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# NONINVASIVE METHOD FOR MAPPING BURIED COAL ASH

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## ABSTRACT

Coal Combustion Products (CCP) are one of the largest industrial waste streams in the world and, in some cases, the final disposition of this toxic material is not carefully controlled resulting in undocumented landfills, illegal dump sites, and mixing with Municipal Solid Waste (MSW). A new approach for discovering and mapping CCP sites based on radiation measurements has been tested in a Philadelphia neighborhood where CCP was extensively used as fill material.

## KEYWORDS

Gamma Radiation, Coal Ash, CCP and Landfills

## CITATION

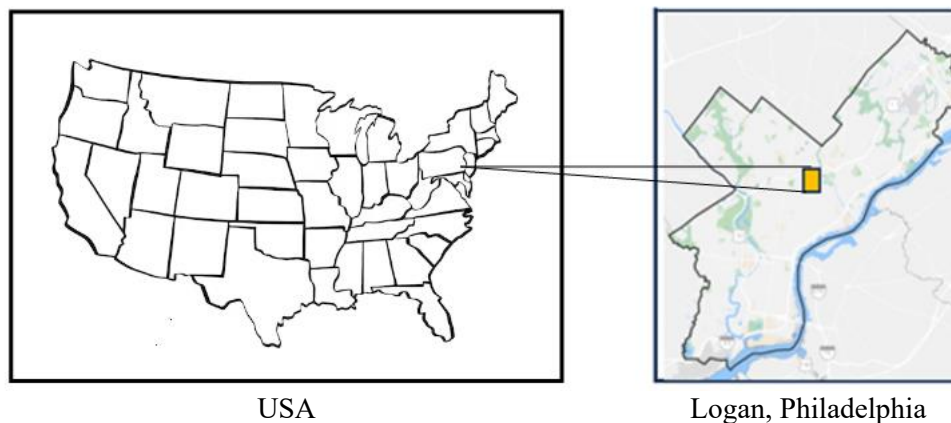
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## Introduction

In the early twentieth century, Philadelphia was a preeminent manufacturing center with a growing population that spurred residential development in the city's northern section. This required the leveling of stream valleys, and in the case of Wingohocking Creek, the city decided to use its abundant supply of CCP as fill material. Eight decades later, homes in Philadelphia's Logan neighborhood began showing signs of distress because of differential soil settlement. The distressed properties were located directly above the loosely compacted CCP used to level the 12-meter deep Wingohocking Creek valley. As conditions worsened, the city demolished 900 homes [1] that were considered unstable.



**Fig. 1.**

Following these events, the U.S. Geological Survey (USGS), the U.S. Army Corp of Engineers (USACE), and Lippincott Engineering Associates (LEA) undertook geotechnical studies of the area. The USACE and LEA studies used the standard approach of advancing boreholes to determine the depth and range of the CCP fill. In addition to the test bores, the USACE applied topographic methods to identify sites in Logan likely to have received CCP fill. Likewise, the USGS study utilized topographic methods but extended their analysis over a broader area of North Philadelphia and included nearby suburbs.

These studies and topological models are invaluable since few other sites of this type are as well documented, allowing special opportunities for testing radiological methods and comparing the results with the prior work. More specifically, the LEA drilling logs from 38 test bores provided a reliable standard against which the radiation survey results could be judged.

### Methods and Materials

Coal is largely composed of organic material and small amounts of naturally occurring radionuclides including  $^{238}\text{U}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$ . When coal is burnt, the organic matter is volatilized resulting in an enhancement of radioactivity concentrations in the combustion products [2]. This enhancement can range from 5 to 7 times the activity level of the parent coal in the United States [3] and 3.1 to 3.5 times the activity level of the parent coal in Bangladesh [4].

Although gamma radiation from CCP is low [5] in terms of human safety, it is higher than naturally occurring background radiation [6] and, for this reason, potentially detectable with suitable equipment. Support for this idea is suggested in a study of CCP where the radiation from the Uranium series of CCP was found to be well above background levels [7].

