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Intelligent Monitoring of Methane at a Reclaimed Landfill Wasteland Transformed into a Valuable Public Park

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Abstract

Landfills are a necessity for the proper disposal of solid waste. However, when the landfill is closed and capped, the land is rarely used for any productive purpose. Overpeck Park in New Jersey was successfully transformed from a landfill wasteland to a public park. A methane monitoring system was designed to provide real-time information of methane leaks into any of the buildings (zones) to ensure corrective action. The installed system detected methane in one of the seven zones. Further scrutiny using cluster analysis confirmed the intermittent methane emissions to be associated with precipitation events, possibly due to moisture leaking into the capped landfill. The designed system successfully used telemetry to transmit methane detector activity to a centralized location (controller) which can send out notifications about any methane emission events. Furnishing the park management team with such information in a timely manner offers opportunities to mobilize corrective measures quickly. Besides landfills, the described gas monitoring technology has applications in other areas such as oil/gas extraction, mining, building complexes (e.g., dormitories and hotels), enclosed/underground parking lots, highway/subway tunnels, and wastewater treatment systems.

Keywords

Cluster Analysis, Gas Monitoring, Macurco, RSSI, TracXP Detector, Telemetry

1. Introduction

Landfills are a necessity to society for the proper disposal of solid waste. The United States has more than 2600 active and 10,000 closed landfills [1] [2]. Landfills reduce the amount of waste haphazardly disposed of into the environment, which in turn reduces disease transmission. However, landfills still have a significant environmental and social impact. Decomposing organic waste within the landfill environment undergoes anaerobic degradation due to microbial activity. This process occurs in the absence of oxygen, primarily two potent greenhouse gases (GHGs): methane (CH_4) and carbon dioxide (CO_2) among other products. The former is 84 times more effective at absorbing the sun's heat than carbon dioxide [3] [4]. This characteristic makes methane one of the most potent GHGs and a huge contributor to climate change. Until more recently, the effects of methane in the climate change conversation were overlooked. Reducing or eliminating methane emissions is an opportunity to effectively slow the rate of global warming, as we decarbonize our energy systems. Landfills contribute about 13% of global anthropogenic methane gas emissions into the atmosphere [5] [6]. When a landfill is capped, gases may still escape into the atmosphere through cracks and fissures. Little is known about where leaks of fugitive emissions of methane in closed landfills occur, and the best way to fix them. It is thus imperative to monitor capped landfills for potential gas migration and unintended release to identify and manage such emissions and minimize detrimental effects.

Minority and low-income areas tend to bear the brunt of landfills as they have fewer resources to oppose the placement of these facilities. This makes them an easier target for landfill placement than higher income areas. Furthermore, the presence of a landfill in the area can depress adjacent land values by 2.5% - 12.9% [7]. From a land use perspective, landfills can put large parcels of land out of active profitable use for several decades or even centuries once active landfilling operations cease. To that effect, most mature landfill spaces are deemed wasteland. When located in densely populated areas, pressures in such urbanscapes dictate the need for more space for development, justifying investments into regenerating such mature capped landfills. However, even after regeneration, uses for such spaces may be limited. One of the most viable uses of regenerated landfill space is greenery such as trails and public parks.

Increasing green areas in urban environments has a positive influence on urban dwellers, increasing their interaction with the living environment [8]. More specifically, parks enhance the quality of life by availing more venues for exercise, leisure, and social interaction. Parks can also increase property values, attract businesses, improve air quality, provide shade, cool cities prone to extreme heat and absorb storm water to reduce flooding and property damage [9]-[11]. Overpeck Park is a prime example of a public park that emerged from a landfill wasteland. Its history as a public nuisance and unsanitary site prior to capping and transformation into a public park was eloquently documented by [12]. Developing the landfill into a public park greatly increased the acreage of green land space for the peri-urban population, changing the urban derelict into a beneficial resource.

In general, the New Jersey Department of Environmental Protection (NJDEP) sets permitting requirements to ensure landfills are operated to minimize impact on waterfront development and avoid or minimize encroachment on streams. These steps are imposed to ensure clean air quality, control soil erosion, and control sediments [13]. Intricacies of remediation, capping and redevelopment of

Overpeck Park into the present-day public space are discussed elsewhere [14]-[17]. Currently, Overpeck Park, spanning nearly 800 acres, is one of the largest open spaces in this densely populated area [18]. As part of the monitoring requirements set by NJDEP, built structures on the reclaimed property must monitor methane. Thus, a methane monitoring system was installed and its functionality validated under the work reported herein.

2. Materials and Methods

2.1. Project Area

Overpeck Park is on the outskirts of New York City. The area is a highly urbanized region of Bergen County, New Jersey where the New Jersey Turnpike and I-80 intersect (**Figure 1(A)**). The park is in Zip Code 07660 and mainly serves residents from 10 other surrounding zip codes (**Figure 1(B)**). The zip codes occupy 29 square miles. At the time, total population in the zip codes was 236,397 and, depending on the zip code, population density ranged between 3686 people/sq. mile and 15,987 people/sq. mile (average 9777 people/sq. mile) (**Table 1**). The area was majority minority inhabited and considerably wealthy since median house values were, depending on zip code, \$370,300 to \$723,400. This observation contrasts with most instances where landfills tend to be placed in low-income areas. However, this must be interpreted in the context of the area having been settled by farmers and therefore historically less well-off compared to, back then, a vibrant New York City commercial neighborhood nearby. Median household incomes ranged between \$79,476 and \$137,847. The population was relatively middle aged (median age of 39 to 46) and household average size was 2 - 3 people. The community was quite active throughout the day as evidenced from area traffic into and out of the public park.

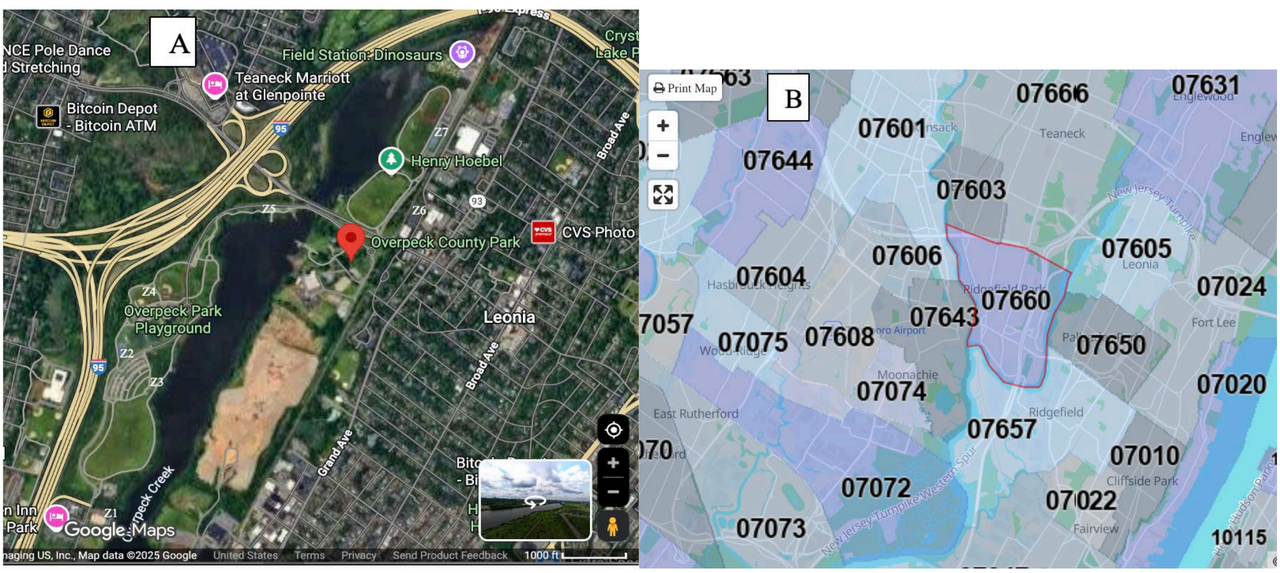

Figure 1. Location of Overpeck Park (Panel A) and collection of zip codes in its vicinity (Panel B). Note: Z1 to Z7 in panel A refer to Zone 1 - 7. Maps in the 2 panels are not on the same scale.

Visitor to the park enjoy walking trails, biking, various sports courts (for soccer, football, baseball, softball, tennis, pickleball), children's playgrounds, catch-and-release fishing, and picnic areas. The park also features an amphitheater, athletic fields, boating, and equestrian activities. It is open to the public from 6 am to 10 pm throughout the year.

Table 1. Statistics and demographic characteristics of the study area.

