5091
PROJECT LOCATION Tooele Army Depot - South, Utah
GROUND ELEVATION NA **DATUM** NA
TOP OF CASING ELEVATION NA **DATUM** NA
NORTHING NA **EASTING** NA
LOGGED BY S.T. Robinson, GIT **CHECKED BY** K.L. Walker
BORING DIAMETER (in) 4.5

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								Traffic-Rated Well Vault
	CONCRETE								
	CLAY (CH): light brown, no odor, damp, high plasticity, soft		CH				2.5		Bentonite
	Medium brown, slightly stiff								20/40 Filter Sand Vapor Probe
							3.6		Bentonite
							5.9		20/40 Filter Sand Vapor Probe
	Silty, soft								
							6.7		Bentonite
	Stiff								1-in I.D. PVC Riser
							5.4		20/40 Filter Sand Vapor Probe
5									
							8		Bentonite
	Very stiff, crumbly								
							3.1		20/40 Filter Sand Vapor Probe
							7		Bentonite



Total Depth = 8.0 feet.

GSI ENVIRONMENTAL

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Houston, TX 77098
Telephone: 713-522-6300

Log of Soil Boring & Well Construction: BG-1 Temperature Monitoring Location

CLIENT ESTCP

GSI JOB NUMBER 5186

DATE STARTED 3 Jun. 2020 **COMPLETED** 3 Jun. 2020

DRILLING CONTRACTOR Cascade Drilling

DRILLING METHOD Mini-Sonic

DRILLING EQUIPMENT Mini-Sonic

GROUND SURFACE Concrete

PROJECT NAME ER19-5091

PROJECT LOCATION Tooele Army Depot - South, Utah

GROUND ELEVATION NA **DATUM** NA

TOP OF CASING ELEVATION NA **DATUM** NA

NORTHING NA **EASTING** NA

LOGGED BY S.T. Robinson, GIT **CHECKED BY** K.L. Walker

BORING DIAMETER (in) 4.5

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								Well Stick-Up
	CONCRETE								Bentonite
	CLAY (CH): light brown, no odor, damp, high plasticity, soft		CH				24.4		Temperature Probe Temperature Probe
							24.9		
	Dry, abundant gravel								Temperature Probe
							8		
	Damp								Temperature Probe
							13.4		Temperature Probe
							16.1		
5	Dry, medium plasticity, medium stiff								Temperature Probe
							27.2		
	High plasticity, stiff								Temperature Probe
							20.8		
	CLAY (CL): gray/brown, no odor, damp, low plasticity, stiff		CL						Temperature Probe
							7.2		20/40 Filter Sand
	Soft								Temperature Probe
							15		2-in I.D. PVC
									Temperature Probe
							22.7		
10	CLAY (CH): light brown, dry, high plasticity, stiff, some very-fine grained sand		CH						Temperature Probe
							17.8		
	CLAY (CL): light brown, dry, medium plasticity, very stiff, crumbly		CL						
							24.1		
	Some silt								Temperature Probe
							15.1		
	Damp								
							22.9		
	Slightly stiff								Temperature Probe
							18.9	▼	Water Level = 14.97 ft BGS

(Continued Next Page)

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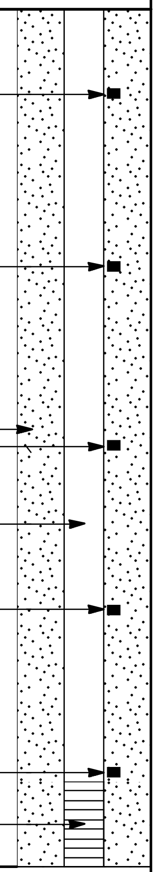
Log of Soil Boring & Well Construction: BG-1 Temperature Monitoring Location

CLIENT ESTCP | **PROJECT NAME** ER19-5091

GSI JOB NUMBER 5186 | **PROJECT LOCATION** Tooele Army Depot - South, Utah

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								
	Tan, low plasticity		CL				17.8		Temperature Probe
	CLAY (CH): tan, no odor, damp, medium-high plasticity, stiff		CH				18.1		
	Dry, very stiff						18.5		Temperature Probe
	Crumbly						15.5		
							21.8		20/40 Filter Sand
20	CLAYEY GRAVEL (GC): brown/tan, odor, moist, soft, gravel lense		GC				18.8		Temperature Probe
	GRAVELLY CLAY (CH): brown/tan, odor, moist, high plasticity, stiff, gravel		CH				21.9		2-in I.D. PVC
	Very moist, soft						26.6		Temperature Probe
	CLAYEY GRAVEL (GC): brown/tan, odor, very moist, soft		GC				18.5		Temperature Probe
	SILTY GRAVEL (GM): brown/tan, odor, very moist, soft		GM				14.6		2-in I.D. 0.010-in Slot PVC Screen
25	Total Depth = 25.0 feet.								



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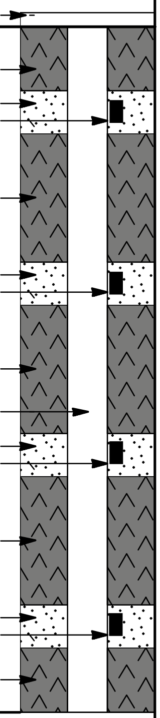
Log of Soil Boring & Well Construction: BG-2 Soil Vapor Monitoring Location

CLIENT ESTCP	**PROJECT NAME** ER19-5091
GSI JOB NUMBER 5186	**PROJECT LOCATION** Tooele Army Depot - South, Utah
DATE STARTED 4 Jun. 2020 **COMPLETED** 4 Jun. 2020	**GROUND ELEVATION** NA **DATUM** NA
DRILLING CONTRACTOR Cascade Drilling	**TOP OF CASING ELEVATION** NA **DATUM** NA
DRILLING METHOD Mini-Sonic	**NORTHING** NA **EASTING** NA
DRILLING EQUIPMENT Mini-Sonic	**LOGGED BY** S.T. Robinson, GIT **CHECKED BY** K.L. Walker
GROUND SURFACE Brushland	**BORING DIAMETER (in)** 4.5

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								Traffic-Rated Well Vault
	SILTY SAND (SM): light brown, no odor, damp, soft, very fine-grained, some clay clasts		SM				17.6		Bentonite
									20/40 Filter Sand Vapor Probe
							18.7		Bentonite
							18.1		
	SILTY CLAY (CL): medium brown, no odor, damp, medium-high plasticity, very stiff		CL						20/40 Filter Sand Vapor Probe
							20		Bentonite
							17.6		1-in I.D. PVC Riser
5	CLAY (CH): medium brown, no odor, damp, high plasticity, very stiff		CH						20/40 Filter Sand Vapor Probe
							15.6		Bentonite
	SILTY CLAY (CL): medium brown, no odor, dry, low plasticity, very stiff		CL				14		20/40 Filter Sand Vapor Probe
	Light brown/tan						12.8		Bentonite



Total Depth = 8.0 feet.

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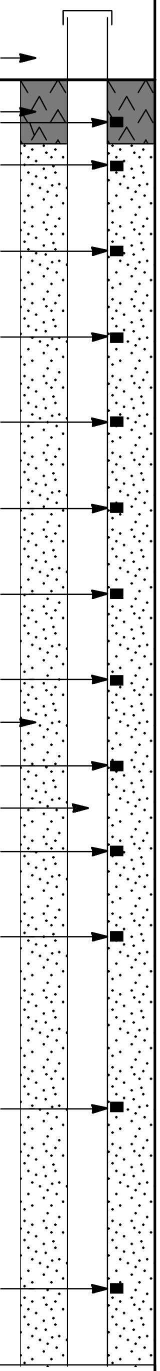
Log of Soil Boring & Well Construction: BG-2 Temperature Monitoring Location

CLIENT ESTCP
GSI JOB NUMBER 5186
DATE STARTED 4 Jun. 2020 **COMPLETED** 4 Jun. 2020
DRILLING CONTRACTOR Cascade Drilling
DRILLING METHOD Mini-Sonic
DRILLING EQUIPMENT Mini-Sonic
GROUND SURFACE Brushland

PROJECT NAME ER19-5091
PROJECT LOCATION Tooele Army Depot - South, Utah
GROUND ELEVATION NA **DATUM** NA
TOP OF CASING ELEVATION NA **DATUM** NA
NORTHING NA **EASTING** NA
LOGGED BY S.T. Robinson, GIT **CHECKED BY** K.L. Walker
BORING DIAMETER (in) 4.5

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								Well Stick-Up
	SANDY SILT (ML): light brown, no odor, dry, soft, some very fine-grained sand, hard clasts		ML				19.1		Bentonite; Temperature Probe; Temperature Probe
	Very stiff, crumbly						2.9		Temperature Probe
	SILTY CLAY (CL): light brown, no odor, dry, medium plasticity, very stiff		CL				13.5		Temperature Probe
							12.7		Temperature Probe
	Medium stiff						12.7		Temperature Probe
5	CLAY (CH): medium brown, no odor, dry, high plasticity, very stiff		CH				16.5		Temperature Probe
	Crumbly						8.8		Temperature Probe
	SILTY CLAY (CL): tan, no odor, dry, low plasticity, very stiff, crumbly		CL				17.1		20/40 Filter Sand; Temperature Probe
	CLAYEY SAND (SC): tan, no odor, damp, soft, fine-grained sand		SC				19.2		2-in I.D. PVC; Temperature Probe
	Some clay chunks						24		Temperature Probe
10	Medium-light brown						14.3		
	SAND (SP): medium-light brown, no odor, moist, soft, very fine-grained		SP				23		Temperature Probe
	CLAYEY SAND (SC): medium-light brown, no odor, moist, slightly stiff, very fine-grained		SC				21.5		
	CLAY (CL): medium-light brown, no odor, damp, medium-high plasticity, slightly stiff, some very fine-grained sand		CL				19.7	▼	Water Level = 13.81 ft BGS; Temperature Probe
	SAND (SP): gray, no odor, moist, soft, slightly clayey, medium-grained		SP				20.2		



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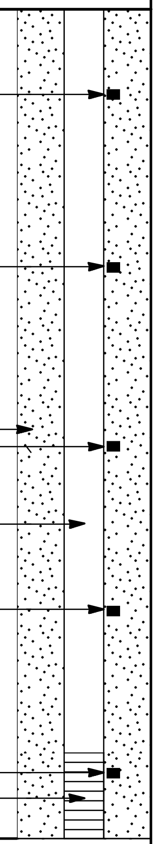
Log of Soil Boring & Well Construction: BG-2 Temperature Monitoring Location

CLIENT ESTCP
PROJECT NAME ER19-5091
GSI JOB NUMBER 5186
PROJECT LOCATION Tooele Army Depot - South, Utah

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								
							17.7		
	SANDY CLAY (CL): light brown/gray, no odor, damp, medium plasticity, stiff, some very fine-grained sand		CL				19.2		Temperature Probe
	CLAYEY SAND (SC): light brown/gray, no odor, moist, soft, very fine-grained		SC				14.3		
	CLAY (CH): light brown/gray, no odor, damp, medium plasticity, very stiff, crumbly		CH				18.5		Temperature Probe
	CLAYEY SAND (SC): light brown/gray, no odor, dry, very fine-grained		SC				13.2		20/40 Filter Sand
20	SANDY CLAY (CL): medium gray, no odor, slightly damp, low plasticity, very stiff, some very fine-grained sand		CL				14.3		Temperature Probe
	Dry						15.1		2-in I.D. PVC
							17.5		Temperature Probe
	Light brown, damp, high plasticity, slightly stiff						8.7		
	CLAYEY SAND (SC): light brown, no odor, moist, soft, very fine to fine grained		SC				9.5		Temperature Probe 2-in I.D. 0.010-in Slot PVC Screen

Total Depth = 24.7 feet.



Log of Soil Boring & Well Construction: L-1 Soil Vapor Monitoring Location

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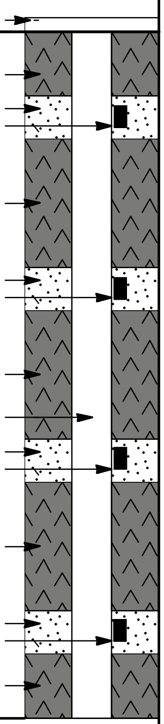
Telephone: 713-522-6300

CLIENT	ESTCP	**PROJECT NAME**	ER19-5091
GSI JOB NUMBER	5186	**PROJECT LOCATION**	Tooele Army Depot - South, Utah
DATE STARTED	4 Jun. 2020	**COMPLETED**	4 Jun. 2020
GROUND ELEVATION	NA	**DATUM**	NA
DRILLING CONTRACTOR	Cascade Drilling	**TOP OF CASING ELEVATION**	NA
DATUM	NA	**DRILLING METHOD**	Mini-Sonic
NORTHING	NA	**EASTING**	NA
DRILLING EQUIPMENT	Mini-Sonic	**LOGGED BY**	S.T. Robinson, GIT
CHECKED BY	K.L. Walker	**GROUND SURFACE**	Concrete
BORING DIAMETER (in)	4.5		

Depth (ft bgs)	Soil Description	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE							Traffic-Rated Well Vault
	CONCRETE							
	SILTY GRAVEL (GM): dark brown, no odor, damp, soft	GM				66.8		Bentonite; 20/40 Filter Sand; Vapor Probe
						53.7		Bentonite
						27.1		20/40 Filter Sand; Vapor Probe
						26.1		Bentonite; 1-in I.D. PVC Riser
5						26.6		20/40 Filter Sand; Vapor Probe
						29.4		
	GRAVELLY CLAY (CH): dark brown, no odor, damp, high plasticity, stiff	CH				27.3		Bentonite; 20/40 Filter Sand; Vapor Probe
	GRAVELLY SAND (SW): dark brown, no odor, damp, slightly stiff, crumbly, very fine-grained sand	SW				26.5		Bentonite

Total Depth = 8.0 feet.



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Log of Soil Boring & Well Construction: L-1 Temperature Monitoring Location

CLIENT ESTCP
PROJECT NAME ER19-5091
GSI JOB NUMBER 5186
PROJECT LOCATION Tooele Army Depot - South, Utah
DATE STARTED 4 Jun. 2020 **COMPLETED** 4 Jun. 2020
GROUND ELEVATION NA **DATUM** NA
DRILLING CONTRACTOR Cascade Drilling
TOP OF CASING ELEVATION NA **DATUM** NA
DRILLING METHOD Mini-Sonic
NORTHING NA **EASTING** NA
DRILLING EQUIPMENT Mini-Sonic
LOGGED BY S.T. Robinson, GIT **CHECKED BY** K.L. Walker
GROUND SURFACE Concrete
BORING DIAMETER (in) 4.5

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								Well Stick-Up
	CONCRETE								Bentonite
	NOT RECOVERED								Temperature Probe
									Temperature Probe
									Temperature Probe
	CLAYEY GRAVEL (GC): brown, no odor, damp, soft		GC						
							11		
									Temperature Probe
							16.4		
	CLAY (CH): brown, no odor, damp, high plasticity, medium stiff, some gravel		CH						Temperature Probe
							32.2		
5									Temperature Probe
							25.5		
	Dark brown, moist, soft								Temperature Probe
							22.6		
	CLAY (CL): gray, no odor, damp, low plasticity, very stiff		CL						Temperature Probe
									20/40 Filter Sand
							22.4		
	Crumbly								Temperature Probe
									2-in I.D. PVC
							23.8		
									Temperature Probe
							27.8		
10	CLAY (CH): black, strong odor, damp, high plasticity, very stiff, charcoal appearance		CH						Temperature Probe
							420.3		
	Dark gray mottling								
							371.7		
	CLAYEY SILT (ML): black, strong odor, dry, very stiff		ML						Temperature Probe
							405.7		
							440.2		
									Temperature Probe
							147.7		

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Log of Soil Boring & Well Construction: L-1 Temperature Monitoring Location

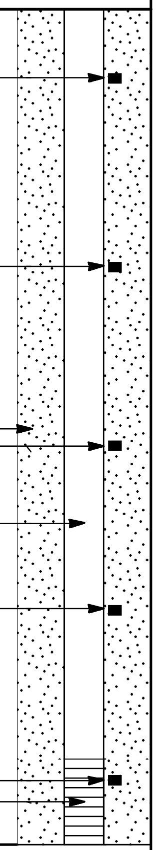
CLIENT ESTCP

PROJECT NAME ER19-5091

GSI JOB NUMBER 5186

PROJECT LOCATION Tooele Army Depot - South, Utah

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								
	CLAY (CH): gray/black, mild odor, damp, high plasticity, stiff, extensive mottling		CH				148.5		Temperature Probe
	CLAYEY SAND (SC): gray/black, mild odor, damp, stiff, fine-grained		SC				323.7	▼	Water Level = 16.07 ft BGS
	Gray/tan, lense of sand with little to no fines (SP)						273.6		
	SANDY CLAY (CL): gray/tan, mild odor, moist, no-low plasticity, stiff, very fine-grained		CL				21.3		Temperature Probe
	SAND (SP): gray/tan, mild odor, moist, soft, medium-grained, clay nodules		SP				38.1		20/40 Filter Sand
20	Slight-no odor, 1-2" clay lenses (stiff, damp, high plasticity)						24.5		Temperature Probe
							22.6		2-in I.D. PVC
	CLAYEY SAND (SC): tan, slight-no odor, moist, soft, very fine-grained		SC				21.9		Temperature Probe
							20.8		
	CLAY (CH): greenish gray, slight-no odor, damp, high plasticity, stiff, slightly crumbly		CH				16.5		Temperature Probe 2-in I.D. 0.010-in Slot PVC Screen



Total Depth = 24.8 feet.