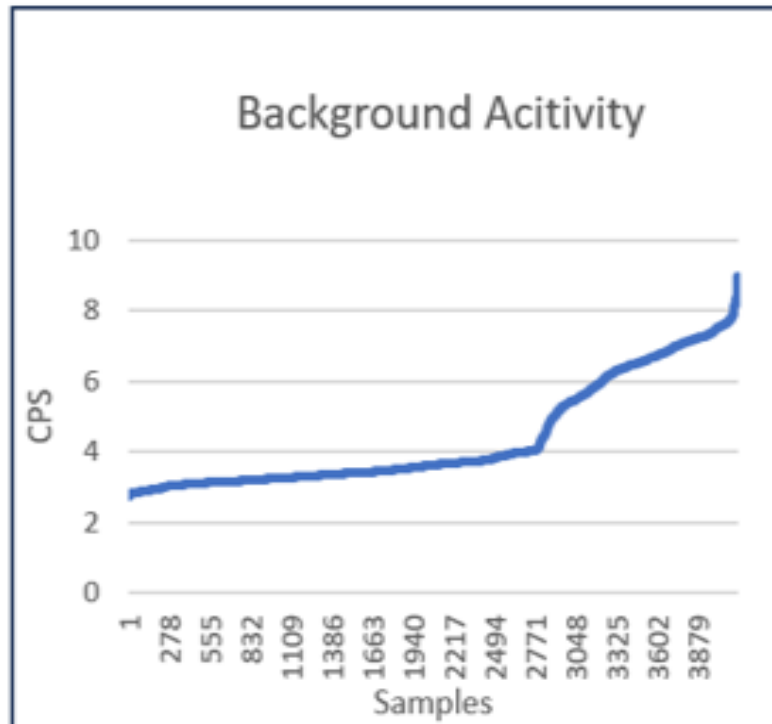
As a proof-of-concept test, a small scale survey was performed in a 5 block area of Logan using a Ludlum 2221 radiation scaler-rate meter with a 5 cm, NaI(Tl) scintillation detector. Test measurements showed that radiation from CCP was measurable at grade level in the Logan area and that mapping buried coal using radiologic measurement was practical. See Appendix A for details.

Following the proof-of-concept test, another survey was performed that included the entire Logan neighborhood. A Radiacode Spectrum Analyzer was selected for the survey instrument because it is field portable, can be used while walking or driving, and continuously updates both radiation levels and GPS data to an Android phone application. These data are converted into a map format which helps the user remain oriented while tracking areas of interest. When the survey is complete, the Android phone files can be uploaded to GIS software such as QGIS for more detailed analysis.

Compared to the Ludlum meter, the Radiacode's 10 mm, CsI(Tl) scintillation detector is smaller and potentially less sensitive since sensitivity is proportional to the cross-section of the detector, though this is only one of several factors that can impact a radiation detector's performance. If survey work is performed in an area where CCP activity is only marginally higher than background level, a more sensitive detector might be required.

While test bores are the standard for understanding subsurface features and their spatial relationships, collecting radiological data is a more efficient strategy for resolving the boundaries of buried CCP. Cost places a limit on the number of test bores that can be drilled whereas radiological surveys are not similarly constrained. This study collected 8,400 radiation readings in a 4.6 square kilometer area whereas the initial LEA survey was limited to 38 test bores in a 0.2-kilometer area.

Background radiation levels were estimated by collecting measurements along a 3 km north-south transect near Logan. Maximum and minimum values of background radiation on the transect measured between 2.6 and 4.0 CPS.



**Fig. 2.** Background Radiation Distribution

A second estimate was obtained by examining the sorted distribution of 4,468 observations from Location 1 which is shown below in Fig 3. The line segment resembling a plateau is interpreted as background radiation while the sharply rising segment starting at 4 CPS is attributed to radiation from CCP. The close agreement between these results suggests that 4 CPS is an adequate estimate of background radiation in the Logan area.