Zip Code	Neighborhood	Land area (Sq. Miles)[1]	Population	Population density	Median Home Value	Median Household Income	Median Age	Female	Race				Average Household Size
									White	Black	Asian	Other	
07660	Ridgefield Park	1.91	13,224	7757	$459,400	$98,184	40	51.9%	40%	6%	11%	43%	3
07650	Palisades Park	1.28	20,292	16,378	$704,400	$101,295	40	50.7%	16%	2%	59%	23%	3
07643	Little Ferry	1.67	10,987	7438	$388,500	$79,476	42	51.2%	41%	5%	25%	29%	2
07605	Leonia	1.61	9324	6186	$634,500	$115,476	44	48.9%	38%	2%	42%	18%	3
07606	S. Hackensack	0.76	2701	3686	$514,700	$82,750	39	51.7%	46%	6%	6%	42%	3
07603	Bogota	0.79	8778	11,632	$443,400	$107,321	40	52.1%	36%	8%	9%	47%	3
07601	Hackensack	4.36	46,030	10,965	$370,300	$82,212	40	51.0%	29%	22%	10%	39%	2
07666	Teaneck	6.24	41,246	6828	$496,400	$131,311	41	52.6%	43%	24%	11%	22%	3
07631	Englewood	4.97	29,308	5925	$497,500	$101,398	40	52.6%	34%	26%	10%	30%	3
07024	Linwood/Fort Lee	2.85	40,171	15,987	$422,200	$105,594	46	53.0%	41%	3%	42%	14%	2
07020	Fort Lee	2.43	14,336	14,763	$723,400	$137,847	40	52.7%	44%	6%	35%	15%	2
Total [Average][2]		**28.87**	**236,397**	**[9776.8]**	**N/A**[3]	**N/A**	**N/A**	**[51.7%]**	**[37.1%]**	**[10.0%]**	**[23.6%]**	**[29.3%]**	**N/A**

Note: [1]Includes waterways; [2][] represents average value; [3]N/A=Not applicable. Source: URL https://www.unitedstateszipcodes.org/ (accessed 03/16/2025).

2.2. Methane Detection Equipment and Installation

Park management identified a need for several methane detectors in each of the seven (7) buildings on the premises. For purposes of this project, the buildings were coded as Zones 1 through 7. The monitored spaces in each building (zone) generally included mechanical rooms, a workshop area, public restrooms, storage rooms, lunchrooms, office spaces, and dressing rooms. Depending on the size and usage of the building, the number of detectors manufactured by Macurco Gas Detection Inc. (Model Macurco TXP_T40) installed in each building ranged between 3 and 10. The TracXP TXP-T40 combines multiple sensor types, including electrochemical, catalytic bead, and infrared sensing technologies, for Class 1, Division 1, or Division 2 toxic and combustible area gas monitoring.

Within Zones 2 - 7, individual detectors were connected in a daisy chain fashion (**Figure 2**) using 18/3 low voltage cable shielded (Cat# 5628; Syston Cable, Chino, CA USA). The first detector in each series within the zone was ultimately connected to a Wireless Modbus Stick (WBS; Cat# MBS-CBBL, SignalFire Wireless Telemetry, Marlborough, MA, USA; Figure 3(A)) using a 3 Cond 18 Gauge shielded wire (Cat# E2203S.30.86; Carol Prysmian Group, Manchester, NH, USA). The manufacturer guidelines outlined under Figure 2 legend notes were followed to ensure robust communication between the WBS and the Wireless Gateway Stick (WGS). For each zone, the WBS was mounted on the rooftop to facilitate wireless communication with a Macurco TXP-C64 (N4X, FIB, DUAL RS-485 PORTS, COM REL, C1D2; (Cat# 88-7000-0300-00)) controller located in Zone 1 at the southwestern end of the park. The controller was pre-configured and housed in a TXP-C64 analog (16) input board. The roof of the building in Zone 1 where the controller was located accommodated 4 wireless gateway stick (WGS; Cat# GWS-CBBL, SignalFire Wireless Telemetry, Marlborough, MA, USA; Figure 3(B)). On the roof, the wireless gateway sticks were installed 6 ft (1.8m) apart to facilitate communication between the 6 WBS in Zone 2 - 7 and the controller in Zone 1 (Figure 4). The gateway sticks were connected to the controller as presented in the wiring diagram (Figure 5). Likewise, the notes following Figure 5 legend provided guidance to ensure robust communication between the WBS and WGS.

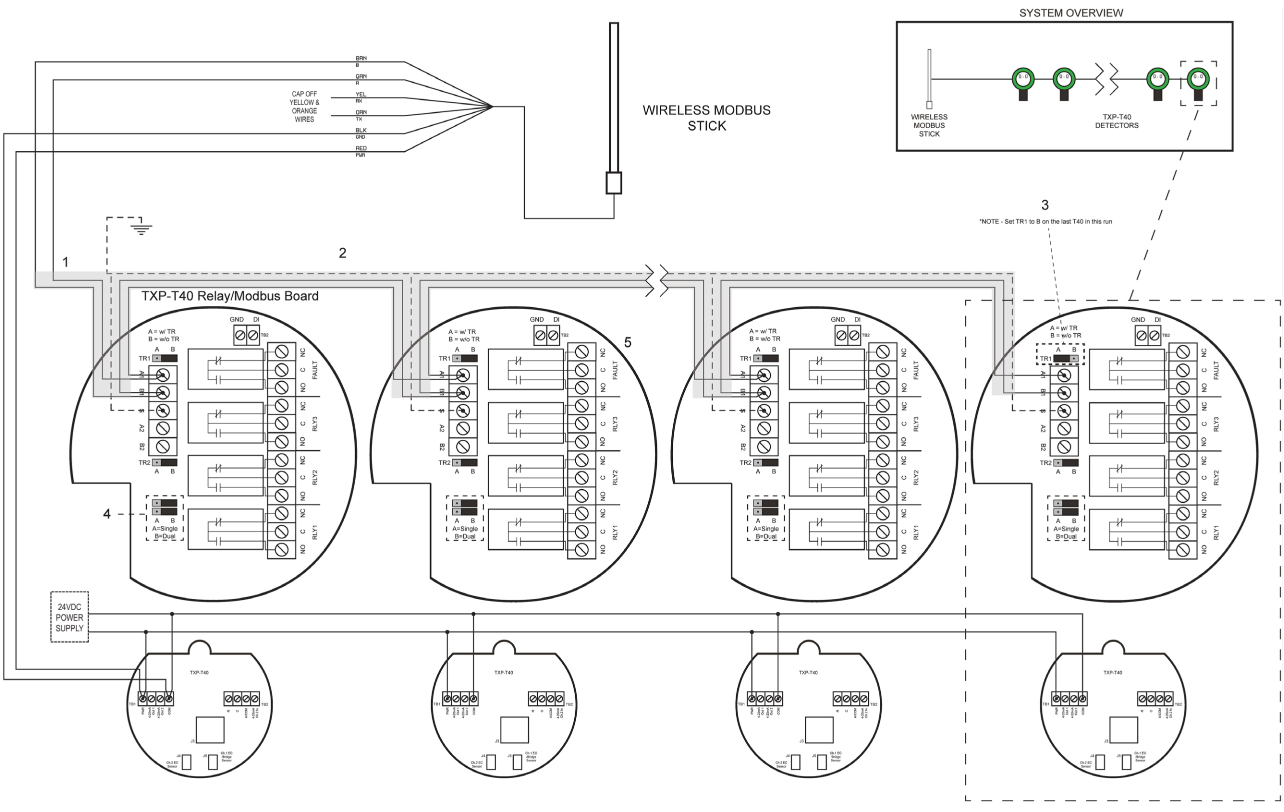

Figure 2. Daisy chain wiring of T40s (**Notes:** 1. Showing typical 2 wire Modbus RS-485 connection from TXP-T40s to Wireless Modbus Stick. The T40s must be set to SLAVE. 2. Wiring must be a 2 wire twisted pair with shield. Sheild should be landed on the "S" terminal at the TXP-T40 Relay/Modbus Boards. 3. Modbus RS-485 loop can continue to the next device otherwise it needs to be terminated at the last T40 via the TR1/TR2 jumpers in the A position. 4. Jumpers need to be set to position B (Dual Channel) to allow each preceding T40's channel information to pass through the loop to the Wireless Modbus Stick. 5. TXP-T40 Relay/Modbus Board must be specified to connect the T40 to the Wireless Modbus Stick using Modbus RS-485).

Four WGS were deemed necessary because the manufacturer recommended transmission of only 60 packets per minute per gateway device. This value practically limited the number of detectors per gateway stick. During the designing phase, the manufacturer tested a rate of 5 packets per minute from a TXP-T40 transmitter and estimated the requirement of no more than 12 gas detectors per gateway stick. Since the whole project comprised 41 detectors, it was estimated each Modbus data wireless would require 4 gateway sticks. The technical specifications for WBS and WGS are presented in Table 2.

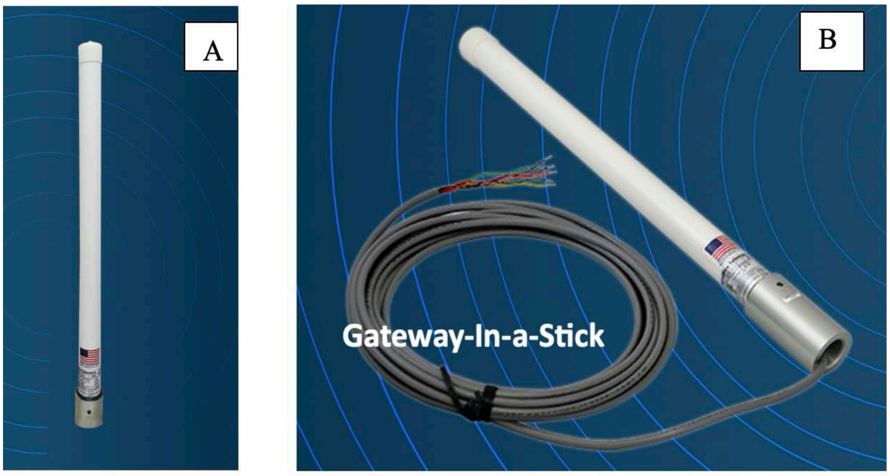

Figure 3. SignalFire Modbus antenna (Panel A) and Gateway stick (Panel B) used at Overpeck Park.