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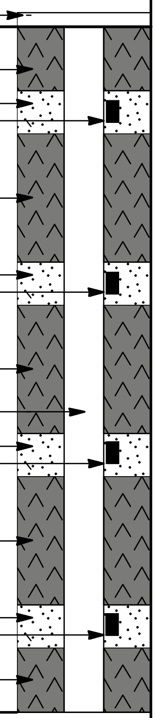
Log of Soil Boring & Well Construction: L-2 Soil Vapor Monitoring Location

CLIENT ESTCP	**PROJECT NAME** ER19-5091
GSI JOB NUMBER 5186	**PROJECT LOCATION** Tooele Army Depot - South, Utah
DATE STARTED 3 Jun. 2020 **COMPLETED** 3 Jun. 2020	**GROUND ELEVATION** NA **DATUM** NA
DRILLING CONTRACTOR Cascade Drilling	**TOP OF CASING ELEVATION** NA **DATUM** NA
DRILLING METHOD Mini-Sonic	**NORTHING** NA **EASTING** NA
DRILLING EQUIPMENT Mini-Sonic	**LOGGED BY** S.T. Robinson, GIT **CHECKED BY** K.L. Walker
GROUND SURFACE Concrete	**BORING DIAMETER (in)** 4.5

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level
	GROUND SURFACE							
	CONCRETE						9.8	
	GRAVELLY CLAY (CH): med/brown, no odor, damp, high plasticity, very stiff		CH				10.2	
	Little to no gravel						9.2	
							8.7	
5	Stiff						11.8	
							9.2	
	CLAY (CL): med/brown, no odor, dry, low plasticity, stiff, silt lense		CL				12.5	
	CLAY (CH): med/brown, no odor, damp, medium plasticity, medium stiff		CH				8.4	

Total Depth = 8.0 feet.

Well Diagram and Remarks



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Log of Soil Boring & Well Construction: L-2 Temperature Monitoring Location

CLIENT ESTCP
GSI JOB NUMBER 5186
DATE STARTED 3 Jun. 2020 **COMPLETED** 3 Jun. 2020
DRILLING CONTRACTOR Cascade Drilling
DRILLING METHOD Mini-Sonic
DRILLING EQUIPMENT Mini-Sonic
GROUND SURFACE Concrete

PROJECT NAME ER19-5091
PROJECT LOCATION Tooele Army Depot - South, Utah
GROUND ELEVATION NA **DATUM** NA
TOP OF CASING ELEVATION NA **DATUM** NA
NORTHING NA **EASTING** NA
LOGGED BY S.T. Robinson, GIT **CHECKED BY** K.L. Walker
BORING DIAMETER (in) 4.5

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								Well Stick-Up
0–1	CONCRETE						11.9		Bentonite; Temperature Probe
1–2	GRAVELLY CLAY (CL): light brown, no odor, slightly damp, high plasticity, medium soft		CL				26.3		Temperature Probe
2–3	CLAY (CH): medium brown, no odor, moist, high plasticity, medium stiff, some cobbles		CH				4.7		Temperature Probe
3–4							12.8		Temperature Probe
4–5	CLAY (CL): medium brown, no odor, dry, low plasticity, very stiff, crumbly		CL				15.7		Temperature Probe
5–6	CLAY (CH): dark brown, no odor, moist, high plasticity, soft		CH				11.4		Temperature Probe
6–7	CLAY (CL): light brown, no odor, dry, low plasticity, very stiff, crumbly		CL				16.6		Temperature Probe
7–8	CLAY (CH): light brown, no odor, dry, high plasticity, very stiff, crumbly		CH				20.7		Temperature Probe; 20/40 Filter Sand
8–9	Crumbly, charcoal-like clay with glistening spots, strong odor						237		Temperature Probe; 2-in I.D. PVC
9–10							373.7		Temperature Probe
10–11	SILTY CLAY (CL): light gray, odor, dry, low plasticity, very stiff		CL				302.9		Temperature Probe
11–12							290.4		
12–13							204.4		Temperature Probe
13–14							140		
14–15	Very silty						353	▼	Temperature Probe; Water Level = 14.95 ft BGS

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Log of Soil Boring & Well Construction: L-2 Temperature Monitoring Location

CLIENT ESTCP

PROJECT NAME ER19-5091

GSI JOB NUMBER 5186

PROJECT LOCATION Tooele Army Depot - South, Utah

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								
	Some very fine-grained sand, black spots		CL				232		
	CLAYEY SAND (SC): light gray, odor, moist, soft, very fine-grained		SC				74		Temperature Probe
	Clay chunks						26.4		
	SAND (SP): light gray, slight odor, moist, soft, fine- to medium-grained sand		SP				26.9		Temperature Probe
							22.1		20/40 Filter Sand
20	CLAY (CH): light gray/brown, no odor, moist, high plasticity, stiff, some very fine grained sand		CH				8.1		Temperature Probe
							8.4		2-in I.D. PVC
							19.8		Temperature Probe
	CLAY (CL): light gray, no odor, dry, medium to low plasticity, very stiff, little to no sand, thin lense of medium to coarse grained sand		CL				19		Temperature Probe
							16		2-in I.D. 0.010-in Slot PVC Screen
25	Total Depth = 25.0 feet.								

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Log of Soil Boring & Well Construction: L-3 Soil Vapor Monitoring Location

CLIENT ESTCP
PROJECT NAME ER19-5091
GSI JOB NUMBER 5186
PROJECT LOCATION Tooele Army Depot - South, Utah
DATE STARTED 5 Jun. 2020 **COMPLETED** 5 Jun. 2020
GROUND ELEVATION NA **DATUM** NA
DRILLING CONTRACTOR Cascade Drilling
TOP OF CASING ELEVATION NA **DATUM** NA
DRILLING METHOD Mini-Sonic
NORTHING NA **EASTING** NA
DRILLING EQUIPMENT Mini-Sonic
LOGGED BY S.T. Robinson, GIT **CHECKED BY** K.L. Walker
GROUND SURFACE Brushland
BORING DIAMETER (in) 4.5

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								Traffic-Rated Well Vault
	GRAVELLY SILT (ML): light brown, no odor, dry, soft, some clumps		ML				15.7		Bentonite
							13.7		20/40 Filter Sand Vapor Probe Bentonite
	SILT (ML): light brown, no odor, dry, soft, clumpy		ML				10.6		20/40 Filter Sand Vapor Probe
	Very stiff						8.5		Bentonite 1-in I.D. PVC Riser
5							13.6		20/40 Filter Sand Vapor Probe
							13.2		Bentonite
							10		20/40 Filter Sand Vapor Probe
	Medium brown, damp, clayey (gray mottling), fining downwards						12.8		Bentonite

Total Depth = 8.0 feet.

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Log of Soil Boring & Well Construction: L-3 Temperature Monitoring Location

CLIENT	ESTCP	**PROJECT NAME**	ER19-5091
GSI JOB NUMBER	5186	**PROJECT LOCATION**	Tooele Army Depot - South, Utah
DATE STARTED	5 Jun. 2020	**COMPLETED**	5 Jun. 2020
GROUND ELEVATION	NA	**DATUM**	NA
DRILLING CONTRACTOR	Cascade Drilling	**TOP OF CASING ELEVATION**	NA
DATUM	NA	**DRILLING METHOD**	Mini-Sonic
NORTHING	NA	**EASTING**	NA
DRILLING EQUIPMENT	Mini-Sonic	**LOGGED BY**	S.T. Robinson, GIT
CHECKED BY	K.L. Walker	**GROUND SURFACE**	Brushland
BORING DIAMETER (in)	4.5		

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								Well Stick-Up
	GRAVELLY SILT (ML): medium brown, no odor, dry, soft		ML				4.7		Bentonite; Temperature Probe
	SAND (SM): medium brown, no odor, dry, soft, very fine-grained, clumpy, silty		SM				11.2		Temperature Probe; Temperature Probe
							12.4		Temperature Probe
	Very stiff						12		Temperature Probe
	SILT (ML): medium brown, no odor, dry, very stiff, clumpy		ML				12.4		Temperature Probe
5	GRAVELLY SILT (ML): light brown, no odor, dry, soft		ML				14.3		Temperature Probe
							11.9		Temperature Probe
	SILTY SAND (SM): light brown, no odor, dry, very stiff, clumpy, very fine-grained		SM				11		Temperature Probe; 20/40 Filter Sand
	Medium brown, strong odor						8.9		Temperature Probe; 2-in I.D. PVC
	CLAY (CH): medium brown/black, strong odor, damp, high plasticity, stiff, some very fine-grained sand, black clusters, mottling		CH				54.5		Temperature Probe
10	CLAYEY SILT (ML): black/gray, strong odor, damp, very stiff, crumbly		ML				359.2		Temperature Probe
	Medium gray, dry, black spots						305.7		
	Light gray						169		Temperature Probe
	CLAYEY SAND (SC): light gray, strong odor, damp, soft, slightly clayey, very fine-grained, downward coarsening		SC				156.7	▼	Water Level = 13.62 ft BGS
	Light gray/tan, black clay chunks (high plasticity, soft)						67.1		Temperature Probe

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Log of Soil Boring & Well Construction: L-3 Temperature Monitoring Location

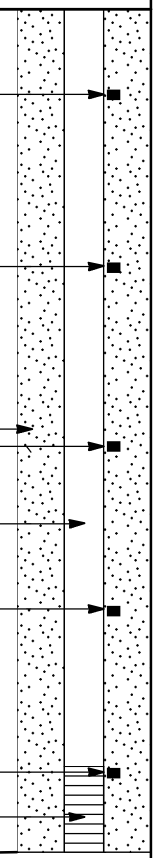
CLIENT ESTCP

PROJECT NAME ER19-5091

GSI JOB NUMBER 5186

PROJECT LOCATION Tooele Army Depot - South, Utah

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								
	SAND (SP): light gray/tan, no odor, moist, slightly stiff, fine to medium-grained, slightly clayey		SP				15		Temperature Probe
	CLAYEY SAND (SC): light gray/tan, no odor, moist, slightly stiff, very fine-grained		SC				15.7		
	Soft						14.9		Temperature Probe
	Fine to medium-grained						17		
	SANDY CLAY (CL): light gray/tan, no odor, moist, low plasticity, very stiff, some very fine-grained sand		CL				15.6		20/40 Filter Sand
20	CLAYEY SAND (SC): light brown, no odor, moist, soft, fine-grained		SC				19		Temperature Probe
	Lenses of clay (very stiff, low plasticity)						18.6		2-in I.D. PVC
							16.9		Temperature Probe
	CLAY (CH): greenish gray, no odor, damp, high plasticity, very stiff, black spots		CH				16.1		Temperature Probe
	Medium gray, crumbly						13.6		2-in I.D. 0.010-in Slot PVC Screen



Total Depth = 24.8 feet.

APPENDIX D: BORING LOGS
ESTCP ER19-5091

Appendix D.2 MN ANGB Boring Logs

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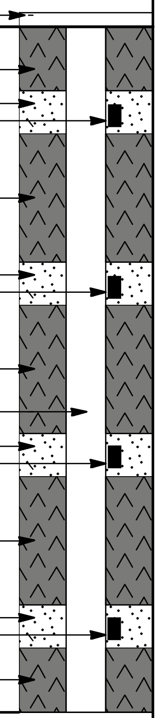
Log of Soil Boring & Well Construction: BG-1 Soil Vapor Monitoring Location

CLIENT	ESTCP	**PROJECT NAME**	ER19-5091
GSI JOB NUMBER	5186	**PROJECT LOCATION**	Minnesota Air National Guard, Minneapolis
DATE STARTED	23 Jul. 2020	**COMPLETED**	23 Jul. 2020
GROUND ELEVATION	821.91	**DATUM**	NGVD29
DRILLING CONTRACTOR	Traut Companies	**TOP OF CASING ELEVATION**	NA
DATUM	NA	**DRILLING METHOD**	Hollow Stem Auger
NORTHING	44.89228	**EASTING**	-93.20350
DRILLING EQUIPMENT	Geoprobe	**LOGGED BY**	S.T. Robinson, GIT
CHECKED BY	K.L. Walker	**GROUND SURFACE**	Grass
BORING DIAMETER (in)	8.25		

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								Traffic-Rated Well Vault
	CLAYEY ORGANIC SILT (OL): black, no odor, dry, stiff		OL				2		Bentonite; 20/40 Filter Sand; Vapor Probe
							2.4		Bentonite
							1.9		20/40 Filter Sand; Vapor Probe
	CLAY (CH): dark brown, no odor, damp, high plasticity, stiff		CH				2.9		Bentonite
	GRAVELLY SAND (SW): tan, no odor, damp, loose fine to medium-grained		SW				5		1-in I.D. PVC Riser
5	SAND (SP): tan, no odor, damp, soft, fine-grained, slightly clayey		SP				1.8		20/40 Filter Sand; Vapor Probe
	Stiff								Bentonite
							3		20/40 Filter Sand; Vapor Probe
							6.4		Bentonite



Total Depth = 8.0 feet.

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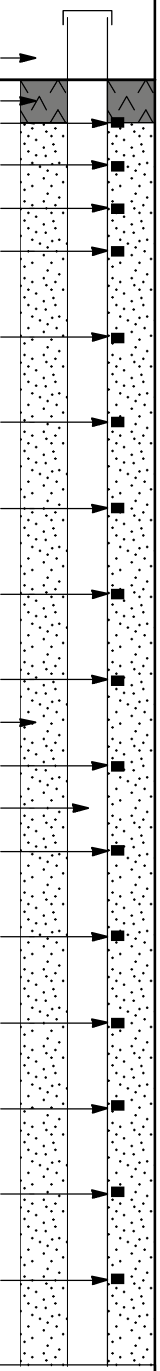
Log of Soil Boring & Well Construction: BG-1 Temperature Monitoring Location

CLIENT ESTCP
GSI JOB NUMBER 5186
DATE STARTED 24 Jul. 2020 **COMPLETED** 24 Jul. 2020
DRILLING CONTRACTOR Traut Companies
DRILLING METHOD Hollow Stem Auger
DRILLING EQUIPMENT Geoprobe
GROUND SURFACE Grass

PROJECT NAME ER19-5091
PROJECT LOCATION Minnesota Air National Guard, Minneapolis
GROUND ELEVATION 821.91 **DATUM** NGVD29
TOP OF CASING ELEVATION 823.98 **DATUM** NGVD29
NORTHING 44.892289 **EASTING** -93.20350
LOGGED BY S.T. Robinson, GIT **CHECKED BY** K.L. Walker
BORING DIAMETER (in) 8.25

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								Well Stick-Up
	ORGANIC SILT (OL): black, no odor, dry, medium stiff, slightly clayey		OL				1.6		Bentonite; Temperature Probe
							2.7		Temperature Probe; Temperature Probe
	CLAY (CH): black, no odor, damp, medium plasticity, stiff		CH				3		Temperature Probe
	High plasticity, medium stiff, some medium-grained sand						3.2		Temperature Probe
	GRAVELLY SAND (SW): reddish tan, no odor, damp, soft, medium to coarse-grained sand		SW				2.5		Temperature Probe
5	SAND (SP): tan, no odor, damp, soft, very fine-grained		SP				3.5		Temperature Probe
	Stiff, minor clay						4.3		Temperature Probe
							3.7		Temperature Probe; 20/40 Filter Sand
	SANDY CLAY (CL): dark tan, no odor, damp, medium plasticity, medium stiff, some fine-grained sand		CL				3.2		Temperature Probe; 1-in I.D. PVC
	High plasticity						3.8		Temperature Probe
10	Medium brown, some very fine to coarse-grained sand lenses						4		Temperature Probe
	CLAY (CH): reddish brown, no odor, damp, high plasticity, medium stiff, minor coarse-grained sand		CH				3.6		Temperature Probe
	Brown to gray, medium-high plasticity, minor tan clay chunks						3.2	▼	Temperature Probe; Water Level = 12.50 ft BGS
	Gray, high plasticity, very stiff, minor gravel						3		Temperature Probe
	GRAVELLY/SANDY CLAY (CL): gray, no odor, damp, medium plasticity, very stiff, some coarse-grained sand		CL				2.8		Temperature Probe



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Log of Soil Boring & Well Construction: BG-1 Temperature Monitoring Location

CLIENT ESTCP **PROJECT NAME** ER19-5091

GSI JOB NUMBER 5186 **PROJECT LOCATION** Minnesota Air National Guard, Minneapolis

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								
	CLAY (CH): gray, no odor, damp, medium-high plasticity, medium stiff, crumbly, minor coarse-grained sand		CH				1.9		Temperature Probe 20/40 Filter Sand 1-in I.D. PVC
	GRAVELLY/SANDY CLAY (CL): gray, no odor, moist, medium-high plasticity, medium stiff, 4" lense of coarse-grained sand and gravel, green clay on bottom 3" of sand lense		CL				0.8		Temperature Probe 1-in I.D. 0.010-in Slot PVC Screen Temperature Probe

Total Depth = 17.5 feet.

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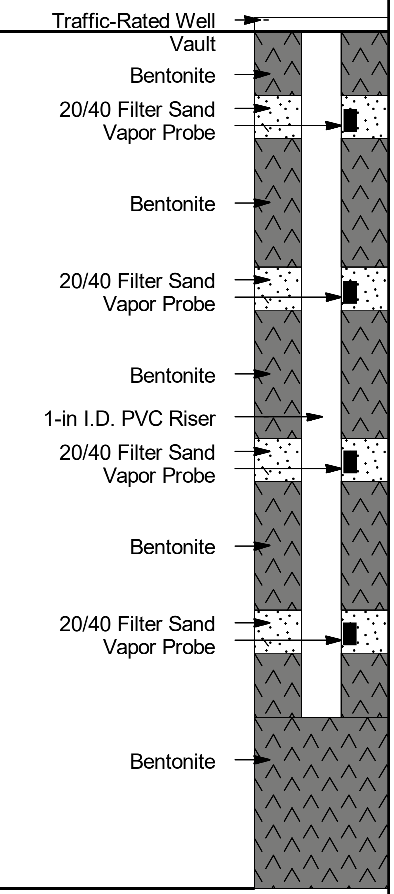
Log of Soil Boring & Well Construction: BG-2 Soil Vapor Monitoring Location

CLIENT ESTCP
PROJECT NAME ER19-5091
GSI JOB NUMBER 5186
PROJECT LOCATION Minnesota Air National Guard, Minneapolis
DATE STARTED 24 Jul. 2020 **COMPLETED** 24 Jul. 2020
GROUND ELEVATION 817.96 **DATUM** NGVD29
DRILLING CONTRACTOR Traut Companies
TOP OF CASING ELEVATION NA **DATUM** NA
DRILLING METHOD Hollow Stem Auger
NORTHING 44.891725 **EASTING** -93.20265
DRILLING EQUIPMENT Geoprobe
LOGGED BY S.T. Robinson, GIT **CHECKED BY** K.L. Walker
GROUND SURFACE Asphalt
BORING DIAMETER (in) 8.25

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level
	GROUND SURFACE							
	ASPHALT						5.6	
	GRAVELLY, CLAYEY SAND (SW): tan/brown, no odor, damp, soft, medium to coarse-grained		SW				2.6	
	SAND (SP): light tan, no odor, damp, soft, medium to coarse-grained, some gravel		SP				2.3	
	Tan/brown, medium stiff, slightly clayey, fine to medium-grained sand						2.6	
							2.9	
5	SANDY CLAY (CL): gray/tan, no odor, damp, high plasticity, stiff, coarse grained		CL				2.8	
	Orange/brown, some gravel						2.2	
	Orangish tan, dry, crumbly						0.8	
	Oxidized orange, damp, high plasticity, medium stiff, some fine to medium-grained sand						1	
	Tan, moist, stiff						0.9	
10	SAND (SP): medium grained		SP					

Total Depth = 10.0 feet.