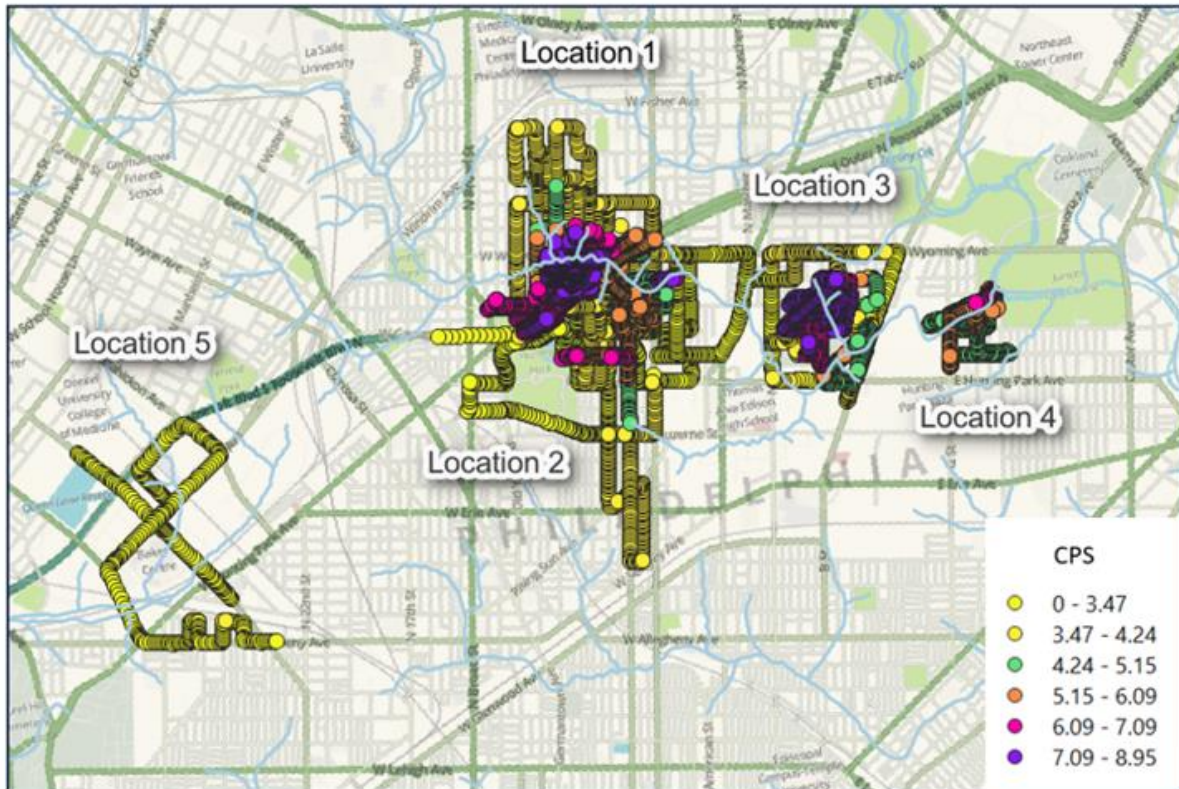
Radiation surveys were performed at 5 locations that included the same sites studied by the LEA, USGS, and USACE reports as well as some adjacent areas. Locations 1 and 3 were open spaces while locations 2, 4, and 5 were built-up areas where access was limited to the streets and sidewalks. The Radiacode device was maintained at a height of 76 cm from the ground to maximize the amount of radiation received by the detector though this resulted in some loss of spatial resolution.