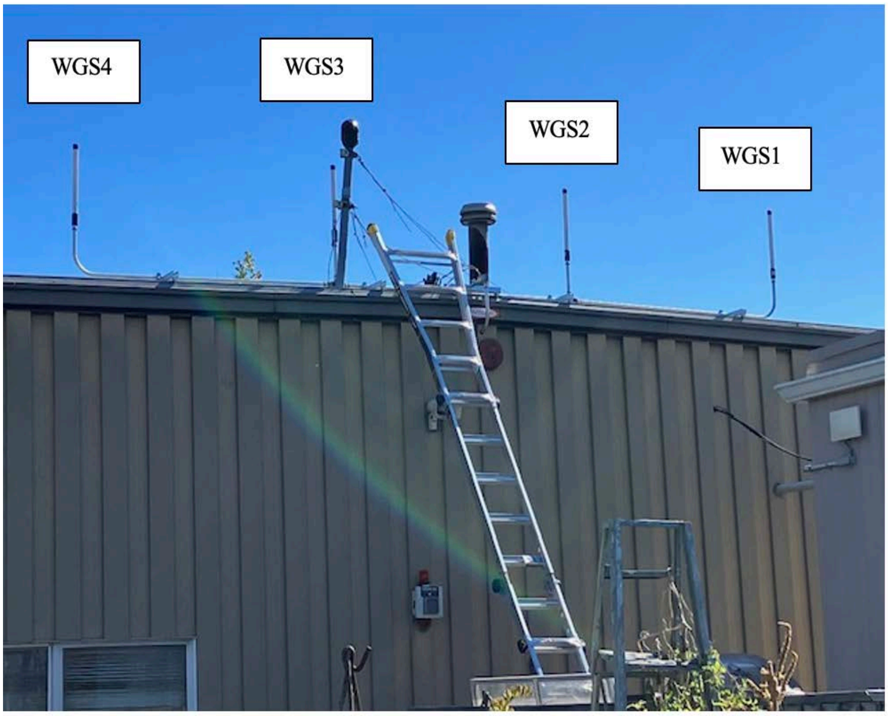

Figure 4. Layout of the 4 gateway sticks on top of the building (Zone 1) where the controller is located.

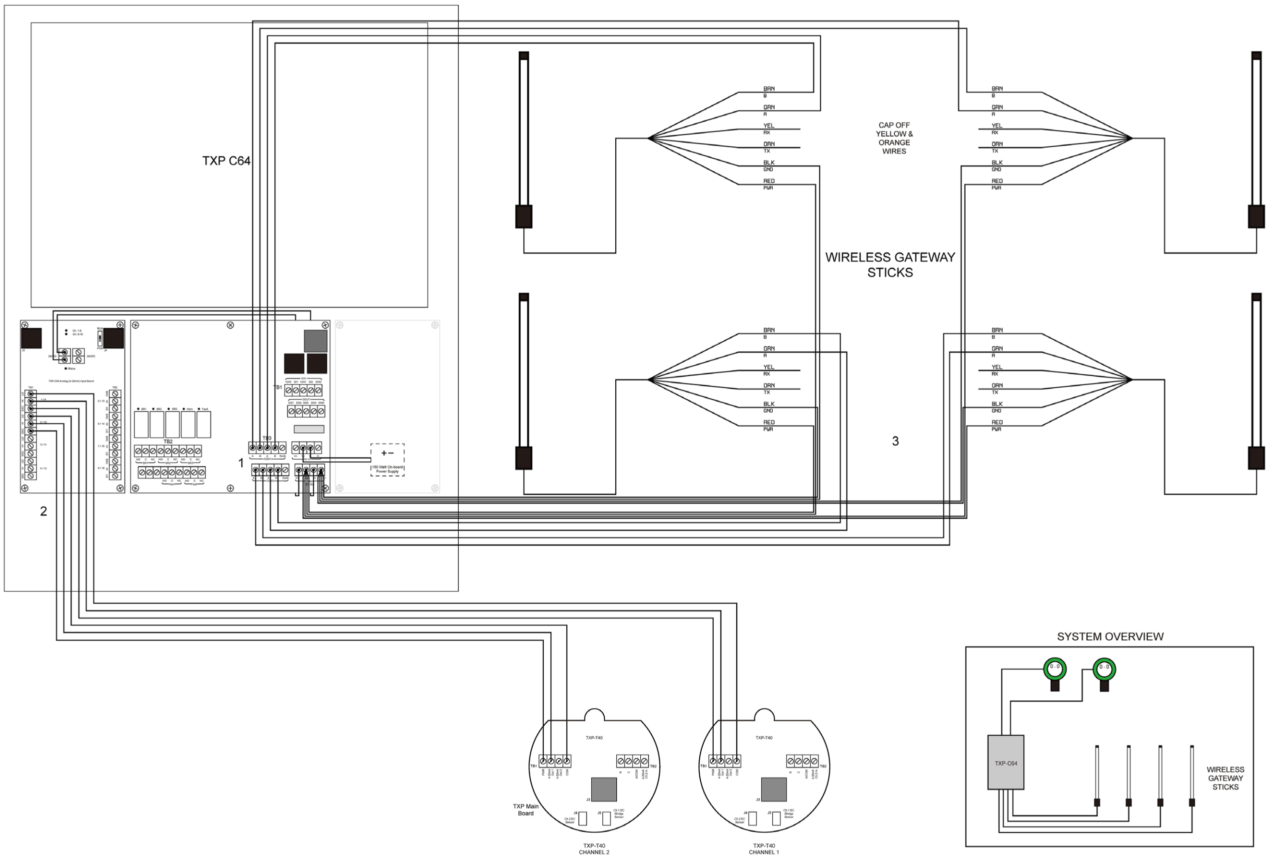

Figure 5. Wiring diagram of four gateway sticks on the Zone 1 roof connection to the controller. (**Notes:** 1. Two wireless Gateway Sticks to each com port. 2. Two local TXP-T40s connected through analog 4 – 20 mA to the Analog Input Board. 3. In this configuration, the Gateway/Modbus Breakout boards are not shown. They were connected later for diagnostic purposes – see Figure 9(B)).

Table 2. Manufacturer-specified technical specifications for the Gateway and Modbus stick.

Attribute	Modbus stick	Gateway antenna
Operating temperature	−40˚C to 70˚C	−40˚C to 85˚C
Humidity	0% - 100%	0% - 100%
Power	6 - 36 VDC	6 - 36 VDC
Data interface	Modbus RS-485	RS-485 Modbus RTU. All readings converted to Modbus registers and stored in the gateway
Data updated rates	User configurable with configuration utility	N/A
Radio power	500 mW	500 mW
Antenna type	Omnidirectional	Omnidirectional
Antenna gain	5 dB	5 dB
Receive sensitivity	−105 dB	−105 dB
Frequency	902 - 928 MHz license-free ISM band compliant with FCC Part 15	902 - 928 MHz license-free ISM band compliant with FCC Part 15
Range	3+ miles (*i.e.*, 15,840 ft; 4.8 km; line of sight)	Typically, 3 miles (*i.e.*, 4.8 km; 15,840 ft); much further with careful placement
Networks	Up to 65,520 separate networks	Up to 64 separate networks

Continued

Enclosure	Weather-tight, integrated electronics and antenna. Integrated cable (25' standard)	Weather-tight, integrated electronics and antenna NEMA 3R (GW stick)
Safety rating	Class 1 Division 2 certified Groups C and D, Temperature Code T5, certified to CSA C22.2 No. 213, Conforms to ISA 12.12.01	Non-invasive, Class 1 Division 2 Groups C and D
Internal diagnostics	Line voltage, Signal Strength, Error conditions	Line voltage, Signal Strength, Error conditions, Internal event logging

2.3. Electrical Mains Step-Down and Horn/Strobe Installation

Within each building (*i.e.*, zone), the system required 12 - 24V DC. The electric power mains were stepped down from 115 V to 12 VDC or 24 VDC using a multi-point system MAC6Amp-4-115VAC, 60 Hz Power Supply-10 Amp or MAC10Amp-4-115VAC, 60 Hz Power Supply-6 Amp (Manufacturer: Altronix® Brooklyn, NY, USA) unit, respectively. For each building, a horn/strobe TXP-Combo alarm red strobe, 103 - 115 DB horn, 12 - 24 VDC, IP65, GP (Cat# 93-9926-R000-10) and TXP-Combo alarm base, 12 - 24 VDC, IP65 (Cat# 93-9926-0000-12) was installed on top of the controller in Zone 1 or on top of the power supply unit (PSU) at each of the 6 buildings (*i.e.*, Zones 2-7). The horn/strobe was wired as presented in Figure 6. The horn/strobe combo was programed to be triggered whenever methane levels exceeded a specified setpoint on any of the methane detector in the daisy chain connected to the system within the respective zone.