Well Diagram and Remarks



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Log of Soil Boring & Well Construction: BG-2 Temperature Monitoring Location

CLIENT	ESTCP	**PROJECT NAME**	ER19-5091
GSI JOB NUMBER	5186	**PROJECT LOCATION**	Minnesota Air National Guard, Minneapolis
DATE STARTED	24 Jul. 2020	**COMPLETED**	24 Jul. 2020
GROUND ELEVATION	817.96	**DATUM**	NGVD29
DRILLING CONTRACTOR	Traut Companies	**TOP OF CASING ELEVATION**	817.81
DATUM	NGVD29	**DRILLING METHOD**	Hollow Stem Auger
NORTHING	44.891731	**EASTING**	-93.20266
DRILLING EQUIPMENT	Geoprobe	**LOGGED BY**	S.T. Robinson, GIT
CHECKED BY	K.L. Walker	**GROUND SURFACE**	Asphalt
BORING DIAMETER (in)	8.25		

Depth (ft bgs)	Soil Description	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE							Traffic-Rated Well Vault
	ASPHALT					1.7		Bentonite; Temperature Probe; Temperature Probe
	GRAVELLY SAND (SW): light tan, no odor, damp, loose, medium to coarse-grained sand with gravel	SW				1.9		Temperature Probe; Temperature Probe
	Black, high plasticity, clay lense					2; 3.8		Temperature Probe; Temperature Probe
	CLAY (CH): black, no odor, damp, high plasticity, very stiff, some orange spots	CH				3.8		Temperature Probe
5	Orange and green, stiff, some coarse grained sand					2.2		Temperature Probe
	CLAY (CL): pink/green/orange, no odor, damp, medium plasticity, medium stiff, some medium-grained sand and gravel	CL				3.6		Temperature Probe
	CLAY (CH): pink/green/orange, no odor, damp, high plasticity, medium stiff, some medium-grained sand and gravel	CH				4.4; 5	Water Level = 8.88 ft BGS	20/40 Filter Sand; Temperature Probe; 1-in I.D. PVC
	CLAYEY SAND (SC): orange, no odor, moist, soft, fine to medium-grained	SC				4.5		Temperature Probe
10	Dark tan, medium to coarse-grained, some gravel					4.3		Temperature Probe; Temperature Probe
	SANDY/GRAVELLY CLAY (CL): tan, no odor, moist, medium plasticity, medium stiff, coarse-grained sand	CL				3.6		Temperature Probe
	SAND (SP): tan, no odor, moist, soft, slightly clayey, coarse-grained	SP				3.3		Temperature Probe
	CLAYEY SAND (SC): tan, no odor, moist, soft, some high plasticity clay chunks	SC				3		1-in I.D. 0.010-in Slot PVC Screen
	NO RECOVERY							Temperature Probe

Total Depth = 14.8 feet

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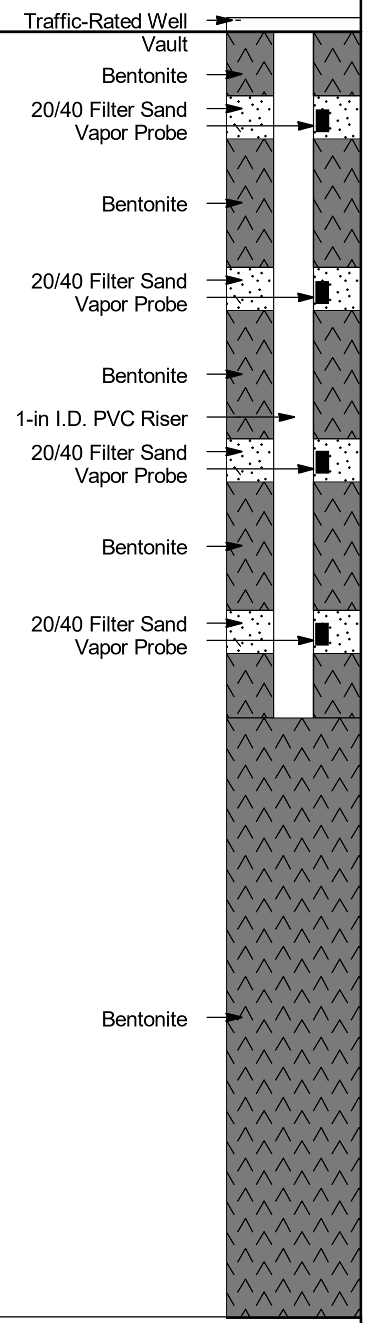
Log of Soil Boring & Well Construction: L-1 Soil Vapor Monitoring Location

CLIENT	ESTCP	**PROJECT NAME**	ER19-5091
GSI JOB NUMBER	5186	**PROJECT LOCATION**	Minnesota Air National Guard, Minneapolis
DATE STARTED	22 Jul. 2020	**COMPLETED**	23 Jul. 2020
GROUND ELEVATION	822.89	**DATUM**	NGVD29
DRILLING CONTRACTOR	Traut Companies	**TOP OF CASING ELEVATION**	NA
DATUM	NA	**DRILLING METHOD**	Hollow Stem Auger
NORTHING	44.892252	**EASTING**	-93.20311
DRILLING EQUIPMENT	Geoprobe	**LOGGED BY**	S.T. Robinson, GIT
CHECKED BY	K.L. Walker	**GROUND SURFACE**	Grass
BORING DIAMETER (in)	12.25		

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level
	GROUND SURFACE							
	ORGANIC SILT (OL): black, no odor, dry, soft, some gravel		OL				0.3	
	SILTY GRAVEL (GM): tan, no odor, dry, soft		GM				5.3	
	CLAY (CH): dark brown, damp, high plasticity, very stiff		CH				4.5	
	Medium brown, tan and red clay chunks						5.5	
	Light brown, red and black clay chunks, stiff						3.9	
5	NO RECOVERY							
	SANDY CLAY (CL): tan, no odor, damp, medium to high plasticity, medium stiff, fine-grained sand		CL				3.2	
10	NO RECOVERY							
	SILTY CLAY (CL): maroon, no odor, dry, low plasticity, soft		CL				302.5	
	CLAYEY SAND (SC): dark tan, no odor, wet, soft, very fine-grained		SC				758.9	

Well Diagram and Remarks



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Log of Soil Boring & Well Construction: L-1 Soil Vapor Monitoring Location

CLIENT ESTCP **PROJECT NAME** ER19-5091

GSI JOB NUMBER 5186 **PROJECT LOCATION** Minnesota Air National Guard, Minneapolis

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								
	CLAYEY GRAVEL (GC): green/tan, strong odor, wet, stiff		GC				981.7		
	Some coarse-grained sand						1084		Bentonite

Total Depth = 17.0 feet.

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Log of Soil Boring & Well Construction: L-1 Temperature Monitoring Location

CLIENT	ESTCP	**PROJECT NAME**	ER19-5091
GSI JOB NUMBER	5186	**PROJECT LOCATION**	Minnesota Air National Guard, Minneapolis
DATE STARTED	23 Jul. 2020	**COMPLETED**	23 Jul. 2020
GROUND ELEVATION	822.89	**DATUM**	NGVD29
DRILLING CONTRACTOR	Traut Companies	**TOP OF CASING ELEVATION**	824.85
DATUM	NGVD29		
DRILLING METHOD	Hollow Stem Auger	**NORTHING**	44.892253
EASTING	-93.20312		
DRILLING EQUIPMENT	Geoprobe	**LOGGED BY**	S.T. Robinson, GIT
CHECKED BY	K.L. Walker		
GROUND SURFACE	Grass	**BORING DIAMETER (in)**	8.25

Depth (ft bgs)	Soil Description	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE							Well Stick-Up
	ORGANIC CLAYS/SILTS (OL): black, no odor, dry, low plasticity, soft	OL				2		Bentonite; Temperature Probe
	CLAYEY SILT (ML): dark brown, no odor, dry, very stiff, crumbly	ML				3.7		Temperature Probe; Temperature Probe
	SILTY/SANDY GRAVEL (GW): tan/white, no odor, dry, loose, coarse-grained sand	GW				4.1		Temperature Probe
	CLAY (CH): black, no odor, dry, high plasticity, very stiff, crumbly, red lense (3" thick)	CH				8		Temperature Probe
						5		Temperature Probe
5	SAND (SP): tan, no odor, damp, soft, minor gravel, coarse-grained, minor clay near bottom	SP				6.1		Temperature Probe
	Medium to coarse-grained sand, clay chunks					9.2		Temperature Probe
	CLAYEY SAND (SC): tan, no odor, damp, soft, very fine-grained, very clayey	SC				4.2		Temperature Probe; 20/40 Filter Sand
	SANDY CLAY (CL): tan, no odor, damp, high plasticity, medium stiff, very fine-grained, very sandy clay	CL				9.9		Temperature Probe; 1-in I.D. PVC
	CLAYEY SAND (SC): tan, no odor, damp, soft, very fine to medium-grained	SC				5.9		Temperature Probe
10	SAND (SP): tan, no odor, damp, soft, fine to coarse-grained	SP				5.7		Temperature Probe
	Transition from tan to black					27.9		Temperature Probe
	CLAYEY SAND (SC): greenish black, no odor, moist, stiff, coarse-grained	SC				302.5	▼	Temperature Probe; Water Level = 12.24 ft BGS
	Strong odor					1192		Temperature Probe
	GRAVELLY CLAY (CL): greenish gray with red and orange, strong odor, moist, high plasticity, stiff, gravel, some coarse-grained sand	CL				984		Temperature Probe

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Log of Soil Boring & Well Construction: L-1 Temperature Monitoring Location

CLIENT ESTCP
PROJECT NAME ER19-5091
GSI JOB NUMBER 5186
PROJECT LOCATION Minnesota Air National Guard, Minneapolis

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								
	CLAYEY GRAVEL (GC): greenish gray with red and orange, strong odor, moist, soft, coarse-grained sand		GC				932		Temperature Probe; 20/40 Filter Sand; 1-in I.D. PVC; Temperature Probe
	Tannish gray, gravel, some clay and very fine to fine-grained sand						816		1-in I.D. 0.010-in Slot PVC Screen; Temperature Probe

Total Depth = 17.5 feet.

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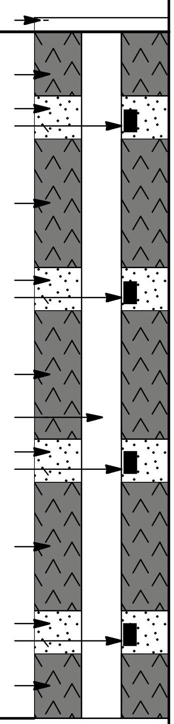
Log of Soil Boring & Well Construction: L-2 Soil Vapor Monitoring Location

CLIENT	ESTCP	**PROJECT NAME**	ER19-5091
GSI JOB NUMBER	5186	**PROJECT LOCATION**	Minnesota Air National Guard, Minneapolis
DATE STARTED	21 Jul. 2020	**COMPLETED**	21 Jul. 2020
GROUND ELEVATION	819.04	**DATUM**	NGVD29
DRILLING CONTRACTOR	Traut Companies	**TOP OF CASING ELEVATION**	NA
DATUM	NA	**DRILLING METHOD**	Hollow Stem Auger
NORTHING	44.8922	**EASTING**	-93.20289
DRILLING EQUIPMENT	Geoprobe	**LOGGED BY**	S.T. Robinson, GIT
CHECKED BY	K.L. Walker	**GROUND SURFACE**	Asphalt
BORING DIAMETER (in)	8.25		

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level
	GROUND SURFACE							
	ASPHALT						2.1	
	SAND (SP): tan, no odor, dry, soft, gravelly, medium-grained		SP				7.4	
							6.3	
	SANDY CLAY (CL): black, no odor, dry, high plasticity, very stiff Brown gray, damp, stiff		CL				5.7	
	CLAYEY SAND (SC): gray, no odor, damp, soft, fine-grained		SC				7.7	
5	Tan, medium stiff, medium grained, clay chunks						3.7	
	Greenish gray with tan lenses, stiff, minor gravel						7.4	
							10.6	

Total Depth = 8.0 feet.

Well Diagram and Remarks



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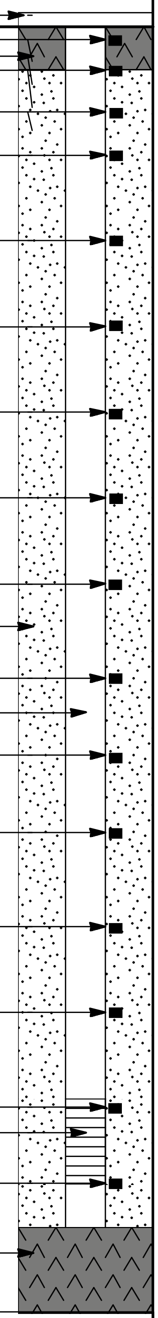
Log of Soil Boring & Well Construction: L-2 Temperature Monitoring Location

CLIENT ESTCP	**PROJECT NAME** ER19-5091
GSI JOB NUMBER 5186	**PROJECT LOCATION** Minnesota Air National Guard, Minneapolis
DATE STARTED 22 Jul. 2020 **COMPLETED** 22 Jul. 2020	**GROUND ELEVATION** 819.04 **DATUM** NGVD29
DRILLING CONTRACTOR Traut Companies	**TOP OF CASING ELEVATION** 818.89 **DATUM** NGVD29
DRILLING METHOD Hollow Stem Auger	**NORTHING** 44.892193 **EASTING** -93.20290
DRILLING EQUIPMENT Geoprobe	**LOGGED BY** S.T. Robinson, GIT **CHECKED BY** K.L. Walker
GROUND SURFACE Asphalt	**BORING DIAMETER (in)** 12.25

Depth (ft bgs)	Soil Description	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level
	GROUND SURFACE						
	ASPHALT					3.7	
	GRAVELLY SAND (SW): black/brown, no odor, damp, soft, slightly clayey, fine to medium-grained	SW				3.1	
	SAND (SP): tan, no odor, dry, soft, gravelly, medium-grained	SP				2.3	
	CLAY (CH): medium brown, no odor, damp, very stiff, some medium-grained sand lenses	CH				3.5	
						5.8	
5	SAND (SP): brown tan, no odor, damp, high plasticity, soft, medium-grained	SP				3.1	
	Clay lenses					6	
	CLAYEY SAND (SC): greenish gray, no odor, damp, stiff, medium-grained, some gravel	SC				6.2	
						8.2	
	CLAY (CH): greenish gray, no odor, damp, high plasticity, very stiff	CH/					
	SANDY CLAY (SC): greenish gray, no odor, dry-damp, high plasticity, stiff, medium-grained sand, minor gravel	CL				3.2	▼
10	NO RECOVERY						
	SAND (SP): whitish green, strong odor, dry-damp, very soft, fine to medium-grained	SP				826	

Well Diagram and Remarks



(Continued Next Page)

GSI ENVIRONMENTAL

GSI Environmental Inc.
2211 Norfolk St. Suite 1000
Houston, TX 77098
Telephone: 713-522-6300

Log of Soil Boring & Well Construction: L-2 Temperature Monitoring Location

CLIENT ESTCP

PROJECT NAME ER19-5091

GSI JOB NUMBER 5186

PROJECT LOCATION Minnesota Air National Guard, Minneapolis

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								
	SILTY CLAY (CL): brown, strong odor, very wet, very soft, some fine to medium-grained sand		CL				701		Bentonite Note: 14 to 16 ft was cored, not drilled.

Total Depth = 16.0 feet.

Note: Bedrock at 16 ft

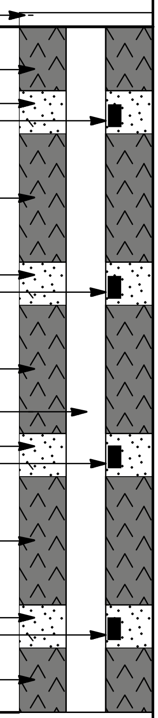
GSI ENVIRONMENTAL

GSI Environmental Inc.
2211 Norfolk St. Suite 1000
Houston, TX 77098
Telephone: 713-522-6300

Log of Soil Boring & Well Construction: L-3 Soil Vapor Monitoring Location

CLIENT ESTCP		**PROJECT NAME** ER19-5091	
GSI JOB NUMBER 5186		**PROJECT LOCATION** Minnesota Air National Guard, Minneapolis	
DATE STARTED 25 Jul. 2020	**COMPLETED** 25 Jul. 2020	**GROUND ELEVATION** 819.10	**DATUM** NGVD29
DRILLING CONTRACTOR Traut Companies		**TOP OF CASING ELEVATION** NA	**DATUM** NA
DRILLING METHOD Hollow Stem Auger		**NORTHING** 44.892168	**EASTING** -93.20278
DRILLING EQUIPMENT Geoprobe		**LOGGED BY** S.T. Robinson, GIT	**CHECKED BY** K.L. Walker
GROUND SURFACE Asphalt		**BORING DIAMETER (in)** 8.25	

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								Traffic-Rated Well Vault
	ASPHALT						2.8		Bentonite
	GRAVELLY SAND (SW): light tan, no odor, damp, loose, fine to medium-grained, gravel		SW				2.9		20/40 Filter Sand; Vapor Probe
	SANDY CLAY (CH): black, no odor, damp, high plasticity, stiff, some coarse-grained sand		CH				5.1		Bentonite
	SANDY CLAY (CL): black, no odor, damp, low to medium plasticity, stiff, some coarse-grained sand		CL				4.7		20/40 Filter Sand; Vapor Probe
	Medium to high plasticity, medium stiff						5.2		Bentonite; 1-in I.D. PVC Riser
5	SAND (SP): orange tan, no odor, damp, loose, medium to coarse-grained		SP				4.5		20/40 Filter Sand; Vapor Probe
	Soft, minor silt chunks, minor gravel						2.9		Bentonite
	GRAVELLY, CLAYEY SAND (SC): orange tan, no odor, damp, medium stiff, medium to coarse-grained		SC				4.6		20/40 Filter Sand; Vapor Probe; Bentonite



Total Depth = 8.0 feet.