### Results

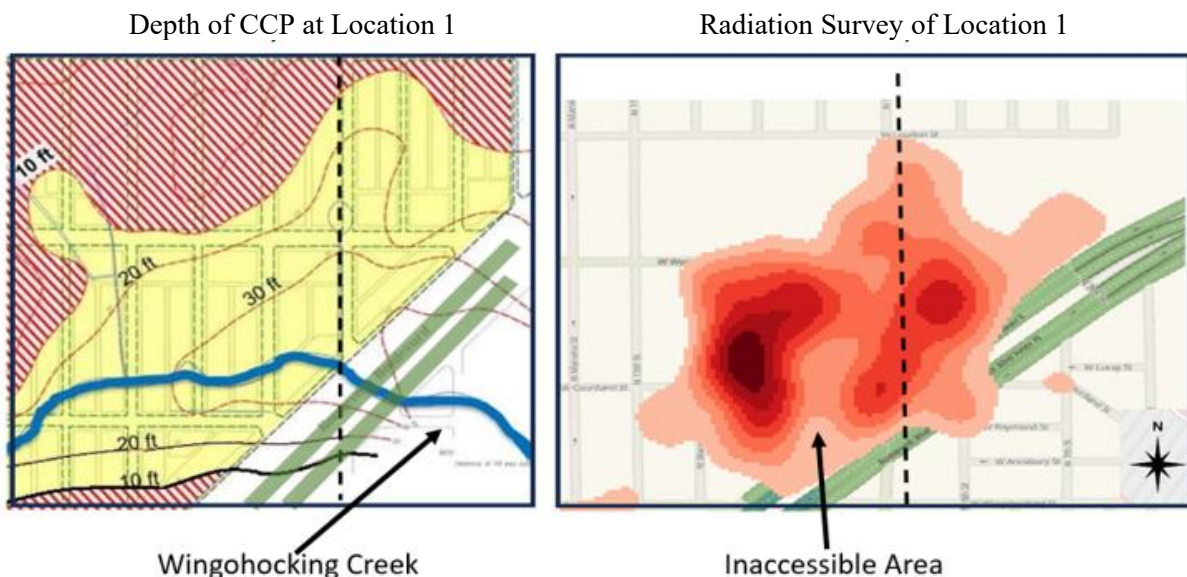
High radiation levels were detected along portions of the Wingohocking Creek bed consistent with historical information concerning efforts to level this area with CCP fill. Both the USACE and USGS studies predicted that CCP fill would be found as a continuous strip along the Wingohocking Creek bed, however, the survey results did not agree with this prediction. Since test bore data is available only for Location 1, it is not possible determine which finding is correct.

Location 1 contains the 8 square block area where 900 homes had to be demolished because of differential soil subsidence. Figure 4 demonstrates that the map produced by a radiation survey is generally congruent with the drilling data. However, the highest levels of radiation do not correlate with the greatest depth of CCP shown on the LEA map.





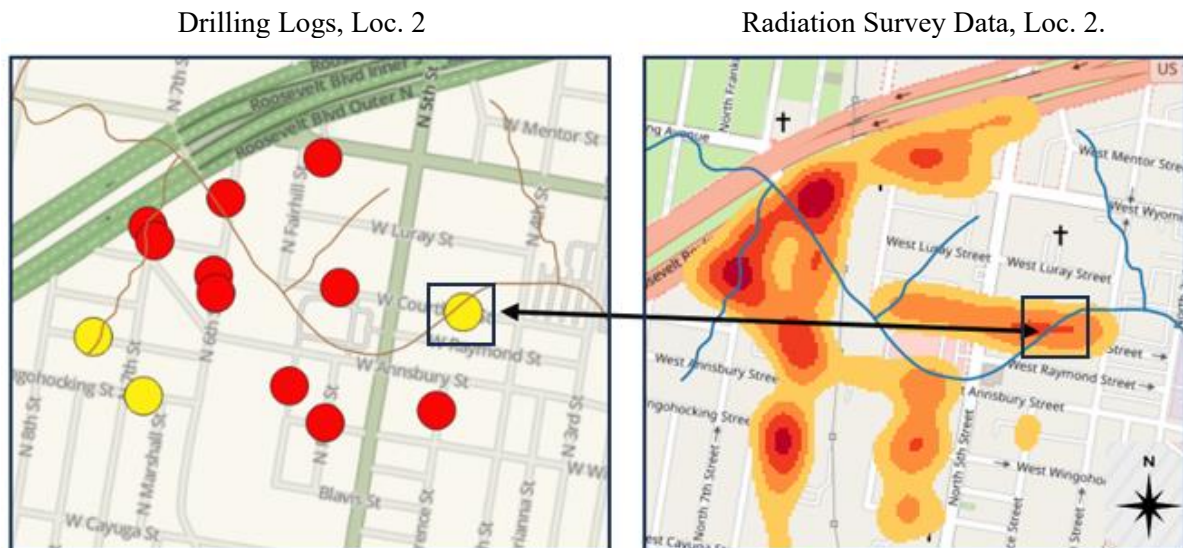
**Fig. 3.** All Radiation Survey Points.