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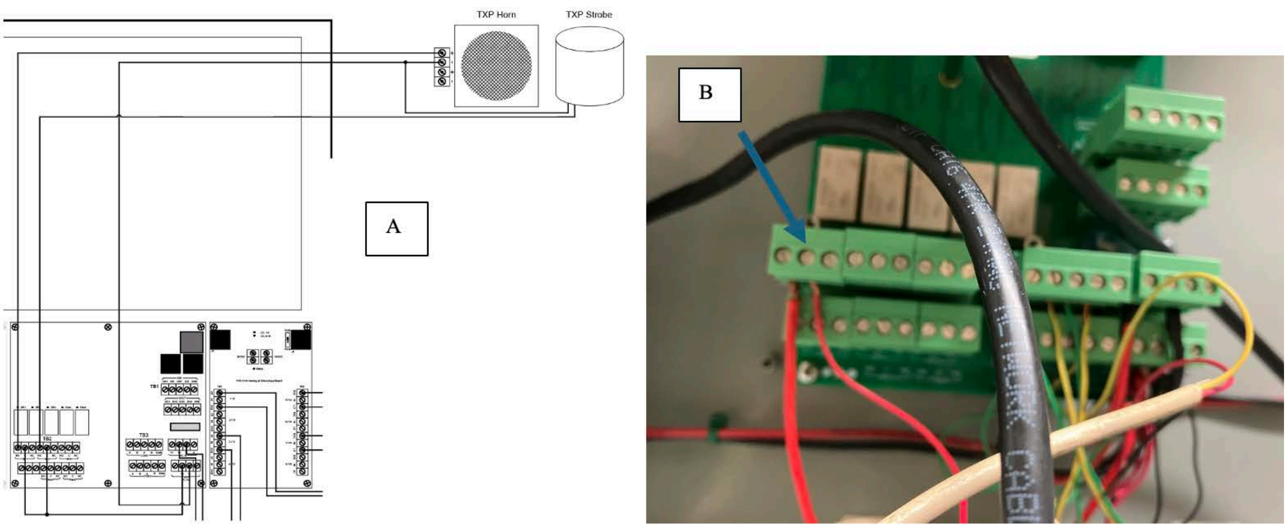

Figure 6. Horn/strobe wiring schematic (A) and landing location on the controller (B).

2.4. Electrical and Communication Wiring

Within each building, electric and communication cable was installed to accommodate the methane detector system design and manufacturer specifications. Most of the wire installation was through electric conduit pipe to the ceiling and similar confined spaces per electrical code requirements (Figure 7(A) and Figure 7(B)). Final connection to the respective detector included connecting electric power not only to the detector base but also to the display board (Figure 7(C)). Once completed, the system at each building was powered on to display the detector home screen (Figure 7(D)).

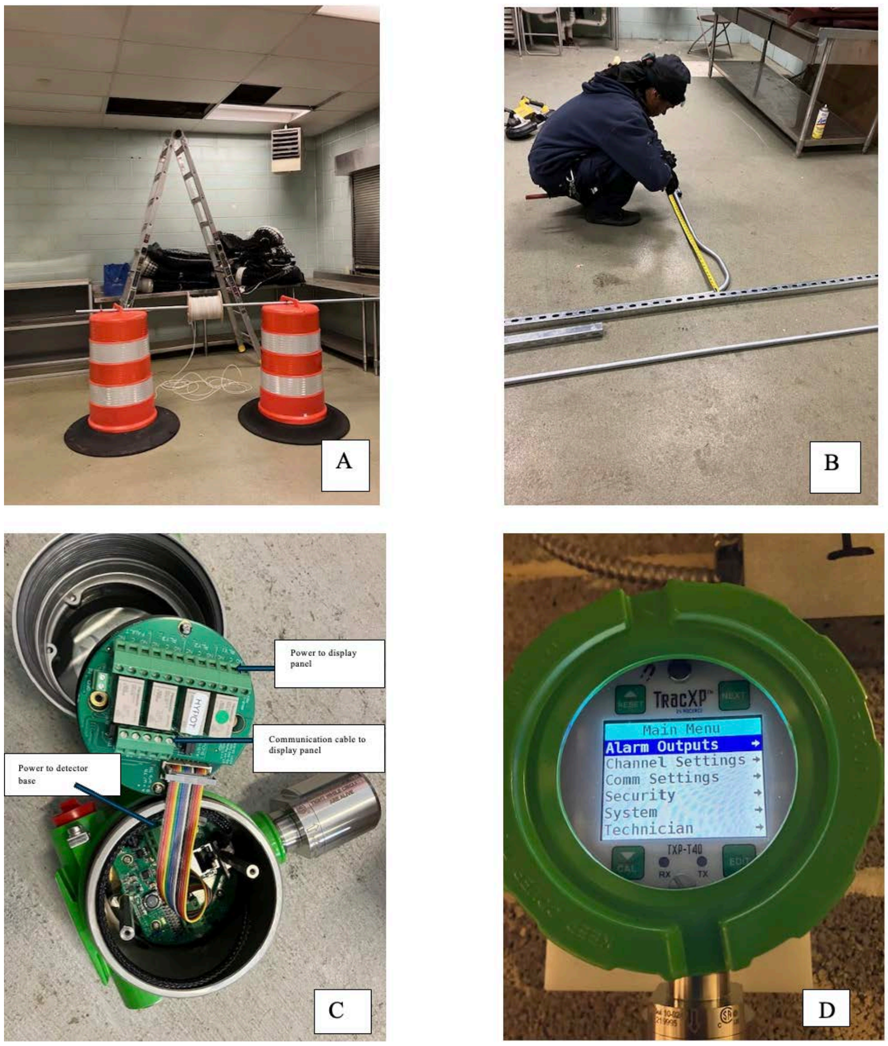

Figure 7. Wiring in each building (Panels A and B) and the connection points on each detector (C) in the daisy chain to attain complete electrical and communication circuitry (D).

2.5. Splash Guard Installation

A splash guard with a calibration port (p/n 88-C50G-0000-00) was installed on each methane detector prior to mounting the detector in place. Figure 8 displays the geometry of the detector-splash guard fitting. As is evident from the geometry, air movement around and into the sensor housing is unimpeded, even when the splash guard is fitted on the detector. Because the methane detectors were mounted at 2.7 m (9 ft) or higher, each detector had a dedicated splash guard to make routine bump testing and calibration exercises conveniently manageable.

Figure 8. Geometry around the sensor when the splash guard is inserted.

2.6. Equipment Programming

Although most programming was conducted by the manufacturer prior to shipping the equipment, some adjustments had to be made to suit local/field conditions. All necessary adjustments were done following manufacturer specifications as outline in the Comprehensive TracXP TXP-C64 Manual and TracXP-TXP-T40 Manual. After installation, each detector was bump tested with a methane gas standard (CH_4 2.5% volume; 50%LEL; Macurco Gas Detection Inc.). The same standard gas was also used to calibrate each unit as specified by the manufacturer.

2.7. Electronic Notification and Signal Strength Determination

Using a CAT5 cable, the C64 controller was connected to the internet and programmed to transmit email notifications to several addresses. The email system was configured by logging into the device (based on IP address). The process provided a replica of controller functions on the laptop, enabling the desired programming including email recipient addresses and types of notifications using the menu ribbon (Figure 9(A)). A breakout board was installed between each gateway stick and the controller (Figure 9(B)). A USB DB25 cable was plugged into each breakout board and connected to a laptop to determine signal strength using the SignalFire Toolkit (Singal-Fire.com).

2.8. Methane Detection Equipment and Installation

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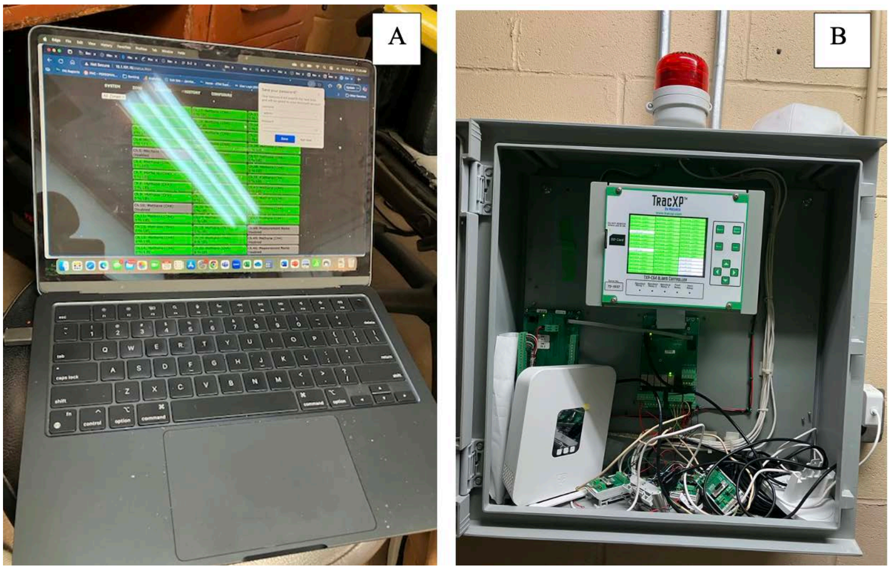

Figure 9. Replica of the controller displayed on a laptop screen after connecting for further programming (A). Four breakout boards corresponding to the 4 gateway sticks were installed at the controller for diagnostic purposes (B).