GSI ENVIRONMENTAL

GSI Environmental Inc.
2211 Norfolk St. Suite 1000
Houston, TX 77098
Telephone: 713-522-6300

Log of Soil Boring & Well Construction: L-3 Temperature Monitoring Location

CLIENT ESTCP	**PROJECT NAME** ER19-5091
GSI JOB NUMBER 5186	**PROJECT LOCATION** Minnesota Air National Guard, Minneapolis
DATE STARTED 25 Jul. 2020 **COMPLETED** 25 Jul. 2020	**GROUND ELEVATION** 819.10 **DATUM** NGVD29
DRILLING CONTRACTOR Traut Companies	**TOP OF CASING ELEVATION** 818.79 **DATUM** NGVD29
DRILLING METHOD Hollow Stem Auger	**NORTHING** 44.892163 **EASTING** -93.20278
DRILLING EQUIPMENT Geoprobe	**LOGGED BY** S.T. Robinson, GIT **CHECKED BY** K.L. Walker
GROUND SURFACE Asphalt	**BORING DIAMETER (in)** 8.25

Depth (ft bgs)	Soil Description	Lithology	USCS	Sample Type	Blows/ 6 inches	Lab Sample	PID (ppm)	Water Level	Well Diagram and Remarks
	GROUND SURFACE								Traffic-Rated Well Vault
	ASPHALT						5.6		Bentonite; Temperature Probe
	GRAVELLY SAND (SW): grayish tan, no odor, damp, soft, medium to coarse-grained, minor clay		SW				3.1		Temperature Probe; Temperature Probe
	GRAVELLY CLAY (CH): black to orangish tan, no odor, damp, high plasticity, stiff		CH				1.2		Temperature Probe
	Soft						1.5		Temperature Probe; Temperature Probe
	CLAYEY SAND (SC): black to orangish tan, no odor, damp, soft, medium-grained		SC				2.2		Temperature Probe
5	Orangish tan						2		Temperature Probe
							4.5		Temperature Probe; 20/40 Filter Sand; Temperature Probe
	CLAYEY, GRAVELLY SAND (SC): orangish tan, no odor, damp, soft		SC				3.3		Temperature Probe
	Medium stiff						3.4		1-in I.D. PVC
	Greenish brown, stiff, fine to coarse-grained sand, gravel, even mixture of the 3 components						92.2		Temperature Probe; Temperature Probe
10	Greenish gray, strong odor, soft, gravel, medium to coarse-grained sand						335	▼	Water Level = 10.25 ft BGS
	SANDY GRAVEL (GP): grayish white, strong odor, dry, loose, coarse-grained		GP				1645		Temperature Probe; Temperature Probe
	GRAVELLY SAND (SP): greenish gray, strong odor, moist, soft, gravel, medium to coarse-grained		SP				1560		Temperature Probe
	CLAYEY, GRAVELLY SAND (SC): greenish gray, strong odor, wet, low plasticity, loose, coarse-grained		SC				798.5		1-in I.D. 0.010-in Slot PVC Screen; Temperature Probe

Total Depth = 14.5 feet.

APPENDIX E INVESTIGATION-DERIVED WASTE MANIFESTS

ESTCP ER19-5091

Appendix E.1 TEAD-S Waste Manifest
Appendix E.2 MN ANGB Waste Manifest

APPENDIX E: INVESTIGATION-DERIVED WASTE MANIFESTS
ESTCP ER19-5091

Appendix E.1 TEAD-S Waste Manifest

23

6214

NON-HAZARDOUS WASTE MANIFEST

79 2003304681

Please print or type (Form designed for use on elite (12 pitch) typewriter)

NON-HAZARDOUS WASTE MANIFEST	1. Generator's US EPA ID No. UT5210090002	Manifest Document No. NH03304681	2. Page 1 of 1

3. Generator's Name and Mailing Address
Tooele Army Depot South Area
1 Tooele Army Depot BLDG 501
Tooele UT 84074

Site Address :
11500 Stark Road.
Stockton,UT 84071

4. Generator's Phone ( )

5. Transporter 1 Company Name	6. US EPA ID Number	A. State Transporter's ID
Clean Harbors Environmental Services, Inc.	MAD039322250	B. Transporter 1 Phone (781) 792-5000
7. Transporter 2 Company Name	8. US EPA ID Number	C. State Transporter's ID
		D. Transporter 2 Phone
9. Designated Facility Name and Site Address	10. US EPA ID Number	E. State Facility's ID
Clean Harbors Grassy Mountain LLC 3 Miles East 7 Miles North of Knolls Grantsville, UT 84029	UTD991301748	F. Facility's Phone (435) 884-8900

11. WASTE DESCRIPTION	12. Containers No.	Type	13. Total Quantity	14. Unit Wt./Vol.
a. NOT REGULATED BY DOT, (CONTAMINATED SOIL, DIESEL)	5	DM	2750	P
b. NOT REGULATED BY DOT, (GROUNDWATER, DIESEL)	2	DM	400	P
c. NOT REGULATED BY DOT, (CONCRETE)	1	DM	300	P
d.				

G. Additional Descriptions for Materials Listed Above
11a.CH2001086 5 DM @55
11b.CH2001107 2 DM @55
11c.CH2037379 1 DM @55

H. Handling Codes for Wastes Listed Above
H132
H132
H132

15. Special Handling Instructions and Additional Information

EMERGENCY PHONE #: (800) 483-3718
GENERATOR: Tooele Army Depot,South Area

GENERATOR

16. GENERATOR'S CERTIFICATION: I hereby certify that the contents of this shipment are fully and accurately described and are in all respects in proper condition for transport. The materials described on this manifest are not subject to federal hazardous waste regulations.

Printed/Typed Name: Jay Nelson
Signature:
Date: Month Day Year

TRANSPORTER

17. Transporter 1 Acknowledgement of Receipt of Materials
Printed/Typed Name: Joe Quintana
Signature:
Date: Month Day Year 6 25 20

18. Transporter 2 Acknowledgement of Receipt of Materials
Printed/Typed Name
Signature
Date: Month Day Year

FACILITY

19. Discrepancy Indication Space

20. Facility Owner or Operator: Certification of receipt of the waste materials covered by this manifest, except as noted in item 19.

2020W3327

Printed/Typed Name: Wendy Riddle
Signature:
Date: Month Day Year 07 06 20

NON-HAZARDOUS WASTE

Generator acknowledges that no material change has occurred either in the characteristics or in the process generating the material.

APPENDIX E: INVESTIGATION-DERIVED WASTE MANIFESTS
ESTCP ER19-5091

Appendix E.2 MN ANGB Waste Manifest

Certificate of Disposal / Treatment - Storage and Transfer

Run Date: 9/23/2020

Manifested To Site: Deer Trail, CO Facility
108555 East Highway 36
Deer Trail, CO 80105

EPA ID/Prov ID: COD991300484

Generator ID	Manifest No.	Generation Date	Received Date
MI50836	BOL1328915	8/27/2020	9/11/2020

The above described waste, received at the Clean Harbors facility listed above pursuant to the manifest(s) listed above, has/will be treated and/or disposed of by Clean Harbors, or another licensed facility approved by Clean Harbors, in accordance with applicable federal, state and provincial laws and regulations. Any waste received by Clean Harbors and subsequently shipped to another licensed facility has been or shall be identified as being generated by Clean Harbors in accordance with 40CFR 264.71(c).

For waste imported/exported to/from Canada the waste has/will be disposed or recycled according to the Canadian export and import of hazardous waste or hazardous recyclable material regulation as published in the Canadian Gazette Part II, vol 139, No 11, SOR/2005-149 May 17, 2005

Under civil and criminal penalties of law for the making of submission of false or fraudulent statements or representations (18 U.S.C. 1001 and 15 U.S.C. 2615), I certify that the information contained in or accompanying this document is true, accurate, and complete. As to the identified section(s) of this document for which I cannot personally verify truth and accuracy, I certify as the company official having supervisory responsibility for the persons who, acting under my direct instructions, made the verification that this information is true, accurate, and complete.

Signed: Paul A. Mello

Date: **9/23/2020**

Title: **Director Facility Applications**

APPENDIX F NSZD RATE STUDY

ESTCP ER19-5091

Appendix F.1 NSZD Rate Study

The study methods, results, and conclusions of the NSZD multiple site study that evaluated site-wide NSZD rates compiled from 40 petroleum LNAPL source zones in the United States, Canada, Europe, and Australia, have been documented in a scientific paper published in the journal Water Research:

Kulkarni, P.R., K.L. Walker, C.J. Newell, K. Karimi Askarani, Y. Li, T.E. McHugh, 2022. Natural source zone depletion (NSZD) insights from over 15 years of research and measurements: A multi-site study. Water Research 225: 119170.

doi: 10.1016/j.watres.2022.119170.

Available online at: https://www.sciencedirect.com/science/article/abs/pii/S0043135422011150?via%3Dihub

APPENDIX G ESTCP COMMENTS

ESTCP ER19-5091

Appendix G.1ESTCP Comments

ESTCP Comment (assigned 2/9/2020): Please complete your FY19 and FY20 expenditure plans; planned expenditures must match what has been distributed. Also, your invoiced amount is significantly ahead of expenditures as reported in the monthly financial reports. Please correct the monthly financial reports accordingly.

Response: FY19 and FY2020 expenditure plans were revised, completed, and submitted in SEMS.

ESTCP Comment (assigned 2/9/2020): Provide a project-related high-quality photo or video to be added to your project webpage. Also, if available, provide a link to a project-related website to be added to your Point of Contact information on your project webpage. The photo or video file can be uploaded as a miscellaneous document in SEMS.

Response: We uploaded an image file as a miscellaneous document for the requested project photo or graphic. We will take detailed installation photos when we are able to continue our field installation and upload additional photos at that time.

ESTCP Comment (assigned 2/9/2020): The Program Office believes that a tertiary line of evidence may be necessary to validate natural source zone depletion. In a white paper, discuss the feasibility as well as the advantages and disadvantages of adding an additional line of evidence to the project. Include any associated costs.

Response: The project team produced a White Paper that proposed a variety of tertiary lines of evidence to validate natural source zone depletion, as well as associated costs. The White Paper was submitted in SEMS on 24 April 2020.

ESTCP Comment (assigned 3/14/2021): Provide a list of keywords for the project to assist users of the SERDP & ESTCP web page with searching for project information. The keywords can be provided in the comment box for this action.

Response: The following keywords were submitted via SEMS on 26 March 2021: LNAPL, NSZD, Thermal NSZD, natural source zone depletion, internet of things, dashboard, data analytics

ESTCP Comment (assigned 3/17/2021): Invoices need to be submitted on a monthly basis. Work with your financial contact and in the response to this action, provide the plan for future invoicing.

Response: A revised monthly milestone billing schedule was sent to our financial contact, and we received approval to proceed with the monthly billing schedule. Invoices have been submitted on a monthly basis for months where milestones were completed for the remainder of the project.

ESTCP Comment (assigned 3/14/2021): Even if the equipment is relatively simple to install, it would be advantageous to have an idea of the NSZD potential at a site before equipment installation. In the next Quarterly Progress Report, please discuss whether any commonly collected measurements may indicate good potential for NSZD potential before installing equipment.

Response: An approach to indicate potential for NSZD prior to the installation of permanent monitoring equipment will be added in a separate implementation guide to be provided as a project deliverable.

ESTCP Comment (assigned 3/14/2021): We believe this project's information would be of interest to the ITRC group that is conducting training on TPH Risk Evaluation at Petroleum-Contaminated sites; please contact the ITRC to determine whether additional training is planned and if so, whether information from this project could be incorporated. Report on the results of this interaction in the July 2021 Quarterly Report.

Response: As discussed in the July 2021 Quarterly Progress Report, we reached out to the "TPH Risk Evaluation at Petroleum-Contaminated Sites" ITRC team lead and key staff to discuss including our project results in their training. Due to their training cycle and approval timeline, we are not able to include our results in their training. However, we do have colleagues involved with the new ITRC team "Effective Application of Guidance Documents to Hydrocarbon Sites", who were engaged with our ESTCP project and who have assisted with incorporating results from this project into that ITRC project. In addition, we have several team members who volunteered with and participated in the ASTM Task Group on Estimating Natural Attenuation Rates for LNAPLs in the Subsurface – ASTM WK76688.

ESTCP Comment (assigned 3/14/2021): In the July 2021 Quarterly Progress Report, please discuss the following issues:

1. Each of the three methodologies used to determine NSZD rates have their advantages and disadvantages based on site-specific conditions and contaminant distributions. In that respect, it would be useful to provide guidance on the appropriateness of each methodology for implementation based on site conditions. Discuss the feasibility of including such an assessment in the Final Report.
2. After the Task 3 Plume-a-thon exercise, in the event the thermal methods to calculate NSZD rates prove at best semi-quantitative or qualitative for certain cases, please include guidance under what site specific conditions these methods would be quantitative and more definitive and whether the utility of such methodology could be extended to semi-quantitative screening for identifying LNAPL source zone areas for a broader range of sites.
3. Please discuss in more detail how the background correction methodology is utilized to deconvolute the thermal imaging data as well as the reference method data to develop NSZD rates with a higher degree of confidence. Please also explain the situations when the NSZD rates need to be spatially integrated or volume averaged.
4. Consider developing and testing the one-dimensional source zone model at a real site to show how well the application of these methodologies work; include pertinent assumptions in deriving the inputs to the model. This can all be done before working on more complex sites as part of the Task 3 plume-a-thon exercise.

Response: In a separate implementation guide to be provided as a project deliverable, we will provide guidance on the application of the thermal NSZD method, as well as the other commonly utilized methods to estimate NSZD rates. We will discuss advantages and disadvantages of each method and provide guidance on situations where each method may be appropriate.

This implementation guide will also include guidance on how these methods may be employed under different site conditions and as a screening technique to identify source zone areas for a broader suite of LNAPL-impacted sites.

Additional details on existing background-correction methodologies have been included in this Final Report, and these methodologies have been published in the peer-reviewed literature (Karimi Askarani and Sale 2020; Kulkarni et al. 2020).

The project team does not believe the one-dimensional source zone model would provide additional insights into these NSZD methods, and the objective of the Task 3 plume-a-thon exercise was to develop a broader range of NSZD rates measured at real sites with different site conditions to provide additional insights into which site conditions may be conducive to higher or lower NSZD rates.

APPENDIX H DATA TABLES AND LAB REPORTS

ESTCP ER19-5091

APPENDIX H: DATA TABLES AND LAB REPORTS
ESTCP ER19-5091

Appendix H.1 TEAD-S Carbon Trap Analysis Laboratory Reports

Report
CO_2 Flux and NSZD Rate Results

KENNETH WALKER
GSI ENVIRONMENTAL
PROJECT: TOOELE, UT
SAMPLING DATES:
06/05/2020 - 06/25/2020

For technical support questions contact:

Julio Zimbron, Ph.D.
E-Flux, LLC
3185-A Rampart Road, Room D214
Fort Collins, CO 80521
o: (970) 492-4360 c: (970) 219-2401
jzimbron@soilgasflux.com

Report Date: 08/19/2020

The purpose of this document is to provide sample calculations for the reported results and to explain the method for differentiating petroleum hydrocarbon-derived CO_2 from that produced from natural soil respiration processes. The value of the ^{14}C analysis, site-specific study results and applicable notes, calculation explanations, and references are included.

The Value of the ^{14}C Analysis

How to differentiate between petroleum hydrocarbon-derived CO_2 and natural process-derived CO_2 using CO_2 flux traps:

Unimpacted soils naturally produce CO_2 due to microbial root zone activity and/or the degradation of natural organic matter. Thus, the total measured CO_2 flux at an impacted location is a function of the rates of both natural soil respiration and LNAPL degradation (Sihota and Mayer, 2012). The latter, which is caused by Natural Source Zone Depletion (NSZD), can be estimated by subtracting measured CO_2 fluxes at unimpacted locations from the total measured CO_2 fluxes at LNAPL-impacted locations (Sihota and Mayer, 2012). This spatial "background correction" assumes that bio-based CO_2 fluxes are similar at both impacted and unimpacted locations. This approach is complicated to implement, given that at many industrial facilities it is difficult to find unimpacted areas and vegetation cover can vary across a site. Alternatively, carbon isotope analysis can be used to carry out a location-specific correction for total measured CO_2 fluxes, and this approach effectively overcomes the limitations of the background correction.

Theory of Carbon Isotope Analysis:

Our method for NSZD rate estimation relies on the analysis of ^{14}C, an unstable carbon isotope with an absolute half-life of 5,730 years. ^{14}C is generated by cosmic rays in the atmosphere and is quickly oxidized to $^{14}CO_2$; thus, bio-based living carbon is ^{14}C-rich, while ancient fossil fuel carbon is completely ^{14}C-depleted. Additionally, bio-based organic carbon and the atmosphere have the same characteristic amount of ^{14}C. The short half-life of ^{14}C only allows for dating of samples younger than 60,000 years using accelerator mass spectrometry (Stuiver and Polach, 1977). ^{14}C analysis can therefore be used to differentiate between anthropogenic (i.e., fossil fuel) and natural sources of atmospheric carbon (see Klouda and Connolly, 1995; Levin et al., 1995; Avery et al., 2006), and this analysis is the basis for ASTM D6866-18.

For samples that contain both bio-based and fossil fuel-derived carbon, such as E-Flux's fossil fuel traps, measurement of ^{14}C enables quantitation of *both* source contributions. The fossil fuel-derived percentage of the sample (ff_{sample}) and the bio-based percentage ($1-ff_{sample}$, or bb_{sample}) are related by the following two-component mass balance (modified from Avery, Jr. et al., 2006):

$$Fm_{sample} = (ff_{sample})(Fm_{ff}) + (1 - ff_{sample})(Fm_{atm})$$

Here, Fm_x represents the fraction modern, a measure of how close the present $^{14}C/^{12}C$ ratio of the sample is to the ratio from 1950, which is derived from a pre-industrial era standard. Fm_{sample} is the total measured fraction modern of the sample. Fm_{ff} is the fraction modern of only the fossil fuel portion of the sample. This number is 0, as there is no ^{14}C in fossil fuel-derived CO_2. Fm_{atm} is the fraction modern of the part of the sample derived from natural soil respiration processes. This value, currently equal to **1.02** (Cerling et al., 2016, Larsen et al., 2018), has been experimentally determined and is a fixed value at each point in time. By convention, the results of carbon isotope analysis are reported based on a 1950 NBS oxalic acid standard, and so Fm_{sample} is reported as if the analysis took place in 1950. Due to nuclear testing, current ^{14}C atmospheric levels are now higher than they were in 1950. This means that Fm_{atm} is counter-intuitively larger than 1, as the $^{14}C/^{12}C$ sample ratio is higher now than it would have been in 1950.