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2.9. Gas Detection Events

In instances where gas was detected, the horn/strobe was triggered (see Results Section). These events led to short-term decisions manually power off the detectors in the affected building (*i.e.*, zone) pending development of a proper response plan. The power shutdowns mostly coincided with precipitation events. Thus, rainfall data for a consecutive 108 days (*i.e.*, March 6th 2025 to June 22nd 2025) from nearby Teterboro Airport (Zip Code 07608) reported by NOAA (Climate.gov; accessed August 12th 2025) were retroactively compiled to further investigate the suspected environmental circumstances triggering the detected methane emissions. The TRX-T40 event log over the corresponding duration was retrieved by scrolling to the "System" function of the triggered detector. Under this function, each detector registers all the status changes and archives them by date and event type. The detector also tracks all "Sys boot" events each time the detector is powered on. However, it does not show how long the detector stays powered off. The archived information was used to develop a potential theory, based on cluster analysis, behind the intermittent gas emissions detected.

2.10. Cluster Analysis

The Clustering is a powerful widely used tool in pattern recognition. Rainfall data and methane emission events at the location in question were coded as summarized in Table 3. The dates between 3/6/2025 to 6/22/2025 without a rainfall event were coded with NR (no rain) whereas those with a rainfall event were identified with an R as part of the ID. For each date, 10 variables/characteristics were annotated, resulting in a 10-digit algorithm comprised of "0" or "1". More specifically, if the variable in Table 3 occurred/applied, a value of "1" was assigned whereas if it did not occur/apply for that specific date, the variable was assigned a zero (0). For example, if on date designated by month/date/2025 had no rain (*i.e.*, NoRain) and none of the other variables listed in Table 3 applied, mm/dd/2025 algorithm was constructed of 1 (for NoRain) followed by 9 zeros: ending up with 10 digits. The resulting 10-digit algorithm for each day was subjected to cluster analysis (genomes.urv.cat/UPGMA) using Peason correlation coefficient (r) to generate the distance (d) values whereby:

$$d = (1 - r) \times 100 \quad (1)$$

The output dendrogram was exported to https://itol.embl.de/ for further analysis.

Table 3. Description of the identifier and variables used.

No.	Variable	Description
1	NoRain	No rain event
2	LoRain	Less than 0.5" (12.7 mm) rainfall
3	HvyRain	0.5" (12.7 mm) rainfall or greater
4	1DHvyCum	Cumulative rain over 2 days was 0.5" (12.7 mm) or greater
5	2DHvyCum	Cumulative rain over 3 days was 0.5" (12.7 mm) or greater
6	ALOnsite	Strobe/horn physically reported to go off (Note: Not all were reported to the data collector before power supply was turned off)
7	EmailLoCode	Notification sent but %LEL was less than 10 (below strobe/horn threshold)
8	EmailHiCode	Notification sent, and reading was at least 10%LEL (enough to trigger strobe/horn)
9	Al1Code	Alarm level 1 detector data log (archive) captured strobe/horn was triggered due to 10%LEL
10	Al2Code	Alarm level 2 detector data log (archive) captured levels reached 20%LEL or higher

3. Results and Discussion

Considering the population of the area served by the park, per capita cost of installing the monitoring system was less than $1.50. Local parks provide a wide range of benefits to communities, including opportunities for physical activity, social interaction, positive human development, connection to nature as well as mental and emotional rejuvenation [19] (NRPA, 2025). These attributes provide a unique ability to develop and grow social capital in communities; serving as social hubs, offering spaces for people to enjoy activities that build bonds, contributing to physical and community wellbeing. Larson *et al.* [20] (2016) reported a strong predicator of overall wellbeing with increased percentage of city area covered by public parks. The successful transformation of the area into a premier public park was lauded by Macur [21] (2012).

Figure 10 summarizes how the monitoring system functions whereby the Modbus sticks at each of the 6 zones communicates with the corresponding Gateway stick in Zone 1. The installed system showed tremendous ability to sense even the lowest levels of methane for all 41 detectors as evidenced from bump tests and calibration initial (Table 4). During bump testing, a very brief exposure of methane gas to the detector correctly verified whether the sensors and alarms respond in real time, serving as a function check. Bump testing did not measure accuracy of the detector but rather instilled confidence in the ability of all 41 the detectors to recognize and respond when methane was applied. By contrast, calibration involved exposing the sensor to the methane standard at a specific concentration and the detectors in calibration mode for the device to read that gas concentration properly. Calibration ensured that the readings provided by the detector were accurate and reliable.

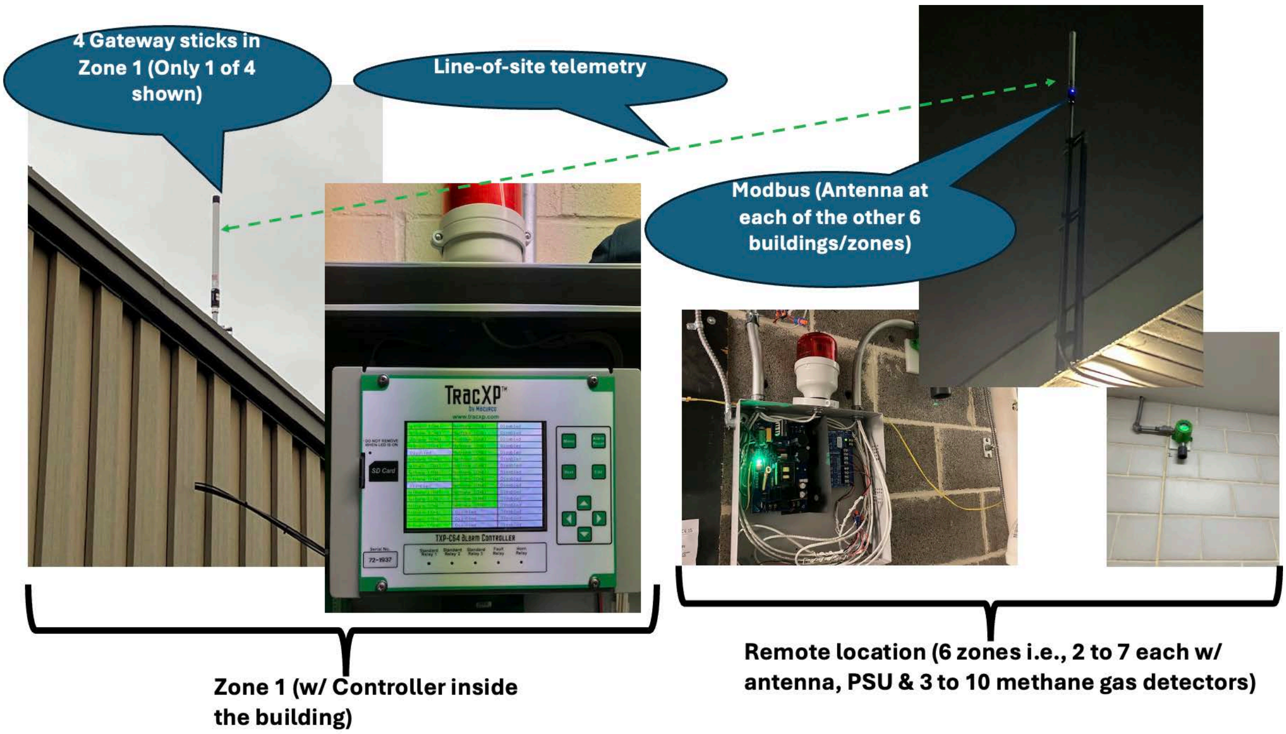


Figure 10. Functionality of the installed Overpeck Park methane detection and monitoring system (Note: PSU = Power supply unit).

3.1. Trigger Setpoints and Alarm Incidents

At the controller, the alarms were set at 2% lower explosive level (LEL) (Table 4). The same setpoint was also initially adapted at each detector. Over time, only one (*i.e.*, Channel 11) in Zone 2 out of 41 detectors registered any methane emissions. None of the other 7 detectors in Zone 2 were activated, which suggested the emissions were localized to only one specific room within the building where Channel 11 was located. The room has a drainage pipe and a few cracks or fissures which may potentially allow the gas to seep into the room. The room is next to a parking lot with sewer drains from which methane was previously detected (Figure 11).

Even then, emissions in the room where Channel 11 is located were detected during or shortly after precipitation events.

Table 4. Bump test, calibration and signal strength for 41 detectors around the park.

					Calibration		Alarm trigger setpoint at							
Zone (Building)	Corresponding Gateway Stick	Approximate distance from controller in meters (Feet)	Channel#	Bump test	Span calibration	Span found	Controller	Detector	RSSI (dBm)[a]	Battery Voltage (V)	Check-in Interval	TTL (min): Current/Max[b]	Mainboard Firmware	Radio Firmware
1	N/A	0	1	✓	48%	49%	2%LEL	2%LEL	N/A[c]	N/A	N/A	N/A	N/A	N/A
			2	✓	44%	48%	2%LEL	2%LEL	N/A	N/A	N/A	N/A	N/A	N/A
2	GW1	762 (2500)	3	✓	45%	49%	2%LEL	2%LEL	−69	28.614	1 min	6/7	0.83	2.52
			4	✓	44%	50%	2%LEL	2%LEL	−69	28.614	1 min	6/7	0.83	2.52
			6	✓	43%	48%	2%LEL	2%LEL	−69	28.614	1 min	6/7	0.83	2.52
			7	✓	49%	50%	2%LEL	2%LEL	−69	28.614	1 min	6/7	0.83	2.52
			8	✓	47%	50%	2%LEL	2%LEL	−69	28.614	1 min	6/7	0.83	2.52
			9	✓	43%	49%	2%LEL	2%LEL	−69	28.614	1 min	6/7	0.83	2.52
			11	✓	43%	47%	2%LEL	**10%LEL**[d]	−69	28.614	1 min	6/7	0.83	2.52
			12	✓	43%	50%	2%LEL	2%LEL	−69	28.614	1 min	6/7	0.83	2.52
3	GW2	732 (2400)	13	✓	43%	51%	2%LEL	2%LEL	−59	26.277	1 min	7/7	0.83	2.52
			14	✓	47%	48%	2%LEL	2%LEL	−59	26.277	1 min	7/7	0.83	2.52
			15	✓	44%	48%	2%LEL	2%LEL	−59	26.277	1 min	7/7	0.83	2.52
			16	✓	39%	50%	2%LEL	2%LEL	−59	26.277	1 min	7/7	0.83	2.52
			17	✓	46%	48%	2%LEL	2%LEL	−59	26.277	1 min	7/7	0.83	2.52
			18	✓	46%	51%	2%LEL	2%LEL	−59	26.277	1 min	7/7	0.83	2.52
4	GW2	3500 (1067)	19	✓	44%	50%	2%LEL	2%LEL	−73	26.233	1 min	7/7	0.83	2.52
			20	✓	43%	48%	2%LEL	2%LEL	−73	26.233	1 min	7/7	0.83	2.52
			21	✓	46%	49%	2%LEL	2%LEL	−73	26.233	1 min	7/7	0.83	2.52
			22	✓	44%	48%	2%LEL	2%LEL	−73	26.233	1 min	7/7	0.83	2.52
			23	✓	46%	49%	2%LEL	2%LEL	−73	26.233	1 min	7/7	0.83	2.52
			24	✓	46%	49%	2%LEL	2%LEL	−73	26.233	1 min	7/7	0.83	2.52
			25	✓	46%	48%	2%LEL	2%LEL	−73	26.233	1 min	7/7	0.83	2.52
			26	✓	47%	48%	2%LEL	2%LEL	−73	26.233	1 min	7/7	0.83	2.52
5	GW3	1890 (6200)	27	✓	47%	50%	2%LEL	2%LEL	−53	13.214	1 min	6/7	0.83	2.52
			28	✓	44%	49%	2%LEL	2%LEL	−54	13.214	1 min	6/7	0.83	2.52
			29	✓	46%	49%	2%LEL	2%LEL	−54	13.214	1 min	6/7	0.83	2.52

Continued

6	GW3	1646 (5400)	30	✓	47%	49%	2%LEL	2%LEL	−86	13.040	1 min	6/7	0.83	2.52
			34	✓	46%	50%	2%LEL	2%LEL	−86	13.040	1 min	6/7	0.83	2.52
			33	✓	45%	50%	2%LEL	2%LEL	−82	13.040	1 min	6/7	0.83	2.52
			32	✓	48%	49%	2%LEL	2%LEL	−83	13.040	1 min	6/7	0.83	2.52
			31	✓	45%	49%	2%LEL	2%LEL	−76	13.040	1 min	6/7	0.83	2.52
7	GW4	2682 (8800)	35	✓	44%	45%	2%LEL	2%LEL	−92	25.984	1 min	6/7	0.83	2.52
			36	✓	44%	49%	2%LEL	2%LEL	−89	26.125	1 min	6/7	0.83	2.52
			37	✓	46%	50%	2%LEL	2%LEL	−89	26.125	1 min	6/7	0.83	2.52
			38	✓	45%	49%	2%LEL	2%LEL	−89	26.125	1 min	6/7	0.83	2.52
			39	✓	41%	37%	2%LEL	2%LEL	−89	26.125	1 min	6/7	0.83	2.52
			40	✓	48%	48%	2%LEL	2%LEL	−89	26.125	1 min	6/7	0.83	2.52
			41	✓	41%	45%	2%LEL	2%LEL	−89	26.125	1 min	6/7	0.83	2.52
			42	✓	47%	50%	2%LEL	2%LEL	−92	25.984	1 min	6/7	0.83	2.52
			43	✓	47%	48%	2%LEL	2%LEL	−92	25.984	1 min	6/7	0.83	2.52

[a]RSSI = Received signal strength indicator; [b]TTL = Transistor-Transistor Logic; [c]N/A = Not applicable; [d]%LEL setpoint adjusted as to minimize routine activity interruption around the location due to strobe/horn (see details under Results and Discussion).

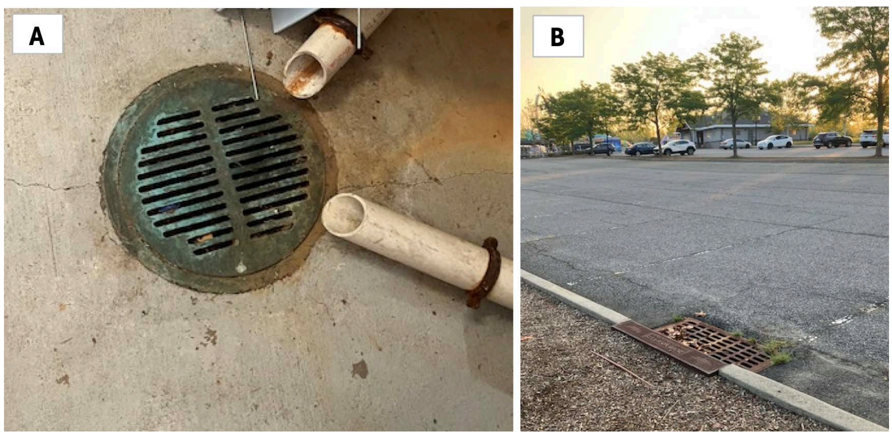


Figure 11. Floor drainage where Channel 11 is located (A) and in nearby parking lot with a history of methane emission (B).

To minimize disruption of park activities, the horn/strobe in Zone 2 was set to go off whenever more than 10%LEL methane was detected. This is as opposed to all the other detectors set at 2%LEL. It is worth noting that email notifications at the controller were left unchanged for Channel 11, set to dispatch email notifications above 2%LEL, just like all the other detectors in the same zone network.

Methane generation in landfills is a biological process that needs moisture [22]. Thus, moisture availability is an important factor in promoting waste decomposition. It is very likely that once water from rainfall (or snow) events somehow seeped into the capped waste underneath, the anaerobic biological was initiated, and the resulting fugitive gases migrated through fissures (or drainage system infrastructure) to the room in question. This conjecture as a plausible explanation for the intermittently detected methane in Zone 2; confined to Channel 11 was further scrutinized using cluster analysis. A subset of the dates and corresponding variable-based algorithms used for the analysis for 108 consecutive days showing the first 4 days and last the last day is shown in **Table 5**. Whereas heavy rainfall at or more than 12.7 mm (0.5 inches) occurred on 10% of the days, lower levels of rainfall were registered 32% of the days. No rainfall was recorded for 59% of the days in the 108 days duration. However, because rainfall effects can linger over time, even another 21% or 32% of days with low or no rainfall were cumulatively impacted over a 1 to 2 days duration as though they had received heavy rainfall. For cluster analysis, this latter was coded 1DHvyCum and 2DHvyCum, respectively. For Channel 11, email notifications about methane emission higher than the setpoints (*i.e.*, >2%LEL at the controller and/or >10%LEL at the detector) was documented on 17 days (*i.e.*, 16% of the days monitored). By comparison, archived information at the Channel 11 detector was triggered on 23 days (*i.e.*, 21% of the days monitored). Occasionally, (*i.e.*, 6 of the 23 days), the emission levels triggered the second level alarm (Al2 code) which signified emissions as high as 20%LEL.

Table 5. Sub-sample of the algorithm based on preset variables in **Table 3**.

Code	NoRain	LoRain	HeavyRain	1DHvyCum	2DHvyCum	ALOnsiteDocCode	EmailLoCode	EmailHiCode	Al1 Code	Al2 Code
03062025R	0	0	1	1	1	1	0	1	1	1
03072025NR	1	0	0	1	1	0	0	0	0	0
03082025NR	1	0	0	0	1	0	0	0	0	0
03092025NR	1	0	0	0	0	0	0	0	0	0
06222025NR	1	0	0	0	0	0	0	0	0	0
Total	**64**	**34**	**11**	**23**	**35**	**7**	**15**	**2**	**23**	**6**
Percent	**59.3%**	**31.5%**	**10.2%**	**21.3%**	**32.4%**	**6.5%**	**13.9%**	**1.9%**	**21.3%**	**5.6%**

Note: Column 1 represents mm/dd/2025 whereby mm=month, dd = day of month, R = Rain and NR = No rain.