^{14}C Calculations:

Conversion of Fraction Modern Carbon to Fossil Fuel Carbon:

The equation for calculating the percentage of fossil fuel carbon (ff_{sample}) is derived from the following mass balance:

$$Fm_{sample} = (ff_{sample})(Fm_{ff}) + (1 - ff_{sample})(Fm_{atm})$$

Solving for ff_{sample} yields:

$$ff_{sample} = 1 - \frac{Fm_{sample}}{Fm_{atm}}$$

Fraction modern (Fm_{sample}, from ^{14}C analysis) is reported by convention based on ^{14}C levels from 1950. Because of atomic testing, current environmental ^{14}C levels are approximately 2% higher than they were in 1950 (Cerling et al., 2016, Larsen et al., 2018) and Fm_{atm} is equal to 1.02. This equation then becomes:

$$ff_{sample} = 1 - \frac{Fm_{sample}}{1.02}$$

As percentages must add to 1, the percentage of bio-based carbon ($bb_{sample.}$) can then be calculated using the following equivalence:

$$bb_{sample} = 1 - ff_{sample} = 1 - \left(1 - \frac{Fm_{sample}}{1.02}\right) = \frac{Fm_{sample}}{1.02}$$

Converting Carbon Flux to Equivalent LNAPL Loss Rate:

The intermediate reactions for LNAPL mineralization include methanogenesis, leading to production of methane and CO_2, and the subsequent aerobic oxidation of methane into CO_2:

$$C_8H_{18} + 3.5\,H_2O \rightarrow 6.25\,CH_4 + 1.75\,CO_2 \text{ (methanogenesis)}$$

$$6.25\,CH_4 + 12.5\,O_2 \rightarrow 6.25\,CO_2 + 12.5\,H_2O \text{ (methane oxidation)}$$

$$C_8H_{18} + 12.5\,O_2 \rightarrow 9H_2O + 8\,CO_2 \text{ (overall reaction)}$$

Assuming a conservative LNAPL density of 0.77 g mL^{-1} (upper range of gasoline) and using the molecular weight of C_8H_{18} (octane, 114.23 g mol^{-1}), µmol m^{-2} s^{-1} of CO_2 can then be converted into gal. $acre^{-1}$ yr^{-1} of LNAPL:

$$1\ \frac{\mu\text{mol CO}_2}{\text{m}^2\text{ s}} \cdot \left(\frac{1\ \mu\text{mol C}_8\text{H}_{18}}{8\ \mu\text{mol CO}_2}\right)\left(\frac{1\text{ mol C}_8\text{H}_{18}}{1\times10^6\ \mu\text{mol C}_8\text{H}_{18}}\right)\left(\frac{114\text{ g C}_8\text{H}_{18}}{1\text{ mol C}_8\text{H}_{18}}\right)\left(\frac{1\text{ mL C}_8\text{H}_{18}}{0.77\text{ g C}_8\text{H}_{18}}\right)$$
$$\left(\frac{1\text{ L}}{1000\text{mL}}\right)\left(\frac{1\text{ gal.}}{3.785\text{ L}}\right)\left(\frac{4{,}046\text{ m}^2}{1\text{ acre}}\right)\left(\frac{3600\text{ s}}{1\text{ h}}\right)\left(\frac{24\text{ h}}{1\text{ d}}\right)\left(\frac{365\text{ d}}{1\text{ yr}}\right).$$
$$= 625.2\ \frac{\text{gal. C}_8\text{H}_{18}}{\text{acre}\cdot\text{yr}}$$

Note that both the LNAPL formula and its density are assumed, and so this conversion is subject to uncertainty. However, site-specific data can be used if available. Using alternative representative hydrocarbon formulas and densities generally results in conversion factors that are within 10-15% of 625.2 gal. $acre^{-1}$ yr^{-1}. Therefore, the uncertainty associated with these values does not preclude an acceptable estimate.

Expected Results and Recommendations:

^{14}C-based techniques offer a built-in, location-specific correction as an alternative to the standard background location correction. Early work on a limited number of samples suggested that ^{14}C-corrected results are equivalent to background-corrected results (Sihota and Mayer, 2012; McCoy et al., 2015). However, a more recent comparison spanning 4 different sites suggests that measured carbon fluxes can differ by up to five times among different locations within the same site (Zimbron and Kasyon, 2015). Depending on the location, the resulting difference between background-corrected and ^{14}C-corrected NSZD rate estimates can be up to one order of magnitude. In contrast, the background correction assumes that the non-fossil fuel CO_2 flux is constant across an entire site; large errors in final estimated NSZD rates might therefore be introduced if the background correction is used. Because the ^{14}C measurement is co-located with the CO_2 flux measurement, it is unbiased by spatial uncertainties related to the background location(s) (e.g., vegetation, lithology, unknown impacts, different gas transport regimes, soil moisture).

The fossil fuel CO_2 content of unexposed sorbent as used in the traps is typically around 30% (as of today) and likely results from material processing and handling (e.g., exposure to fossil fuel fumes). This small mass of fossil fuel CO_2 is removed from samples by carrying out a ^{14}C travel blank correction. ^{14}C analysis is performed on CO_2 sorbent sub-samples after homogenization of the entire bottom sorbent layer (see McCoy et al., 2015). The mass of fossil fuel CO_2 in the unexposed travel blank trap (TB) is then subtracted from the mass of fossil fuel CO_2 in each field-deployed trap.

Easy set-up. Expert results.

Project: Tooele, UT
Customer: GSI Environmental
Customer Contact: Kenneth Walker
Report Date: 19-Aug-2020

Sample ID	Sampling Information			Raw Results[a]				Final CO_2 Results[b]			^{14}C Results[a]			NSZD Results[b]				
	Deployed	Retrieved	Days in Field	Moisture content (%)	Dry Sorbent Mass (g)	Avg. % CO_2[c]	CV[d] CO_2 (%)	CO_2 content (%)	CO_2 mass (g)	CO_2 Flux ($\mu mol\ m^{-2}\ s^{-1}$)	Fm_{sample} As Reported[e]	bb_{sample} As of Today[f]	ff_{sample} As of Today[f]	Bio-based CO_2 Flux ($\mu mol\ m^{-2}\ s^{-1}$)	ff_{sample} As of Today (TB-corrected)	Fossil Fuel CO_2 (g)	Fossil Fuel CO_2 Flux ($\mu mol\ m^{-2}\ s^{-1}$)	Equivalent NSZD Rate (gal. $acre^{-1}\ yr^{-1}$)
10174-R1-CO2-TB	N/A	N/A	N/A	17.9%	40.67	0.90%	0.51%	-	-	-	63.54	62.29%	37.71%	-	-	-	-	-
10174-R1-CO2-01	6/5/20 16:05	6/25/20 10:50	19.8	18.4%	42.46	4.40%	4.81%	3.50%	1.49	2.44	78.43	76.89%	23.11%	1.96	19.35%	0.29	0.47	295
10174-R1-CO2-02	6/5/20 16:03	6/25/20 11:06	19.8	18.6%	41.65	1.32%	1.55%	0.42%	0.17	0.29	60.57	59.38%	40.62%	0.15	46.88%	0.08	0.13	84
10174-R1-CO2-03	6/5/20 16:02	6/25/20 11:12	19.8	6.1%	42.58	4.77%	2.10%	3.87%	1.65	2.70	40.52	39.73%	60.27%	0.93	65.52%	1.08	1.77	1105
10174-R1-CO2-04	6/5/20 16:08	6/25/20 11:15	19.8	19.9%	41.25	1.14%	3.19%	0.24%	0.10	0.16	66.22	64.93%	35.07%	0.12	ND	ND	ND	ND
10174-R1-CO2-05	6/5/20 16:07	6/25/20 11:20	19.8	8.9%	41.87	2.17%	1.48%	1.27%	0.53	0.87	83.72	82.08%	17.92%	0.84	ND	ND	ND	ND

- The flux equivalence is **1** $\mu mol\ m^{-2}\ s^{-1}$ = **625.2** gallons $acre^{-1}\ yr^{-1}$, assuming a representative hydrocarbon density of **0.77** g mL^{-1} with the formula $\mathbf{C_8H_{18}}$.Trap cross-sectional area is $\mathbf{8.11 \times 10^{-3}}$ m^2 (based on a **4-inch** receiver pipe).
- Carbonate analysis of each trap/sample is based on method ASTM 4373-14, which does do not provide acceptable variability (CV) standards. Similar methods (e.g., ASTM D513-16) allow typical errors of ≤ 20%. Analysis is therefore conducted in duplicate if the coefficient of variation (CV) of the duplicates is < 5%. If CV ≥ 5%, duplicate analyses are repeated until CV < 5%.
- NA = Not Applicable; ND = Not Detectable.

a. Raw and ^{14}C Results are not TB-corrected.
b. Final CO_2 and NSZD Results are TB-corrected.
c. Refers to the measured weight percentage of CO_2 with respect to the total dry sorbent mass.
d. Refers to the coefficient of variation of CO_2 measurements for each sample: CV = [standard deviation of %CO_2 measurements] / [average %CO_2 measurement]
e. Refers to the reported fraction modern (Fm_{sample}). As is standard in radiocarbon reporting, this value has not been corrected to account for present-day ^{14}C atmospheric levels. This number is originally reported as pMC (percent modern carbon) and is converted into *Fm* for our calculations using the relation 100.0 pMC = 1.0 *Fm* = 100% *Fm*.
f. "As of Today" means that the value has been adjusted to account for the difference between atmospheric ^{14}C levels from the 1950s and today (Stenström et al., 2011). bb_{sample} is the percentage of the total CO_2 that is derived from bio-based (non-fossil fuel) sources. ff_{sample} refers to the percentage of CO_2 that is derived from fossil fuels. The values reported in the ^{14}C Results section are not TB-corrected, but those in the NSZD Results section are.

Results Snapshot:

- The Travel Blank (TB) concentration is **0.90%**; typically, this number is < 2%.
- Trap tops are not saturated with CO_2 (sorbent saturation is 30%). The maximum measured (raw) top concentration is ***4.1%*** (sample **10174-R1-CO2-03 top**).
- Bio-based carbon fluxes represent the CO_2 contributions from natural soil respiration processes to the total carbon flux; the ^{14}C analysis corrects for this contribution. Average bio-based CO_2 flux is **0.80** μmol m^{-2} s^{-1}, and the coefficient of variation is **94%**. The range of bio-based CO_2 fluxes is between **0.12** and **1.96** μmol m^{-2} s^{-1}. If these interferences were not removed using the results of the radiocarbon analysis, the errors in the NSZD rate estimates would be between **77** and **1228** gallons $acre^{-1}$ yr^{-1}.
- Sample **10174-R1-CO2-04 and 10174-R1-CO2-05** shows non-detectable (ND) fossil fuel CO_2 flux. The entire CO_2 flux for this sample is likely derived from non-fossil fuel sources.

Site-specific Sample Calculations:

Grams of Fossil Fuel CO_2:

The mass of fossil fuel-derived CO_2 in each trap is calculated by subtracting the total fossil fuel CO_2 in the travel blank (TB) from the total fossil fuel CO_2 in the trap. Only data that are ***not*** TB-corrected (i.e., ff_{sample} As of Today and raw % CO_2) are used in this calculation. Using Sample 1 as an example:

$$\left(\mathrm{g\ CO_{2(ff)}}\right)_{sample\ 1} = \mathrm{g_{sorbent}} \cdot \left[\left((\%\ \mathrm{CO_2})_{\mathrm{sample}}\left(ff_{sample}\right)\right) - \left((\%\ \mathrm{CO_2})_{\mathrm{TB}}\left(ff_{TB}\right)\right)\right]$$

$$\left(\mathrm{g\ CO_{2(ff)}}\right)_{sample\ 1} = \mathbf{42.46}\ \mathrm{g} \cdot \left[(\mathbf{4.40}\ \% \cdot \mathbf{23.11}\ \%) - (\mathbf{0.90}\ \% \cdot \mathbf{37.71}\ \%)\right]$$

$$\left(\mathrm{g\ CO_{2(ff)}}\right)_{sample\ 1} = \mathbf{0.2874}\ \mathrm{g}$$

Here, $g_{sorbent}$ is the mass of sorbent used in the bottom layer of the trap, $(\%CO_2)_{sample}$ is the average weight percentage of CO_2 in the sample, ff_{sample} is the percentage of carbon in the sample derived from fossil fuels, $(\%CO_2)_{TB}$ is the average weight percentage of CO_2 in the travel blank, and ff_{TB} is the percentage of carbon in the travel blank that is derived from fossil fuels. In this example, Sample 1 contains **0.2874 g** of fossil-fuel derived CO_2.

Fossil Fuel CO_2 Flux:

Converting grams of CO_2 to CO_2 flux requires the cross-sectional area of the receiver (**8.11 × 10^{-3}** m^2 for a **4**-inch receiver), the number of days that the trap was deployed in the field, and the molecular weight of CO_2 (44 g mol^{-1}). Using Site 1 as an example:

$$\text{Fossil Fuel CO}_2\text{ Flux} = \frac{\mathrm{g\ fossil\ fuel\ CO_2} \cdot \frac{\mathrm{1\ mol\ CO_2}}{\mathrm{44\ g\ CO_2}} \cdot \frac{\mathrm{1{,}000{,}000\ \mu mol\ CO_2}}{\mathrm{1\ mol\ CO_2}}}{\text{days in the field} \cdot \frac{\mathrm{24\ hr}}{\mathrm{day}} \cdot \frac{\mathrm{3600\ s}}{\mathrm{hr}} \cdot (\text{receiver area})}$$

$$\text{Fossil Fuel CO}_2\text{ Flux} = \frac{\mathbf{0.2874}\ \mathrm{g\ fossil\ fuel\ CO_2} \cdot \frac{\mathrm{1\ mol\ CO_2}}{\mathrm{44\ g\ CO_2}} \cdot \frac{\mathrm{1{,}000{,}000\ \mu mol\ CO_2}}{\mathrm{mol\ CO_2}}}{\mathbf{19.8}\ \mathrm{days} \cdot \frac{\mathrm{24\ hr}}{\mathrm{day}} \cdot \frac{\mathrm{3600\ s}}{\mathrm{hr}} \cdot (\mathbf{8.11} \times \mathbf{10^{-3}}\ \mathrm{m^2})}$$

$$\text{Fossil Fuel CO}_2\text{ Flux} = \mathbf{0.47}\ \frac{\mathrm{\mu mol\ CO_2}}{\mathrm{m^2 \cdot s}}$$

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E FLUX

APPENDIX H: DATA TABLES AND LAB REPORTS
ESTCP ER19-5091

Appendix H.2 MN ANGB Carbon Trap Analysis Laboratory Reports

E-FLUX

Report
CO_2 Flux and NSZD Rate Results

KENNETH WALKER
GSI, NAVY
PROJECT: AIR NATIONAL GUARD BASE, MINNESOTA
SAMPLING DATES:
7/25/2020 - 8/20/2020

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Report Date: 9/22/2020

The purpose of this document is to provide sample calculations for the reported results and to explain the method for differentiating petroleum hydrocarbon-derived CO_2 from that produced from natural soil respiration processes. The value of the ^{14}C analysis, site-specific study results and applicable notes, calculation explanations, and references are included.

The Value of the ^{14}C Analysis

How to differentiate between petroleum hydrocarbon-derived CO_2 and natural process-derived CO_2 using CO_2 flux traps:

Unimpacted soils naturally produce CO_2 due to microbial root zone activity and/or the degradation of natural organic matter. Thus, the total measured CO_2 flux at an impacted location is a function of the rates of both natural soil respiration and LNAPL degradation (Sihota and Mayer, 2012). The latter, which is caused by Natural Source Zone Depletion (NSZD), can be estimated by subtracting measured CO_2 fluxes at unimpacted locations from the total measured CO_2 fluxes at LNAPL-impacted locations (Sihota and Mayer, 2012). This spatial "background correction" assumes that bio-based CO_2 fluxes are similar at both impacted and unimpacted locations. This approach is complicated to implement, given that at many industrial facilities it is difficult to find unimpacted areas and vegetation cover can vary across a site. Alternatively, carbon isotope analysis can be used to carry out a location-specific correction for total measured CO_2 fluxes, and this approach effectively overcomes the limitations of the background correction.

Theory of Carbon Isotope Analysis:

Our method for NSZD rate estimation relies on the analysis of ^{14}C, an unstable carbon isotope with an absolute half-life of 5,730 years. ^{14}C is generated by cosmic rays in the atmosphere and is quickly oxidized to $^{14}CO_2$; thus, bio-based living carbon is ^{14}C-rich, while ancient fossil fuel carbon is completely ^{14}C-depleted. Additionally, bio-based organic carbon and the atmosphere have the same characteristic amount of ^{14}C. The short half-life of ^{14}C only allows for dating of samples younger than 60,000 years using accelerator mass spectrometry (Stuiver and Polach, 1977). ^{14}C analysis can therefore be used to differentiate between anthropogenic (i.e., fossil fuel) and natural sources of atmospheric carbon (see Klouda and Connolly, 1995; Levin et al., 1995; Avery et al., 2006), and this analysis is the basis for ASTM D6866-18.

For samples that contain both bio-based and fossil fuel-derived carbon, such as E-Flux's fossil fuel traps, measurement of ^{14}C enables quantitation of *both* source contributions. The fossil fuel-derived percentage of the sample (ff_{sample}) and the bio-based percentage ($1-ff_{sample}$, or bb_{sample}) are related by the following two-component mass balance (modified from Avery, Jr. et al., 2006):

$$Fm_{sample} = (ff_{sample})(Fm_{ff}) + (1 - ff_{sample})(Fm_{atm})$$

Here, Fm_x represents the fraction modern, a measure of how close the present $^{14}C/^{12}C$ ratio of the sample is to the ratio from 1950, which is derived from a pre-industrial era standard. Fm_{sample} is the total measured fraction modern of the sample. Fm_{ff} is the fraction modern of only the fossil fuel portion of the sample. This number is 0, as there is no ^{14}C in fossil fuel-derived CO_2. Fm_{atm} is the fraction modern of the part of the sample derived from natural soil respiration processes. This value, currently equal to **1.02** (Cerling et al., 2016, Larsen et al., 2018), has been experimentally determined and is a fixed value at each point in time. By convention, the results of carbon isotope analysis are reported based on a 1950 NBS oxalic acid standard, and so Fm_{sample} is reported as if the analysis took place in 1950. Due to nuclear testing, current ^{14}C atmospheric levels are now higher than they were in 1950. This means that Fm_{atm} is counter-intuitively larger than 1, as the $^{14}C/^{12}C$ sample ratio is higher now than it would have been in 1950.

^{14}C Calculations:

Conversion of Fraction Modern Carbon to Fossil Fuel Carbon:

The equation for calculating the percentage of fossil fuel carbon (ff_{sample}) is derived from the following mass balance:

$$Fm_{sample} = (ff_{sample})(Fm_{ff}) + (1 - ff_{sample})(Fm_{atm})$$

Solving for ff_{sample} yields:

$$ff_{sample} = 1 - \frac{Fm_{sample}}{Fm_{atm}}$$

Fraction modern (Fm_{sample}, from ^{14}C analysis) is reported by convention based on ^{14}C levels from 1950. Because of atomic testing, current environmental ^{14}C levels are approximately 2% higher than they were in 1950 (Cerling et al., 2016, Larsen et al., 2018) and Fm_{atm} is equal to 1.02. This equation then becomes:

$$ff_{sample} = 1 - \frac{Fm_{sample}}{1.02}$$

As percentages must add to 1, the percentage of bio-based carbon ($bb_{sample.}$) can then be calculated using the following equivalence:

$$bb_{sample} = 1 - ff_{sample} = 1 - \left(1 - \frac{Fm_{sample}}{1.02}\right) = \frac{Fm_{sample}}{1.02}$$

Converting Carbon Flux to Equivalent LNAPL Loss Rate:

The intermediate reactions for LNAPL mineralization include methanogenesis, leading to production of methane and CO_2, and the subsequent aerobic oxidation of methane into CO_2:

$$C_8H_{18} + 3.5\, H_2O \rightarrow 6.25\, CH_4 + 1.75\, CO_2 \text{ (methanogenesis)}$$

$$6.25\, CH_4 + 12.5\, O_2 \rightarrow 6.25\, CO_2 + 12.5\, H_2O \text{ (methane oxidation)}$$

$$C_8H_{18} + 12.5\, O_2 \rightarrow 9H_2O + 8\, CO_2 \text{ (overall reaction)}$$

Assuming a conservative LNAPL density of 0.77 g mL^{-1} (upper range of gasoline) and using the molecular weight of C_8H_{18} (octane, 114.23 g mol^{-1}), µmol m^{-2} s^{-1} of CO_2 can then be converted into gal. acre^{-1} yr^{-1} of LNAPL:

$$1\ \frac{\mu\text{mol CO}_2}{\text{m}^2\ \text{s}} \cdot \left(\frac{1\ \mu\text{mol C}_8\text{H}_{18}}{8\ \mu\text{mol CO}_2}\right)\left(\frac{1\ \text{mol C}_8\text{H}_{18}}{1 \times 10^6\ \mu\text{mol C}_8\text{H}_{18}}\right)\left(\frac{114\ \text{g C}_8\text{H}_{18}}{1\ \text{mol C}_8\text{H}_{18}}\right)\left(\frac{1\ \text{mL C}_8\text{H}_{18}}{0.77\ \text{g C}_8\text{H}_{18}}\right)$$
$$\left(\frac{1\ \text{L}}{1000\text{mL}}\right)\left(\frac{1\ \text{gal.}}{3.785\ \text{L}}\right)\left(\frac{4{,}046\ \text{m}^2}{1\ \text{acre}}\right)\left(\frac{3600\ \text{s}}{1\ \text{h}}\right)\left(\frac{24\ \text{h}}{1\ \text{d}}\right)\left(\frac{365\ \text{d}}{1\ \text{yr}}\right).$$
$$= 625.2\ \frac{\text{gal. C}_8\text{H}_{18}}{\text{acre} \cdot \text{yr}}$$

Note that both the LNAPL formula and its density are assumed, and so this conversion is subject to uncertainty. However, site-specific data can be used if available. Using alternative representative hydrocarbon formulas and densities generally results in conversion factors that are within 10-15% of 625.2 gal. $acre^{-1}$ yr^{-1}. Therefore, the uncertainty associated with these values does not preclude an acceptable estimate.

Expected Results and Recommendations:

^{14}C-based techniques offer a built-in, location-specific correction as an alternative to the standard background location correction. Early work on a limited number of samples suggested that ^{14}C-corrected results are equivalent to background-corrected results (Sihota and Mayer, 2012; McCoy et al., 2015). However, a more recent comparison spanning 4 different sites suggests that measured carbon fluxes can differ by up to five times among different locations within the same site (Zimbron and Kasyon, 2015). Depending on the location, the resulting difference between background-corrected and ^{14}C-corrected NSZD rate estimates can be up to one order of magnitude. In contrast, the background correction assumes that the non-fossil fuel CO_2 flux is constant across an entire site; large errors in final estimated NSZD rates might therefore be introduced if the background correction is used. Because the ^{14}C measurement is co-located with the CO_2 flux measurement, it is unbiased by spatial uncertainties related to the background location(s) (e.g., vegetation, lithology, unknown impacts, different gas transport regimes, soil moisture).

The fossil fuel CO_2 content of unexposed sorbent as used in the traps is typically around 30% (as of today) and likely results from material processing and handling (e.g., exposure to fossil fuel fumes). This small mass of fossil fuel CO_2 is removed from samples by carrying out a ^{14}C travel blank correction. ^{14}C analysis is performed on CO_2 sorbent sub-samples after homogenization of the entire bottom sorbent layer (see McCoy et al., 2015). The mass of fossil fuel CO_2 in the unexposed travel blank trap (TB) is then subtracted from the mass of fossil fuel CO_2 in each field-deployed trap.

Easy set-up. Expert results.

Project: Air National Guard Base, MN
Customer: GSI, Navy
Customer Contact: Kenneth Walker
Report Date: 22-Sep-2020

Sample ID	Sampling Information			Raw Results[a]				Final CO_2 Results[b]			^{14}C Results[a]			NSZD Results[b]				
	Deployed	Retrieved	Days in Field	Moisture content (%)	Dry Sorbent Mass (g)	Avg. % CO_2[c]	CV[d] CO_2 (%)	CO_2 content (%)	CO_2 mass (g)	CO_2 Flux (μmol m^{-2} s^{-1})	Fm_{sample} As Reported[e]	bb_{sample} As of Today[f]	ff_{sample} As of Today[f]	Bio-based CO_2 Flux (μmol m^{-2} s^{-1})	ff_{sample} As of Today (TB-corrected)	Fossil Fuel CO_2 (g)	Fossil Fuel CO_2 Flux (μmol m^{-2} s^{-1})	Equivalent NSZD Rate (gal. $acre^{-1}$ yr^{-1})
10182-R1-CO2-TB	N/A	N/A	N/A	16.9%	40.87	1.21%	2.00%	-	-	-	69.04	67.68%	32.32%	-	-	-	-	-
10182-R1-CO2-01	7/25/20 19:32	8/20/20 12:11	25.7	15.0%	43.25	9.97%	3.00%	8.77%	3.79	4.79	95.86	93.98%	6.02%	4.67	2.40%	0.09	0.12	72
10182-R1-CO2-02	7/25/20 19:56	8/20/20 10:49	25.6	47.9%	43.01	10.62%	0.49%	9.41%	4.05	5.13	45.89	44.99%	55.01%	2.16	57.92%	2.34	2.97	1856
10182-R1-CO2-03	7/25/20 20:06	8/20/20 10:55	25.6	36.1%	42.05	3.51%	0.48%	2.30%	0.97	1.22	55.39	54.30%	45.70%	0.58	52.71%	0.51	0.65	404
10182-R1-CO2-04	7/25/20 19:40	8/20/20 11:25	25.7	16.5%	45.92	15.77%	0.97%	14.57%	6.69	8.46	97.19	95.28%	4.72%	8.25	2.44%	0.16	0.21	129
10182-R1-CO2-05	7/25/20 20:20	8/20/20 11:01	25.6	58.4%	37.70	1.58%	3.30%	0.37%	0.14	0.18	68.80	67.45%	32.55%	0.12	33.32%	0.05	0.06	37

- The flux equivalence is **1** μmol m^{-2} s^{-1} = **625.2** gallons $acre^{-1}$ yr^{-1}, assuming a representative hydrocarbon density of **0.77** g mL^{-1} with the formula $\mathbf{C_8H_{18}}$. Trap cross-sectional area is **8.11 × 10^{-3}** m^2 (based on a **4-inch** receiver pipe).
- Carbonate analysis of each trap/sample is based on method ASTM 4373-14, which does do not provide acceptable variability (CV) standards. Similar methods (e.g., ASTM D513-16) allow typical errors of ≤ 20%. Analysis is therefore conducted in duplicate if the coefficient of variation (CV) of the duplicates is < 5%. If CV ≥ 5%, duplicate analyses are repeated until CV < 5%.
- NA = Not Applicable; ND = Not Detectable.

a. Raw and ^{14}C Results are not TB-corrected.
b. Final CO_2 and NSZD Results are TB-corrected.
c. Refers to the measured weight percentage of CO_2 with respect to the total dry sorbent mass.
d. Refers to the coefficient of variation of CO_2 measurements for each sample: CV = [standard deviation of %CO_2 measurements] / [average %CO_2 measurement]
e. Refers to the reported fraction modern (Fm_{sample}). As is standard in radiocarbon reporting, this value has not been corrected to account for present-day ^{14}C atmospheric levels. This number is originally reported as pMC (percent modern carbon) and is converted into *Fm* for our calculations using the relation 100.0 pMC = 1.0 *Fm* = 100% *Fm*.
f. "As of Today" means that the value has been adjusted to account for the difference between atmospheric ^{14}C levels from the 1950s and today (Stenström et al., 2011). bb_{sample} is the percentage of the total CO_2 that is derived from bio-based (non-fossil fuel) sources. ff_{sample} refers to the percentage of CO_2 that is derived from fossil fuels. The values reported in the ^{14}C Results section are not TB-corrected, but those in the NSZD Results section are.

Results Snapshot:

- The Travel Blank (TB) concentration is **1.21%**; typically, this number is < 2%.
- Trap tops are not saturated with CO_2 (sorbent saturation is 30%). The maximum measured (raw) top concentration is ***2.91%*** (sample **10182-R1-CO2-04 top**).
- Bio-based carbon fluxes represent the CO_2 contributions from natural soil respiration processes to the total carbon flux; the ^{14}C analysis corrects for this contribution. Average bio-based CO_2 flux is **3.16** µmol m^{-2} s^{-1}, and the coefficient of variation is **106%**. The range of bio-based CO_2 fluxes is between **0.12** and **8.25** µmol m^{-2} s^{-1}. If these interferences were not removed using the results of the radiocarbon analysis, the errors in the NSZD rate estimates would be between **74** and **5160** gallons $acre^{-1}$ yr^{-1}.

Site-specific Sample Calculations:

Grams of Fossil Fuel CO_2:

The mass of fossil fuel-derived CO_2 in each trap is calculated by subtracting the total fossil fuel CO_2 in the travel blank (TB) from the total fossil fuel CO_2 in the trap. Only data that are ***not*** TB-corrected (i.e., ff_{sample} As of Today and raw % CO_2) are used in this calculation. Using Sample 1 as an example:

$$\left(\mathrm{g\ CO_{2(ff)}}\right)_{sample\ 1} = \mathrm{g_{sorbent}} \cdot \left[\left((\%\ \mathrm{CO_2})_{\mathrm{sample}}\left(ff_{sample}\right)\right) - \left((\%\ \mathrm{CO_2})_{\mathrm{TB}}\left(ff_{TB}\right)\right)\right]$$

$$\left(\mathrm{g\ CO_{2(ff)}}\right)_{sample\ 1} = \mathbf{43.25}\ \mathrm{g} \cdot [(\mathbf{9.97}\ \% \cdot \mathbf{6.02}\ \%) - (\mathbf{1.21}\ \% \cdot \mathbf{32.32}\ \%)]$$

$$\left(\mathrm{g\ CO_{2(ff)}}\right)_{sample\ 1} = \mathbf{0.0911}\ \mathrm{g}$$

Here, $g_{sorbent}$ is the mass of sorbent used in the bottom layer of the trap, $(\%CO_2)_{sample}$ is the average weight percentage of CO_2 in the sample, ff_{sample} is the percentage of carbon in the sample derived from fossil fuels, $(\%CO_2)_{TB}$ is the average weight percentage of CO_2 in the travel blank, and ff_{TB} is the percentage of carbon in the travel blank that is derived from fossil fuels. In this example, Sample 1 contains **0.0911 g** of fossil-fuel derived CO_2.

Fossil Fuel CO_2 Flux:

Converting grams of CO_2 to CO_2 flux requires the cross-sectional area of the receiver (**8.11 × 10^{-3}** m^2 for a **4**-inch receiver), the number of days that the trap was deployed in the field, and the molecular weight of CO_2 (44 g mol^{-1}). Using Site 1 as an example:

$$\text{Fossil Fuel CO}_2\text{ Flux} = \frac{\text{g fossil fuel CO}_2 \cdot \dfrac{1\text{ mol CO}_2}{44\text{ g CO}_2} \cdot \dfrac{1{,}000{,}000\ \mu\text{mol CO}_2}{1\text{ mol CO}_2}}{\text{days in the field} \cdot \dfrac{24\text{ hr}}{\text{day}} \cdot \dfrac{3600\text{ s}}{\text{hr}} \cdot (\text{receiver area})}$$

$$\text{Fossil Fuel CO}_2\text{ Flux} = \frac{\mathbf{0.0911}\text{ g fossil fuel CO}_2 \cdot \dfrac{1\text{ mol CO}_2}{44\text{ g CO}_2} \cdot \dfrac{1{,}000{,}000\ \mu\text{mol CO}_2}{\text{mol CO}_2}}{\mathbf{25.7}\text{ days} \cdot \dfrac{24\text{ hr}}{\text{day}} \cdot \dfrac{3600\text{ s}}{\text{hr}} \cdot (\mathbf{8.11} \times \mathbf{10^{-3}}\text{ m}^2)}$$

$$\text{Fossil Fuel CO}_2\text{ Flux} = \mathbf{0.12}\ \frac{\mu\text{mol CO}_2}{\text{m}^2 \cdot \text{s}}$$