The analysis revealed 25 clusters (**Figure 12**). At least 15 clusters were associated with days on which methane was detected.

- Clusters with a solid red box are when the gas was detected as evidenced from strobe/horn, email notification and/or Channel 11 detector data log archive.
- Most methane emission incidents were on days with a heavy rainfall event (Cluster 1-4), low rainfall levels preceded by high rainfall events (Cluster 6), or with cumulative rainfall higher than 0.5 inches (12.7 mm) in 1-2 days after a rainfall event (Cluster 9-15).
- Cluster 17, 18, 20, 22, 23, and 24 comprised days without rain but followed cumulative rainfall of 0.5 inches (12.7 mm) or higher within a 1- to 2-day duration.
- Clusters 5, 7, 8, 19, and 21 represent inconclusive results as included days had all the characteristics of triggering the strobe/horn, but the electrical power had been turned off, disabling comprehensive data collection by the installed system. This

is a key limitation which necessitates the system operators to develop a proper protocol for addressing alarm incidents instead of just shutting off the system.

The actual impact of methane detected inside the room in Zone 2 (Channel 11) is not completely clear as not much information about acceptable methane indoors is available in published literature. When measuring combustible gases such as methane, we use a slightly different scale; the lower explosive level (LEL). Overall, the explosive level for methane is 5% by volume (5% bv). The mixture is too lean to burn if less than 5% methane is present. But at 5%, methane can burn or explode if there is an ignition source. EPA Victoria [23] developed guidelines on action levels for methane at different monitoring locations in landfills (**Table 6**).

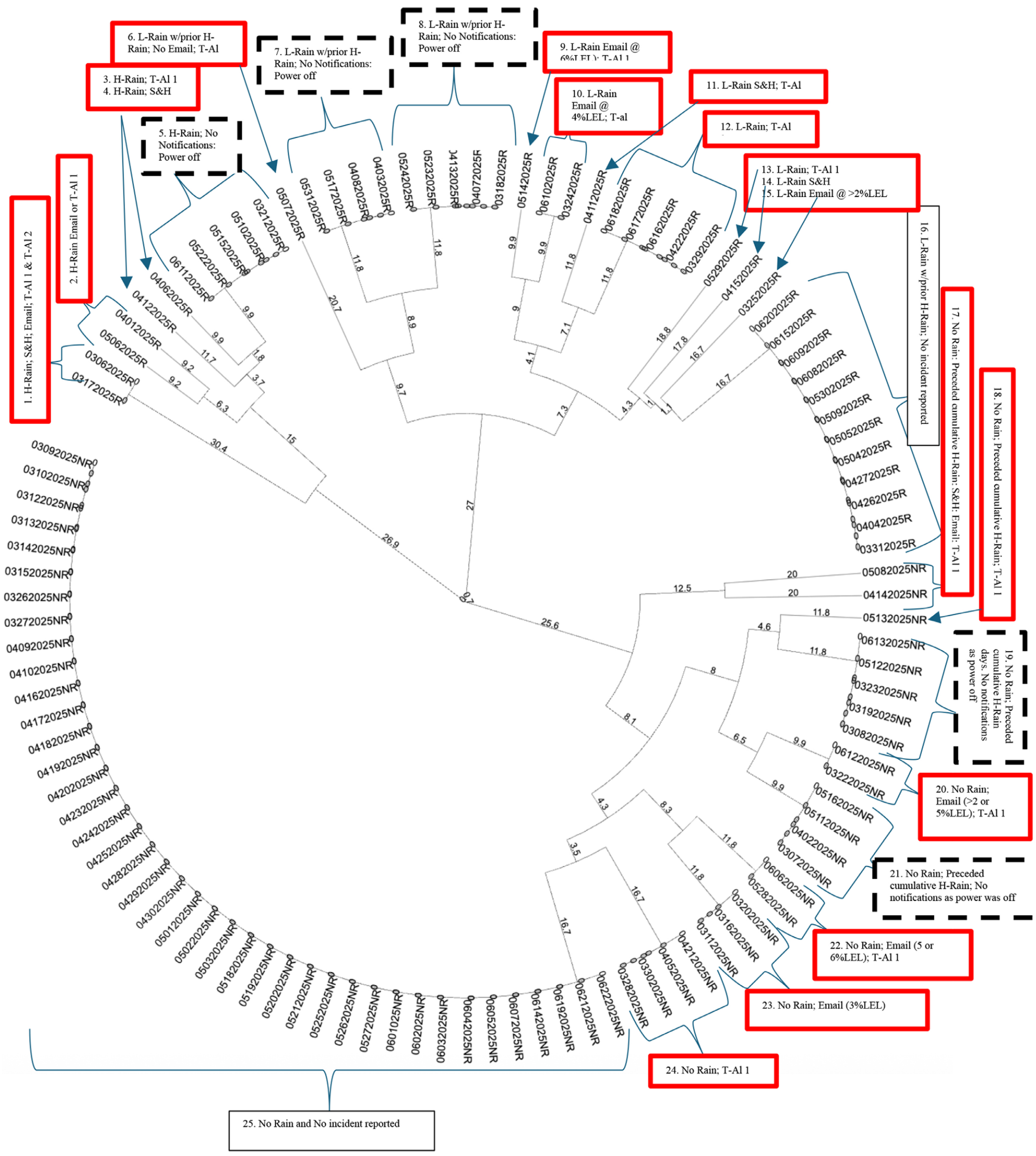


Figure 12. Relationship between rainfall events and the installed monitoring system response to methane (red boxes) at Channel 11. Note: T-Al 1 & T-Al 2 = Channel 11 archived data recorded alarm 1 (≥10%LEL) and/or 2 (≥20%LEL) methane; S&H = strobe and horn activity was visually documented. Dates with R had a rainfall event. Dashed box = Inconclusive (Electric power off).

Based on Table 6, Victoria EPA recommended trigger action levels of 5,000 ppm inside buildings on landfill areas. Since 100%LEL represents 5% methane or 50,000 ppm methane, the equivalent action levels published by Victoria EPA [23], are converted to %LEL (Table 6; Column 4) to relate to the reading provided by the detector system at Overpeck Park. Based on that conversion, an action level of 10%LEL inside any of the buildings at Overpeck Park may elicit concern. This guidance is quite applicable and transferable to other industries such as mining, enclosed/underground parking lots/subway systems and similar confined spaces where methane emissions are of concern. To the authors' knowledge, no other jurisdiction has published comparable guidelines. Based on this information, the 2%LEL setpoints in any of the of the buildings requiring remedial action at Overpeck Park may be overly cautious. For reference, action levels for other landfill-related design and management guidelines are also provided in Table 6.

Table 6. Landfill gas action levels.

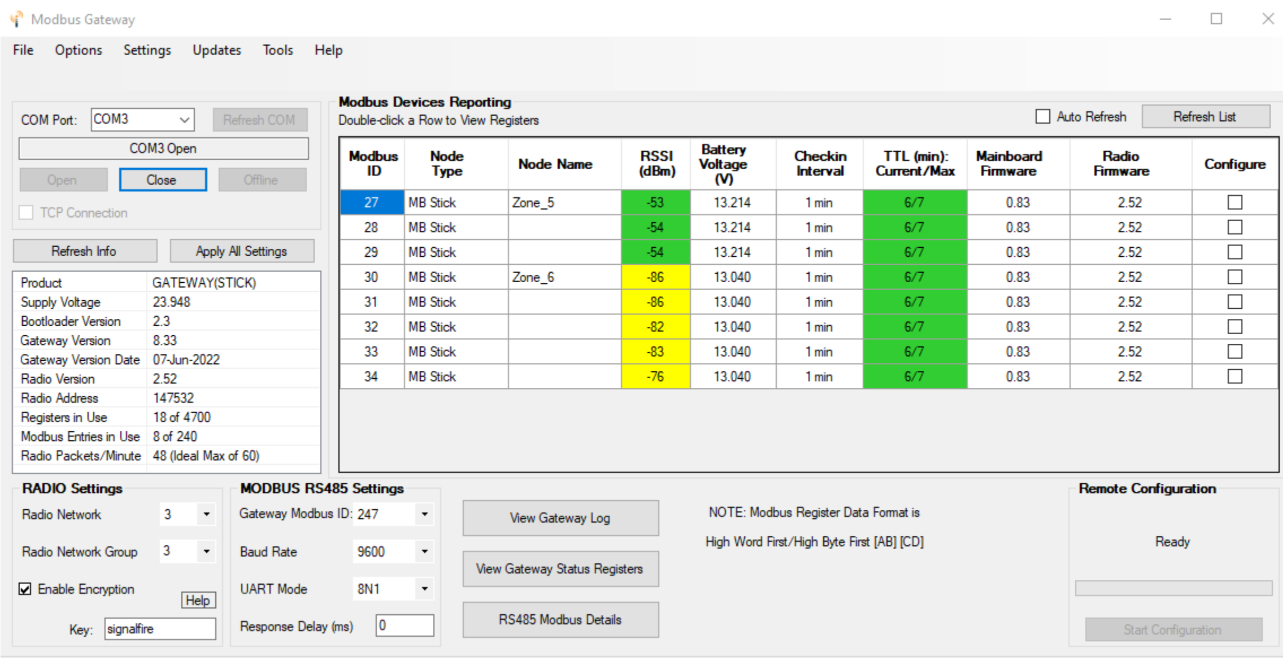
Location	Parameter(s)	Action level	
		Ppm	%LEL CH_4
Landfill surface final cap	Methane concentration in air*	100 ppm	0.2% LEL
Within 50 mm of penetrations through the final cap	Methane concentration in air**	100 ppm	0.2% LEL
Landfill surface intermediate cover areas***	Methane concentration in air*	200 ppm	0.4% LEL
Within 50 mm of penetrations through the intermediate cover	Methane concentration in air**	1000 ppm	2% LEL
Biofilter	Methane flux	1.0 g/m^2/h	N/A
Subsurface geology at the landfill boundary	Methane and Carbon dioxide concentrations	1% v/v methane or 1.5% v/v CO_2 above background	N/A
Subsurface services on and adjacent to the landfill site	Methane concentration	10,000ppm	20%LEL
Building/structure on and adjacent to the landfill site	Methane concentration in air	5000 ppm	10%LEL
Landfill gas flares	Methane and volatile organic compounds	98% destruction efficiency	N/A

Note: *Point of measurement is 50 mm above the landfill surface. **Point of measurement is 50 mm from the point of discharge. ***Intermediate cover areas do not have an engineered landfill cap and are not scheduled to receive waste during the next 3 months. (Source: EPA Victoria [23] with modification).

3.2. Signal Strength and Other Attributes

The equations Received signal strength indicator (RSSI) measures the power present in a received radio signal. In this instance, RSSI is a relative number indicated by a negative dBm value relating the strength from the Modbus antenna to the gateway stick. The higher the number, the better the signal. Thus, the closer to 0 dBm, the stronger the signal. The exact number varies between devices but generally -70 dBm and higher values usually equate to the antenna being in an excellent coverage area [24]. There is a point at which trying to obtain more signal delivered diminishing returns, because the quality of the connection is defined by more factors than just RSSI. At Overpeck Park, Zone 2-6 with RSSI -76 dBm to -59 dBm successfully communicated with the controller in Zone 1 (Table 4).

Voltage at the antenna was 13V for Zone 5 and 6 (Table 4) where a 60Hz power supply-6 Amp (Altonix) unit was installed. The other zones (*i.e.*, 2, 3, 4, and 7) where a 60 Hz power supply-10 Amp (Altonix) unit was installed registered 26 – 28.6V. Irrespective of the voltage supply, message pulse check-in at 1-minute intervals was maintained. Transistor-transistor logic (TTL) of 6/7 or 7/7 were consistently achieved in all 6 zones communicating with Zone 1. TTL is a binary digital signal used in electronic circuits to represent an "off" or "on" state based on input and output voltages. Similar consistency of the mainboard and radio firmware were also attained. A sample RSSI output for gateway 3 (Zones 5 and 6) is presented in Figure 13.



Modbus ID	Node Type	Node Name	RSSI (dBm)	Battery Voltage (V)	Checkin Interval	TTL (min): Current/Max	Mainboard Firmware	Radio Firmware	Configure
27	MB Stick	Zone_5	-53	13.214	1 min	6/7	0.83	2.52	☐
28	MB Stick		-54	13.214	1 min	6/7	0.83	2.52	☐
29	MB Stick		-54	13.214	1 min	6/7	0.83	2.52	☐
30	MB Stick	Zone_6	-86	13.040	1 min	6/7	0.83	2.52	☐
31	MB Stick		-86	13.040	1 min	6/7	0.83	2.52	☐
32	MB Stick		-82	13.040	1 min	6/7	0.83	2.52	☐
33	MB Stick		-83	13.040	1 min	6/7	0.83	2.52	☐
34	MB Stick		-76	13.040	1 min	6/7	0.83	2.52	☐

Figure 13. Received signal strength indicator (RSSI) from Zone 5 and 6.

According to the manufacturer, the Modbus stick and Gateway antenna have a range of 4.8 km (*i.e.*, 3 miles; Table 2). However, the park has natural vegetation which may reduce these specifications. Thus, signal strength from Zone 7 located 2.7 km (*i.e.*, 1.7 miles) from the controller based on "line-of-sight" ranged between -92 dBm and -89 dBm (Table 4) and communication with Zone 1 was initially unsuccessful. Thus, the controller displayed a communication error for all channels in Zone 7 (*i.e.*, Channel 35 to 43). To rectify the situation, a breakout was inserted between the Zone 7 antenna and the first detector in the daisy chain (*i.e.*, Channel 35; Figure 14(A)). The breakout board was connected to a laptop and Zone 7 reprogrammed to use the antenna in Zone 5 as a booster/relay (Figure 14(B)). The modification successfully enabled communication between Zone 7 and the controller in Zone 1 as evidenced by RSSI (Table 7). The modification made GW4 on the roof of Zone 1 redundant.

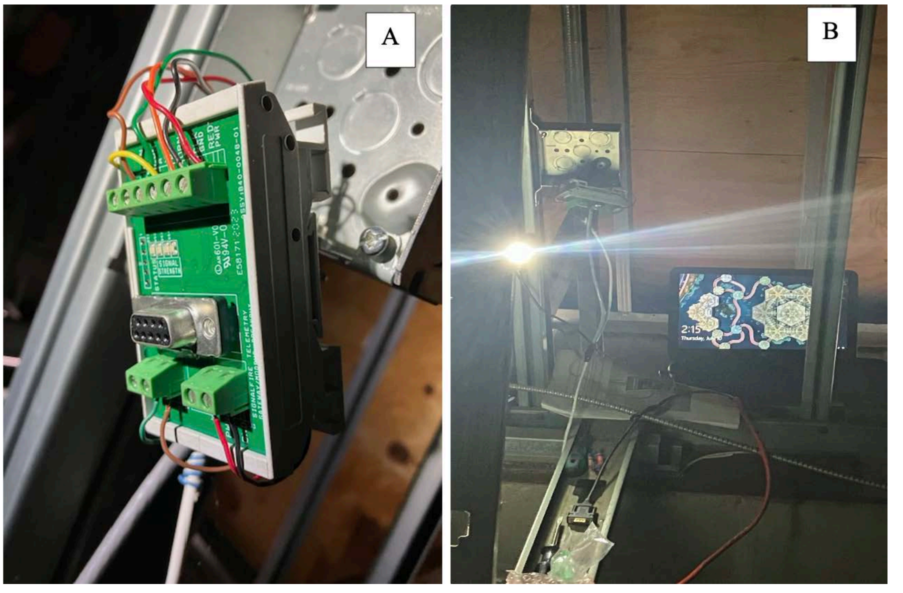


Figure 14. Breakout board inserted between the antenna and first detector in the daisy chain (A). The antenna was reprogrammed (B) to use Zone 5 as a booster.

Figure 15. Controller system display after installation and troubleshooting were completed (Note: Grey spaces represent empty channels).

Table 7. RSSI from zone 7 after using antenna at Building E to relay communication signals.

Channel#	Mode Type	RSSI (dBm)	Battery Voltage (V)	Check-in Interval	TTL (min): Current/Max	Mainboard Firmware	Radio Firmware
35	MB Stick	−81	26.136	1 min	6/7	0.83	2.52
36	MB Stick	−80	26.136	1 min	6/7	0.83	2.52
37	MB Stick	−80	26.136	1 min	6/7	0.83	2.52
38	MB Stick	−80	26.136	1 min	6/7	0.83	2.52
39	MB Stick	−80	26.136	1 min	6/7	0.83	2.52
40	MB Stick	−80	26.136	1 min	6/7	0.83	2.52
41	MB Stick	−80	26.136	1 min	6/7	0.83	2.52
42	MB Stick	−81	26.136	1 min	6/7	0.83	2.52
43	MB Stick	−81	26.136	1 min	6/7	0.83	2.52

Overall, system performance significantly improved, registering RSSI -81 dBM without compromising voltage, check-in intervals, TTL, mainboard as well as radio firmware (Table 7). The signal transmitted to the controller for all 41 channels stabilized for all methane gas detectors, eliminating all communication errors (Figure 15). The empty channels (in grey) can be used for future expansion of the system if needed.

4. Conclusion

Overpeck Park is a green built space designed for human use to provide a variety of physical, psychological, and social benefits to suburban residents. Alarm conditions provided by the monitoring system are visible and audible at the impacted detector. This provision ensures individuals in the respective surroundings would always be immediately alerted to take the necessary action to mitigate methane emissions. The system is also designed to notify responsible parties about any gas emission breach, even when the management team happen to be offsite. To that effect, the system has a multi-layered warning capability that improves safety and protects public assets. Although not specifically investigated herein, the TracXP TXP-T40 universal transmitter can be deployed in single or dual sensor configurations, which allows monitoring combinations of gases such as ammonia, carbon monoxide, carbon dioxide, hydrogen cyanide, nitrous oxides (NOx) and hydrogen sulfide. These attributes make its use applicable in other settings including oil/gas extraction, mining, large building complexes (e.g., dormitories and hotels), and wastewater treatment systems. These additional potential sectors where it can be used would benefit from the wireless scalability of the intelligent monitoring system, the ability to project the signal over a long distance/large area of operation in obstructed areas, as well as its multi-layered notification capability.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper is.

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