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APPENDIX H: DATA TABLES AND LAB REPORTS
ESTCP ER19-5091

Appendix H.3 TEAD-S Soil Gas Measurements

GSI ENVIRONMENTAL

APPENDIX H.3. TEAD-S SOIL GAS MEASUREMENTS - 2020

ESTCP Project ER19-5091

Location ID	Sample Depth (ft)	Sample Date	Sample Time	Length of Sampling (min)	CH_4 (%)	CO_2 (%)	O_2 (%)	Balance (%)	Sum	Notes
GSI-L1-1 ft	1	25-Jun-20	12:17	5	0.0	0.0	18.4	81.6	100.0	Ambient Air - 19.6% O_2, 0% CH_4, 0% CO_2
GSI-L1-3 ft	3	25-Jun-20	12:24	3	0.0	6.1	12.1	81.8	100	Stabilized @ 30 seconds
GSI-L1-5 ft	5	25-Jun-20	12:32	2.5	0.0	9.5	6.7	83.8	100	Ambient Air - 18.2% O_2, 0% CH4, 0% CO2
GSI-L1-7 ft	7	25-Jun-20	12:38	2	1.2	12.0	1.4	85.4	100	Ambient Air - 18.2% O_2, 0% CH4, 0% CO2
GSI-L2-1 ft	1	25-Jun-20	12:52	2	0.0	0.8	17.1	82.1	100	Ambient Air - 18.7% O_2, 0% CH4, 0% CO2
GSI-L2-3 ft	3	25-Jun-20	13:00	1.5	0.0	8.4	8.1	83.4	99.9	Ambient Air - 19.1% O_2, 0% CH4, 0% CO2
GSI-L2-5 ft	5	25-Jun-20	13:02	1	0.0	9.6	6.5	83.9	100	--
GSI-L2-7 ft	7	25-Jun-20	13:10	1.75	0.0	10.7	5.1	84.2	100	Ambient Air - 19.2% O_2, 0% CH4, 0% CO2
GSI-BG1-1 ft	1	25-Jun-20	13:22	1	0.0	0.0	18.6	81.4	100	Ambient Air - 19.3% O_2, 0% CH4, 0% CO2
GSI-BG1-3 ft	3	25-Jun-20	13:24	0.75	0.0	1.5	16.5	82.0	100	Ambient Air - 19.4% O_2, 0% CH4, 0% CO2
GSI-BG1-5 ft	5	25-Jun-20	13:26	1	0.0	1.4	16.3	82.3	100	Ambient Air - 19.6% O_2, 0% CH4, 0% CO2
GSI-BG1-7 ft	7	25-Jun-20	13:31	1.75	0.0	0.0	18.6	81.4	100	Slight retraction of syringe (5 mls)
GSI-BG2-1 ft	1	25-Jun-20	13:45	1.5	0.1	0.0	19.5	80.3	99.9	Ambient Air - 19.9% O_2, 0.1% CH_4, 0% CO2
GSI-BG2-3 ft	3	25-Jun-20	13:46	1	0.1	0.2	19.4	80.3	100	Ambient Air - 19.8% O_2, 0.1% CH_4, 0% CO2
GSI-BG2-5 ft	5	25-Jun-20	13:48	1	0.1	0.3	19.3	80.3	100	Ambient Air - 19.8% O_2, 0.1% CH_4, 0% CO2
GSI-BG2-7 ft	7	25-Jun-20	13:50	1	0.1	0.2	18.9	80.9	100.1	Ambient Air - 20% O_2, 0.1% CH_4, 0% CO2
GSI-L3-1 ft	1	25-Jun-20	14:00	1	0.1	1.7	17.9	80.3	100	Ambient Air - 19.9% O_2, 0.1% CH_4, 0% CO2
GSI-L3-3 ft	3	25-Jun-20	14:03	1.5	0.0	4.2	15.4	80.4	100	Ambient Air - 19.8% O_2, 0.1% CH_4, 0% CO2
GSI-L3-5 ft	5	25-Jun-20	14:06	1	0.0	5.3	13.8	80.9	100	Post-Measuring Ambient Air - 19.8% O2, 0.1% CH4, 0% CO2
GSI-L3-7 ft	7	25-Jun-20	14:08	1	0.1	7.6	11.1	81.2	100	Ambient Air - 20% O_2, 0.1% CH_4, 0% CO2
CSU-L2-0.5 ft	0.5	25-Jun-20	14:59	1	0.0	0.0	19.8	80.2	100	Ambient Air - 19.9% O_2, 0.0% CH_4, 0% CO2
CSU-L2-2 ft	2	25-Jun-20	15:01	1.5	0.0	4.2	14.9	80.9	100	Ambient Air - 19.9% O_2, 0.0% CH_4, 0% CO2
CSU-L2-4 ft	4	25-Jun-20	15:03	1	0.1	7.4	10.4	82.2	100.1	Ambient Air - 19.9% O_2, 0.0% CH_4, 0% CO2
CSU-L2-6 ft	6	25-Jun-20	15:07	1.5	0.1	8.7	8.2	83.0	100	Ambient Air - 19.9% O_2, 0.0% CH_4, 0% CO2
CSU-L2-10 ft	10	25-Jun-20	15:10	1	0.3	9.7	5.6	84.3	99.9	Ambient Air - 19.9% O_2, 0.1% CH_4, 0% CO2
CSU-L2-14 ft	14	25-Jun-20	15:13	1	0.4	8.7	6.3	84.7	100.1	Ambient Air - 19.9% O_2, 0.1% CH_4, 0% CO2
CSU-L2-18 ft	18	25-Jun-20	--	--	BWT	BWT	BWT	BWT	BWT	Syringe reduces to 4 mls from 50 mls
CSU-L3-0.5 ft	0.5	25-Jun-20	15:37	1	0.1	0.5	18.9	80.6	100.1	Ambient Air - 20.2% O_2, 0.1% CH_4, 0% CO2
CSU-L3-2 ft	2	25-Jun-20	15:39	1	0.1	3.1	16.8	80	100	Ambient Air - 19.9% O_2, 0.0% CH_4, 0% CO2
CSU-L3-4 ft	4	25-Jun-20	15:42	1.25	0.1	4.7	14.7	80.6	100.1	Ambient Air - 19.9% O_2, 0.1% CH_4, 0% CO2
CSU-L3-6 ft	6	25-Jun-20	15:44	1.25	0.1	6.2	12.5	81.2	100	Ambient Air - 19.8% O_2, 0.1% CH_4, 0% CO2
CSU-L3-10 ft	10	25-Jun-20	15:47	1.5	0.3	10.9	5.3	83.5	100	Ambient Air - 19.8% O_2, 0.1% CH_4, 0% CO2
CSU-L3-14 ft	14	25-Jun-20	--	--	BWT	BWT	BWT	BWT	BWT	Hard Suction
CSU-L3-18 ft	18	25-Jun-20	--	--	BWT	BWT	BWT	BWT	BWT	Hard Suction
CSU-BG2-0.5 ft	0.5	25-Jun-20	16:01	1.25	0	0	19.7	80.3	100	Ambient Air - 20.1% O_2, 0.1% CH_4, 0% CO2
CSU-BG2-2 ft	2	25-Jun-20	16:04	1	0.1	0.2	19.7	80	100	Ambient Air - 20.0% O_2, 0.1% CH_4, 0% CO2
CSU-BG2-4 ft	4	25-Jun-20	16:06	1	0.1	0.3	19.6	80	100	Ambient Air - 20.0% O_2, 0.1% CH_4, 0% CO2
CSU-BG2-6 ft	6	25-Jun-20	16:10	1	0.1	0.4	19.6	79.9	100	Ambient Air - 20.0% O_2, 0.1% CH_4, 0% CO2
CSU-BG2-10 ft	10	25-Jun-20	16:12	1	0	0.8	19.3	79.8	99.9	Ambient Air - 20.1% O_2, 0.1% CH_4, 0% CO2
CSU-BG2-14 ft	14	25-Jun-20	--	--	BWT	BWT	BWT	BWT	BWT	Hard Suction
CSU-BG2-18 ft	18	25-Jun-20	--	--	BWT	BWT	BWT	BWT	BWT	Hard Suction

Notes:
1. BWT = below water table
2. Stabilization criteria: No more than 5 minutes of purging per port was performed. Instrument values varied =<0.1% over a 10 second interval.
3. Generally, stabilization occurred within the first 30 seconds - 1 minute.
4. Let detector stablize to ambient between readings
5. Purged detector between sample locations

APPENDIX H.3. TEAD-S SOIL GAS MEASUREMENTS - 2021

ESTCP Project ER19-5091

Location ID	Sample Depth (ft)	Sample Date	Sample Time	CH_4 (%)	CO_2 (%)	O_2 (%)	Balance (%)	Length of Sampling (min)	Notes
GSI-BG1-1 ft	1	6-Apr-21	1428	0.0	0.1	19.3	80.6	1.5	Mud to top of casing. Replaced value. No H20, easy pull on syringe
GSI-BG1-3 ft	3	6-Apr-21	1431	0.0	1.0	17.1	81.9	2	Mud to top of casing. Replaced value. No H20, easy pull on syringe
GSI-BG1-5 ft	5	6-Apr-21	1435	0.0	0.9	16.8	82.3	2	Mud to top of casing. Replaced value. No H20, easy pull on syringe
GSI-BG1-7 ft	7	6-Apr-21	1438	0.0	0.8	16.8	82.4	2	Mud to top of casing. Replaced value. No H20, easy pull on syringe
GSI-BG2-1 ft	1	6-Apr-21	856	0.0	0.1	21.4	78.5	5	No H2O, easy pull on syringe
GSI-BG2-3 ft	3	6-Apr-21	913	0.0	0.4	21.1	78.5	2	No H2O, easy pull on syringe
GSI-BG2-5 ft	5	6-Apr-21	920	0.0	0.3	21.3	78.4	2.4	No H2O, easy pull on syringe
GSI-BG2-7 ft	7	6-Apr-21	923	0.0	0.1	21.5	78.4	4	No H2O, easy pull on syringe
CSU-BG2-0.5 ft	0.5	6-Apr-21	1406	0	0.1	19.9	80	1	No H2O, easy pull on syringe
CSU-BG2-2 ft	2	6-Apr-21	1411	0	0.3	19.7	80	1	No H2O, easy pull on syringe
CSU-BG2-4 ft	4	6-Apr-21	1418	0	0.2	19.7	80.1	2	No H2O, easy pull on syringe
CSU-BG2-6 ft	6	6-Apr-21	1415	0	0.4	19.5	80.1	1	No H2O, easy pull on syringe
CSU-BG2-10 ft	10	6-Apr-21	1413	0	0.7	19.2	80.1	1.5	No H2O, easy pull on syringe
CSU-BG2-14 ft	14	6-Apr-21	BWT	BWT	BWT	BWT	BWT	BWT	Syringe would not pull out
CSU-BG2-18 ft	18	6-Apr-21	BWT	BWT	BWT	BWT	BWT	BWT	Syringe would not pull out
GSI-L2-1 ft	1	6-Apr-21	1030	0.0	2.2	18.1	79.6	3.15	No H2O, easy pull on syringe
GSI-L2-3 ft	3	6-Apr-21	1034	0.0	8.7	7.0	84.3	2	No H2O, easy pull on syringe
GSI-L2-5 ft	5	6-Apr-21	1037	0.0	9.2	5.5	85.3	2.3	No H2O, easy pull on syringe
GSI-L2-7 ft	7	6-Apr-21	1041	0.0	10.5	3.6	85.9	3	No H2O, easy pull on syringe
CSU-L2-0.5 ft	0.5	6-Apr-21	1207	0.0	1.6	17.9	80.4	2.4	No H2O, easy pull on syringe
CSU-L2-2 ft	2	6-Apr-21	1210	0.0	4.4	13.3	82.3	3	No H2O, easy pull on syringe
CSU-L2-4 ft	4	6-Apr-21	1214	0.0	7.6	8.2	84.2	3	No H2O, easy pull on syringe
CSU-L2-6 ft	6	6-Apr-21	1218	0.0	9.1	5.8	85.1	1.5	No H2O, easy pull on syringe
CSU-L2-10 ft	10	6-Apr-21	1220	0.0	11.2	3.0	85.8	2	No H2O, easy pull on syringe
CSU-L2-14 ft	14	6-Apr-21	1223	0.0	12.4	1.2	86.4	2	No H2O, easy pull on syringe
CSU-L2-18 ft	18	6-Apr-21	BWT	BWT	BWT	BWT	BWT	BWT	Syringe would not pull out
GSI-L1-1 ft	1	6-Apr-21	1000	0.0	0.2	21.2	78.6	3	No H2O, easy pull on syringe
GSI-L1-3 ft	3	6-Apr-21	1007	0.0	4.2	12.7	83.1	2.5	No H2O, easy pull on syringe
GSI-L1-5 ft	5	6-Apr-21	1010	0.0	7.7	6.1	86.2	2.5	No H2O, easy pull on syringe
GSI-L1-7 ft	7	6-Apr-21	1019	0.4	10.7	0.0	88.9	4	No H2O, easy pull on syringe
GSI-L3-1 ft	1	6-Apr-21	1228	0.0	1.8	18.7	79.5	2	No H2O, easy pull on syringe
GSI-L3-3 ft	3	6-Apr-21	1231	0.0	2.7	17.8	79.5	2	No H2O, easy pull on syringe
GSI-L3-5 ft	5	6-Apr-21	1234	0.0	5.6	13.9	80.5	1.5	No H2O, easy pull on syringe
GSI-L3-7 ft	7	6-Apr-21	1237	0.0	8.8	9.8	81.4	2	No H2O, easy pull on syringe
CSU-L3-0.5 ft	0.5	6-Apr-21	1345	0	0.4	19.4	80.2	2	No H2O, easy pull on syringe
CSU-L3-2 ft	2	6-Apr-21	1348	0	2.7	16.6	80.7	1	No H2O, easy pull on syringe
CSU-L3-4 ft	4	6-Apr-21	1350	0	4.2	14.6	81.2	2	No H2O, easy pull on syringe
CSU-L3-6 ft	6	6-Apr-21	1354	0	6.2	11.9	81.9	1.5	No H2O, easy pull on syringe
CSU-L3-10 ft	10	6-Apr-21	1357	0	13.3	2.5	84.2	1	No H2O, easy pull on syringe
CSU-L3-14 ft	14	6-Apr-21	BWT	BWT	BWT	BWT	BWT	BWT	Syringe would not pull out
CSU-L3-18 ft	18	6-Apr-21	BWT	BWT	BWT	BWT	BWT	BWT	Syringe would not pull out

Notes:
1. BWT = below water table
2. Stabilization criteria: No more than 5 minutes of purging per port performed. Instrument values varied =<0.1% over a 10 second interval.
3. Generally, stabilization occurred within the first 30 seconds - 1 minute.
4. Let detector stablize to ambient between readings
5. Purged detector between sample locations

GSI ENVIRONMENTAL

APPENDIX H.3. TEAD-S SOIL GAS MEASUREMENTS - 2022

ESTCP Project ER19-5091

Location ID	Sample Depth (ft)	Sample Date	Sample Time	CH_4 (%)	CO_2 (%)	O_2 (%)	Balance (%)	Length of Sampling (min)	Notes
GSI-BG1-1 ft	1	4/4/2022	810	0.0	0.1	20.6	79.1	2	Mud to TOC; no H2O in syringe; easy pull
GSI-BG1-3 ft	3	4/4/2022	813	0.0	0.1	20.7	79.1	2	Mud to TOC; no H2O in syringe; easy pull
GSI-BG1-5 ft	5	4/4/2022	816	0.0	0.1	20.7	79.1	2	Mud to TOC; no H2O in syringe; easy pull
GSI-BG1-7 ft	7	4/4/2022	819	0.1	0.1	20.7	79.0	2	Mud to TOC; no H2O in syringe; easy pull
GSI-BG2-1 ft	1	4/4/2022	828	0.0	0.1	20.8	78.9	1.5	Mud to TOC; no H2O in syringe; easy pull
GSI-BG2-3 ft	3	4/4/2022	831	0.1	0.1	20.8	78.9	2	Mud to TOC; no H2O in syringe; easy pull
GSI-BG2-5 ft	5	4/4/2022	834	0.1	0.1	20.8	79.0	3	Mud to TOC; no H2O in syringe; easy pull
GSI-BG2-7 ft	7	4/4/2022	838	0.0	0.1	20.8	79.0	1.5	Mud to TOC; no H2O in syringe; easy pull
CSU-BG2-0.5 ft	0.5	4/4/2022	1235	0	0	20.5	79.3	2	No H2O in syringe; easy pull
CSU-BG2-2 ft	2	4/4/2022	1232	0	0	20.4	79.4	2	No H2O in syringe; easy pull
CSU-BG2-4 ft	4	4/4/2022	1228	0.1	0	20.4	79.4	2	No H2O in syringe; easy pull
CSU-BG2-6 ft	6	4/4/2022	1225	0.2	0	20.7	79.2	2	No H2O in syringe; easy pull
CSU-BG2-10 ft	10	4/4/2022	1221	0.2	0	20.4	79.3	2.5	No H2O in syringe; easy pull
CSU-BG2-14 ft	14	4/4/2022	BWT	BWT	BWT	BWT	BWT	BWT	Syringe would not pull out.
CSU-BG2-18 ft	18	4/4/2022	BWT	BWT	BWT	BWT	BWT	BWT	Syringe would not pull out.
GSI-L2-1 ft	1	4/4/2022	1126	0.1	1.1	18.7	80.1	2	Mud to TOC; no H2O in syringe; easy pull
GSI-L2-3 ft	3	4/4/2022	1121	0.1	2.6	15.9	81.3	2	Mud to TOC; no H2O in syringe; easy pull
GSI-L2-5 ft	5	4/4/2022	1118	0.0	2.4	16.4	81.1	2	Mud to TOC; no H2O in syringe; easy pull
GSI-L2-7 ft	7	4/4/2022	1123	0.1	3.0	15.3	81.6	2	Mud to TOC; no H2O in syringe; easy pull
CSU-L2-0.5 ft	0.5	4/4/2022	1132	0.1	0.2	20.6	79.2	2	No H2O in syringe; easy pull
CSU-L2-2 ft	2	4/4/2022	1145	0.1	0.8	19.5	79.5	3	No H2O in syringe; easy pull
CSU-L2-4 ft	4	4/4/2022	1130	0.1	0.7	19.6	79.6	2	No H2O in syringe; easy pull
CSU-L2-6 ft	6	4/4/2022	1142	0.1	0.9	19.3	79.7	2	No H2O in syringe; easy pull
CSU-L2-10 ft	10	4/4/2022	1135	0.2	0.8	19.5	79.6	2	No H2O in syringe; easy pull
CSU-L2-14 ft	14	4/4/2022	1139	0.1	0.5	20.0	79.4	2	No H2O in syringe; easy pull
CSU-L2-18 ft	18	4/4/2022	BWT	BWT	BWT	BWT	BWT	BWT	Syringe would not pull out.
GSI-L1-1 ft	1	4/4/2022	1206	0.0	0.1	20.4	79.6	3	Mud to TOC; no H2O in syringe; easy pull
GSI-L1-3 ft	3	4/4/2022	1159	0.1	0.8	19.1	79.9	2	Mud to TOC; no H2O in syringe; easy pull
GSI-L1-5 ft	5	4/4/2022	1156	0.1	2.6	15.7	81.5	2	Mud to TOC; no H2O in syringe; easy pull
GSI-L1-7 ft	7	4/4/2022	1203	0.3	3.1	13.8	82.6	2	Mud to TOC; no H2O in syringe; easy pull
GSI-L3-1 ft	1	4/4/2022	1107	0.0	1.6	19.2	79.1	2	Mud to TOC; no H2O in syringe; easy pull
GSI-L3-3 ft	3	4/4/2022	1103	0.0	2.5	18.3	79.3	3	Mud to TOC; no H2O in syringe; easy pull
GSI-L3-5 ft	5	4/4/2022	1110	0.0	2.4	18.0	79.5	2	Mud to TOC; no H2O in syringe; easy pull
GSI-L3-7 ft	7	4/4/2022	1100	0.0	2.6	18.0	79.3	2	Mud to TOC; no H2O in syringe; easy pull
CSU-L3-0.5 ft	0.5	4/4/2022	1050	0	0.4	20.4	79.2	2	No H2O in syringe; easy pull
CSU-L3-2 ft	2	4/4/2022	1045	0	0.6	19.8	79.3	3	No H2O in syringe; easy pull
CSU-L3-4 ft	4	4/4/2022	1040	0	0.6	20	79.2	5	No H2O in syringe; easy pull
CSU-L3-6 ft	6	4/4/2022	1053	0.1	0.8	19.8	79.4	3	No H2O in syringe; easy pull
CSU-L3-10 ft	10	4/4/2022	1057	0	1	19.4	79.5	5	No H2O in syringe; easy pull
CSU-L3-14 ft	14	4/4/2022	BWT	BWT	BWT	BWT	BWT	BWT	Syringe would not pull out.
CSU-L3-18 ft	18	4/4/2022	BWT	BWT	BWT	BWT	BWT	BWT	Syringe would not pull out.

Notes:
1. BWT = below water table
2. Stabilization criteria: No more than 5 minutes of purging per port performed. Instrument values varied =<0.1% over a 10 second interval.
3. Generally, stabilization occurred within the first 30 seconds - 1 minute.
4. Let detector stablize to ambient between readings
5. Purged detector between sample locations

APPENDIX H: DATA TABLES AND LAB REPORTS
ESTCP ER19-5091

Appendix H.4 MN ANGB Soil Gas Measurements

APPENDIX H.4. MN ANGB SOIL GAS MEASUREMENTS - 2020

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Location ID	Sample Depth (ft)	Sample Date	Sample Time	Length of Sampling (min)	CH_4 (%)	CO_2 (%)	O_2 (%)	Balance (%)	Sum	Notes
CSU-L2-0.5 ft	0.5	20-Aug-20	16:14	1.5	0.1	0.0	19.4	80.5	100	Ambient Air - 19.3% O_2, 0.1% CH_4, 0% CO_2
CSU-L2-2 ft	2	20-Aug-20	16:25	10	28.0	4.5	11.4	56.2	100.1	Tubing cut shorter after this measurement. Minor moisture. Ambient Air - 19.5% O_2, 0.1% CH_4, 0% CO_2.
CSU-L2-4 ft	4	20-Aug-20	16:45	10	61.3	8.9	1.7	26.1	98.0	CH_4 continued to rise past 10 minutes. Ambient Air - 19.6% O_2, 0.7% CH_4, 0% CO_2
CSU-L2-6 ft	6	20-Aug-20	17:04	1	**100.0**	8.8	0.5	**0.0**	>100	Methane exceeded 100%. Balance was <0%. Ambient Air - 20.1% O_2, 0.2% CH_4, 0% CO_2
CSU-L2-8 ft	8	20-Aug-20	17:09	1	**100.0**	8.5	0.4	**0.0**	>100	Methane exceeded 100%. Balance was <0%. Water in line after valve closed. Ambient Air - 20.2% O_2, 0.4% CH_4, 0% CO_2
CSU-L2-10 ft	10	20-Aug-20	--	--	--	--	--	--	BWT	Hard suction- water in syringe.
CSU-L2-14 ft	14	20-Aug-20	--	--	--	--	--	--	BWT	Hard suction- water in syringe.
GSI-L2-1 ft	1	20-Aug-20	17:20	1	0.8	1.0	17.8	80.4	100	Ambient Air - 20.2% O_2, 0.2% CH_4, 0% CO_2
GSI-L2-3 ft	3	20-Aug-20	17:23	1	0.4	0.1	20.0	79.5	100	Some suction. Ambient Air - 20.3% O_2, 0.2% CH_4, 0% CO_2
GSI-L2-5 ft	5	20-Aug-20	17:24	1	47.3	2.5	13.0	37.1	99.9	CH_4 continued to rise past 5 minutes. Ambient Air - 20.2% O_2, 0.2% CH_4, 0% CO_2
GSI-L2-5 ft	5	20-Aug-20	17:29	5	44.0	2.3	13.5	39.9	99.7	CH_4 continued to rise past 5 minutes. Ambient Air - 20.2% O_2, 0.2% CH_4, 0% CO_2
GSI-L2-7 ft	7	20-Aug-20	17:33	1	53.4	1.9	13.5	29.3	98.1	Ambient Air - 20.2% O_2, 0.3% CH_4, 0% CO_2
GSI-L2-7 ft	7	20-Aug-20	17:35	3	55.9	1.9	14.8	27.3	99.9	Ambient Air - 20.2% O_2, 0.3% CH_4, 0% CO_2
CSU-L3-0.5 ft	0.5	20-Aug-20	--	--	--	--	--	--	0	Pump shuts off due to flashing "pump flow" error. Ambient Air - 20.1% O_2, 0.2% CH_4, 0% CO_2
CSU-L3-2 ft	2	20-Aug-20	18:00	1	0.2	0.3	19.2	80.3	100	Ambient Air - 20.1% O_2, 0.2% CH_4, 0% CO_2
CSU-L3-4 ft	4	20-Aug-20	18:02	1	1.2	1.5	16.8	80.3	99.8	Ambient Air - 20.21 O_2, 0.1% CH_4, 0% CO_2
CSU-L3-6 ft	6	20-Aug-20	18:04	1	13.9	2.5	13.6	70.0	100	Ambient Air - 20.1% O_2, 0.1% CH_4, 0% CO_2
CSU-L3-8 ft	8	20-Aug-20	18:07	1	**100.0**	3.3	10.4	**0.0**	>100	Methane exceeded 100%. Balance was <0%. Minor moisture. Ambient Air - 20.0% O_2, 0.2% CH_4, 0% CO_2
CSU-L3-10 ft	10	20-Aug-20	--	--	--	--	--	--	BWT	Hard suction- water in syringe.
CSU-L3-14 ft	14	20-Aug-20	--	--	--	--	--	--	BWT	Hard suction- water in syringe.
GSI-L3-1 ft	1	20-Aug-20	18:29	1	0.2	0.1	19.7	80.0	100	Replaced 3-way valve before pumping. Ambient Air - 20.3% O_2, 0.2% CH_4, 0% CO_2
GSI-L3-3 ft	3	20-Aug-20	18:31	1	0.2	0.2	19.1	80.5	100	Ambient Air - 20.3% O_2, 0.2% CH_4, 0% CO_2
GSI-L3-5 ft	5	20-Aug-20	18:33	1	0.2	0.2	19.0	80.6	100	Ambient Air - 20.2% O_2, 0.1% CH_4, 0% CO_2
GSI-L3-7 ft	7	20-Aug-20	18:35	1	0.2	0.1	18.8	80.9	100	Ambient Air - 20.3% O_2, 0.2% CH_4, 0% CO_2
CSU-BG2-0.5 ft	0.5	20-Aug-20	18:47	0.5	0.1	0.0	20.4	79.5	100	Ambient Air - 20.4% O_2, 0.1% CH_4, 0% CO_2
CSU-BG2-2 ft	2	20-Aug-20	18:49	1	0.1	1.4	17.5	81.0	100	Ambient Air - 20.4% O_2, 0.1% CH_4, 0% CO_2
CSU-BG2-4 ft	4	20-Aug-20	18:52	1	0.1	1.5	17.1	81.3	100	Ambient Air - 20.4% O_2, 0.1% CH_4, 0% CO_2
CSU-BG2-6 ft	6	20-Aug-20	18:54	1	0.1	1.4	16.7	81.8	100	Ambient Air - 20.1% O_2, 0.1% CH_4, 0% CO_2
CSU-BG2-8 ft	8	20-Aug-20	18:58	1	0.1	1.4	16.7	81.8	100	Water in syringe. Ambient Air - 20.2% O_2, 0.1% CH_4, 0% CO_2
CSU-BG2-10 ft	10	20-Aug-20	--	--	--	--	--	--	BWT	Hard suction- water in syringe.
CSU-BG2-14 ft	14	20-Aug-20	--	--	--	--	--	--	BWT	Hard suction- water in syringe.
GSI-BG2-1 ft	1	20-Aug-20	19:10	1	0.1	0.7	18.7	80.5	100	Replaced 3-way valve before pumping. Ambient Air - 20.0% O_2, 0% CH_4, 0% CO_2
GSI-BG2-3 ft	3	20-Aug-20	19:12	1	0	0.5	18.7	80.8	100	Ambient Air - 20.2% O_2, 0.1% CH_4, 0% CO_2
GSI-BG2-5 ft	5	20-Aug-20	19:14	1	0.1	0.4	18.2	81.3	100	Ambient Air - 20.2% O_2, 0.1% CH_4, 0% CO_2
GSI-BG2-7 ft	7	20-Aug-20	19:16	1	0	0.2	18.9	80.9	100	Ambient Air - 20.3% O_2, 0.1% CH_4, 0% CO_2
GSI-BG1-1 ft	1	20-Aug-20	19:23	1	0	0.3	18.6	81.1	100	Ambient Air - 20.2% O_2, 6.0% CH_4, 0% CO_2
GSI-BG1-3 ft	3	20-Aug-20	19:26	1	0	0.1	19	80.9	100	Ambient Air - 20.3% O_2, 0% CH_4, 0% CO_2
GSI-BG1-5 ft	5	20-Aug-20	--	--	--	--	--	--	BWT	Hard suction- water in syringe.
GSI-BG1-7 ft	7	20-Aug-20	--	--	--	--	--	--	BWT	Did not install because water table was too high.
GSI-L1-1 ft	1	20-Aug-20	19:38	1	0	0.1	19.3	80.6	100	Ambient Air - 20.5% O_2, 0% CH_4, 0% CO_2
GSI-L1-3 ft	3	20-Aug-20	19:40	1	0	0	18.9	81.1	100	Ambient Air - 20.5% O_2, 0% CH_4, 0% CO_2
GSI-L1-5 ft	5	20-Aug-20	19:42	1	0	0	19	81	100	Ambient Air - 20.5% O_2, 0% CH_4, 0% CO_2
GSI-L1-7 ft	7	20-Aug-20	19:43	1	0	0	19.4	80.6	100	Ambient Air - 20.5% O_2, 0% CH_4, 0% CO_2

Notes:
1. BWT = below water table
2. Stabilization criteria: No more than 10 minutes of purging per port was performed. Instrument values varied =<0.1% over a 10 second interval.
3. Generally, stabilization occurred within the first 30 seconds - 1 minute.
4. Values in **Bold** were greater than 100% for CH_4 and less than 0% for BAL.

APPENDIX H.4. MN ANGB SOIL GAS MEASUREMENTS - 2021

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Location ID	Sample Depth (ft)	Sample Date	Sample Time	Length of Sampling (min:sec)	CH_4 (%)	CO_2 (%)	O_2 (%)	Balance (%)	Sum	Notes
CSU-L2-0.5 ft	0.5	30-Mar-21	15:35	1:00	0.1	0.0	21.5	78.4	100.0	Ambient Air - 0.2% CH4, 0.0% CO2, 21.5% O2, 78.3% BAL, port in ambient air.
CSU-L2-2 ft	2	30-Mar-21	15:37	1:00	0.5	0.3	21.1	78.1	100.0	Ambient Air - 0.1% CH4, 0.0% CO2, 21.5% O2, 78.4% BAL
CSU-L2-4 ft	4	30-Mar-21	15:39	1:00	0.7	0.5	20.9	77.9	100.0	Ambient Air - 0.2% CH4, 0.0% CO2, 21.4% O2, 78.4% BAL
CSU-L2-6 ft	6	30-Mar-21	15:41	1:00	1.0	0.8	20.3	77.1	99.2	Ambient Air - 0.2% CH4, 0.0% CO2, 21.4% O2, 78.4% BAL
CSU-L2-8 ft	8	30-Mar-21	15:42	1:00	16.0	2.9	15.1	66.0	100.0	Ambient Air - 0.2% CH4, 0.0% CO2, 21.4% O2, 78.4% BAL
CSU-L2-10 ft	10	30-Mar-21	--	--	--	--	--	--	--	BWT
CSU-L2-14 ft	14	30-Mar-21	--	--	--	--	--	--	--	BWT
GSI-L2-1 ft	1	30-Mar-21	15:46	1:00	0.2	1.1	19.6	79.1	100.0	Ambient Air - 0.2% CH4, 0.0% CO2, 21.3% O2, 78.5% BAL
GSI-L2-3 ft	3	30-Mar-21	--	--	--	--	--	--	--	Hard suction, not measured. Water or Clay blocking?
GSI-L2-5 ft	5	30-Mar-21	15:48	5:00	15.8	6.8	0.1	76.5	99.2	Ambient Air - 0.1% CH4, 0.0% CO2, 21.5% O2, 78.4% BAL, constant CH4 rise.
GSI-L2-7 ft	7	30-Mar-21	15:58	4:00	58.0	5.6	7.8	29.3	100.7	Ambient Air - 0.2% CH4, 0.1% CO2, 21.3% O2, 78.4% BAL, constant CH4 drop.
CSU-L3-0.5 ft	0.5	30-Mar-21	15:18	1:00	0.2	0.0	21.9	77.9	100.0	Ambient Air - 0.2% CH4, 0.0% CO2, 21.9% O2, 77.9% BAL
CSU-L3-2 ft	2	30-Mar-21	15:20	1:00	0.2	0.1	21.8	77.9	100.0	Ambient Air - 0.1% CH4, 0.0% CO2, 21.9% O2, 78.0% BAL
CSU-L3-4 ft	4	30-Mar-21	15:22	1:00	0.2	0.2	21.8	77.8	100.0	Ambient Air - 0.2% CH4, 0.0% CO2, 21.9% O2, 77.9% BAL
CSU-L3-6 ft	6	30-Mar-21	15:23	1:00	0.2	0.5	21.5	77.8	100.0	Ambient Air - 0.2% CH4, 0.1% CO2, 21.9% O2, 77.8% BAL
CSU-L3-8 ft	8	30-Mar-21	15:25	1:00	0.5	2.6	18.6	78.3	100.0	Ambient Air - 0.2% CH4, 0.1% CO2, 21.8% O2, 78.0% BAL
CSU-L3-10 ft	10	30-Mar-21	15:28	1:00	2.5	6.3	13.7	77.5	100.0	Ambient Air - 0.2% CH4, 0.1% CO2, 21.7% O2, 78.1% BAL
CSU-L3-14 ft	14	30-Mar-21	--	--	--	--	--	--	--	BWT
GSI-L3-1 ft	1	30-Mar-21	15:09	1:00	0.3	0.2	22.2	77.3	100.0	Ambient Air - 0.0% CH4, 0.0% CO2, 22.4% O2, 77.6% BAL
GSI-L3-3 ft	3	30-Mar-21	15:13	1:30	0.2	1.3	17.6	80.9	100.0	Ambient Air - 0.2% CH4, 0.1% CO2, 22.1% O2, 77.8% BAL
GSI-L3-5 ft	5	30-Mar-21	15:14	1:00	0.2	1.4	18.1	80.3	100.0	Ambient Air - 0.2% CH4, 0.1% CO2, 21.8% O2, 77.9% BAL
GSI-L3-7 ft	7	30-Mar-21	15:16	1:00	0.2	1.4	15.1	83.3	100.0	
CSU-BG2-0.5 ft	0.5	30-Mar-21	16:03	1:00	0.2	0.0	21.8	78.0	100.0	Ambient Air - 0.3% CH4, 0.1% CO2 , 21.5% O2, 78.1% BAL
CSU-BG2-2 ft	2	30-Mar-21	16:04	0:45	0.2	0.3	21.4	78.1	100.0	Ambient Air - 0.2% CH4, 0.0% CO2, 21.8% O2, 78.0% BAL
CSU-BG2-4 ft	4	30-Mar-21	16:05	0:45	0.2	0.7	21.0	78.1	100.0	Ambient Air - 0.2% CH4, 0.0% CO2, 21.9% O2, 77.9% BAL
CSU-BG2-6 ft	6	30-Mar-21	16:07	0:45	0.2	1.0	20.8	78.0	100.0	Ambient Air - 0.2% CH4, 0.0% CO2, 22.1% O2, 77.7% BAL
CSU-BG2-8 ft	8	30-Mar-21	16:08	0:45	0.2	1.2	20.8	77.8	100.0	Ambient Air - 0.2% CH4, 0.0% CO2, 22.2% O2, 77.6% BAL
CSU-BG2-10 ft	10	30-Mar-21	--	--	--	--	--	--	--	BWT
CSU-BG2-14 ft	14	30-Mar-21	--	--	--	--	--	--	--	BWT
GSI-BG2-1 ft	1	30-Mar-21	16:12	0:45	0.2	0.3	21.7	77.8	100	Ambient Air - 0.2% CH4, 0.1% CO2, 22.4% O2, 77.3% BAL
GSI-BG2-3 ft	3	30-Mar-21	16:13	0:45	0.2	0.5	21	78.3	100	Ambient Air - 0.2% CH4, 0.0% CO2, 22.4% O2, 77.4% BAL
GSI-BG2-5 ft	5	30-Mar-21	16:15	0:45	0.2	2.9	11.6	85.3	100	Ambient Air - 0.2% CH4, 0.0% CO2, 22.4% O2, 77.4% BAL
GSI-BG2-7 ft	7	30-Mar-21	16:16	0:45	0.2	2.7	1.5	95.5	99.9	Ambient Air - 0.2% CH4, 0.1% CO2, 22.3% O2, 77.4% BAL
GSI-BG1-1 ft	1	30-Mar-21	16:21	0:45	0.2	0.2	22.4	77.2	100.0	Ambient Air - 0.2% CH4, 0.1% CO2, 22.4% O2, 77.4% BAL
GSI-BG1-3 ft	3	30-Mar-21	16:22	1:00	0.2	0.8	18.4	80.2	99.6	Ambient Air - 0.2% CH4, 0.1% CO2, 22.4% O2, 77.4% BAL
GSI-BG1-5 ft	5	30-Mar-21	16:24	1:00	0.2	0.8	19.2	79.8	100.0	--
GSI-BG1-7 ft	7	30-Mar-21	--	--	--	--	--	--	--	Not installed - Water table too high
GSI-L1-1 ft	1	30-Mar-21	--	--	--	--	--	--	0	Hard suction, not measured.
GSI-L1-3 ft	3	30-Mar-21	16:30	0:45	0.2	0.3	4.2	95.3	100.0	Ambient Air - 22.5% O2, 77.3% BAL
GSI-L1-5 ft	5	30-Mar-21	16:32	0:45	0.2	0.4	1.2	98.2	100.0	--
GSI-L1-7 ft	7	30-Mar-21	16:34	~ :45-1:00	0.2	0.5	2.5	96.7	99.9	Ambient Air - 0.2% CH4, 0.1% CO2, 22.3% O2, 77.5% BAL

Notes:

1. BWT = below water table
2. Stabilization criteria: No more than 5 minutes of purging per port was performed. Instrument values varied =<0.1% over a 10 second interval.
3. Generally, stabilization occurred within the first 30 seconds - 1 minute.

APPENDIX H: DATA TABLES AND LAB REPORTS
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Appendix H.5 TEAD-S Hourly Raw Temperature Data (degrees Celsius)
(*see attached supplementary spreadsheet*)

APPENDIX H: DATA TABLES AND LAB REPORTS
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Appendix H.6 TEAD-S Hourly Interpolated Temperature Data (degrees Celsius)
(*see attached supplementary spreadsheet*)

APPENDIX H: DATA TABLES AND LAB REPORTS
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Appendix H.7 MN ANGB Hourly Raw Temperature Data (degrees Celsius)
(*see attached supplementary spreadsheet*)

APPENDIX H: DATA TABLES AND LAB REPORTS
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Appendix H.8 MN ANGB Hourly Interpolated Temperature Data (degrees Celsius)
(*see attached supplementary spreadsheet*)

APPENDIX H: DATA TABLES AND LAB REPORTS
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Appendix H.9 TEAD-S Daily NSZD Rates (gallons/acre/year)
(*see attached supplementary spreadsheet*)

APPENDIX H: DATA TABLES AND LAB REPORTS

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Appendix H.10 MN ANGB Daily NSZD Rates (gallons/acre/year)

(*see attached supplementary spreadsheet*)

APPENDIX H: DATA TABLES AND LAB REPORTS

ESTCP ER19-5091

Appendix H.11 TEAD-S Hourly ORP Measurements (mV)

(*see attached supplementary spreadsheet*)

Appendix H.12 MN ANGB Hourly ORP Measurements (mV)

(*see attached supplementary spreadsheet*)