**Fig. 4.** Comparison of the Drilling Log data with the Radiation Survey Data for Loc. 1.

This discrepancy occurred because the LEA contour map is a generalization of the drilling logs that does not reveal the complex subsurface features controlling the amount of radiation detected at grade level. LEA Drilling logs [8] reveal that CCP was deposited in varying amounts as a series of layers mixed with varying amounts of other fill materials such as soil, brick, wood, and glass. Sometimes CCP layers were interbedded with layers composed only of soil and rarely was CCP found as an uninterrupted layer from bedrock to the surface. See Appendix B for a 3-dimensional projection

Location 2 is a short distance southeast of Location 1 and was investigated by the US Army Corp of Engineers who advanced 13 boreholes in an area of about 20 square blocks. The drilling logs did not record the percentage of coal ash and only noted whether coal ash was found or not. Figure 6 presents the test bore data. The red circles represent the presence of CCP, and the yellow circles represent the absence of CCP.

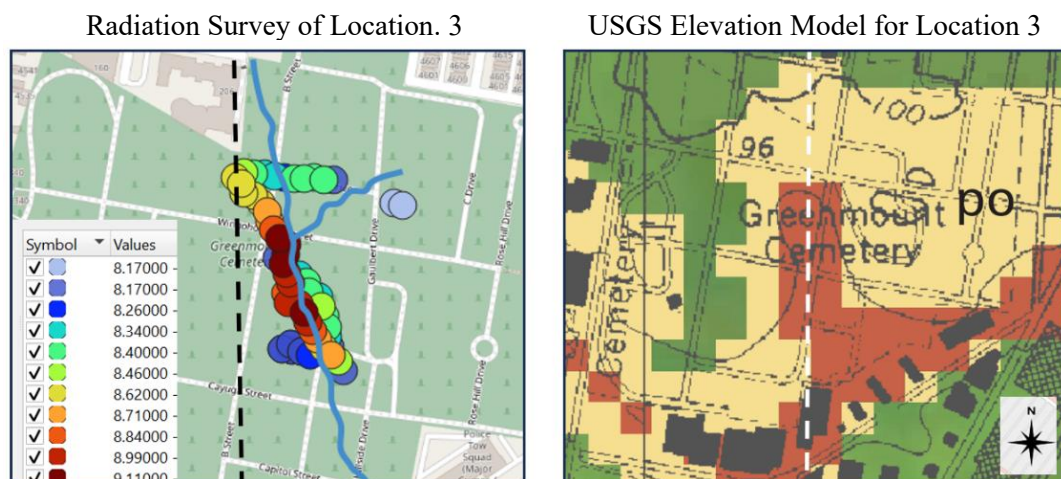


**Fig. 5.** Comparison of Drilling Log Data with the Radiation Survey Data.

The two surveys diverge in one instance highlighted by an arrow that spans both maps. The yellow circle in the box represents a borehole that encountered no CCP despite high levels of radiation detected in the survey. Although this contradiction cannot be resolved, the maps show this area is underlain by the Wingohocking Creek bed which was likely to be filled with coal ash as were several other parts of the historic creek bed in the Logan neighborhood. The drilling logs indicate that the test bore in question, FBH -12, was drilled to a 20-foot (6.1 m) depth but did not recover samples at the 6 (1.8 m) to 8-foot (2.4 m) level or the 15 (4.6 m) to 18-foot (5.4 m) level. (The drilling log sheets reported the depth data in feet rather than meters.)

Locations 3 and 4 are southeast of location 1 and were chosen for their proximity to the Wingohocking Creek bed. These are open spaces that allowed unrestricted access for survey work. The USACE bored no test holes at Locations 3 and 4, though the USGS report included some estimates of CCP locations in this area based on a topological model (Chirico and Epstein, 2000).

Location 3 is the Greenmount Cemetery, and no test bores were advanced in this area or in Location 4 that would allow a comparison with the radiation survey results. However, the USGS model produced a map [9] of potential CCP sites based on a topological analysis that can be used as an independent estimate.

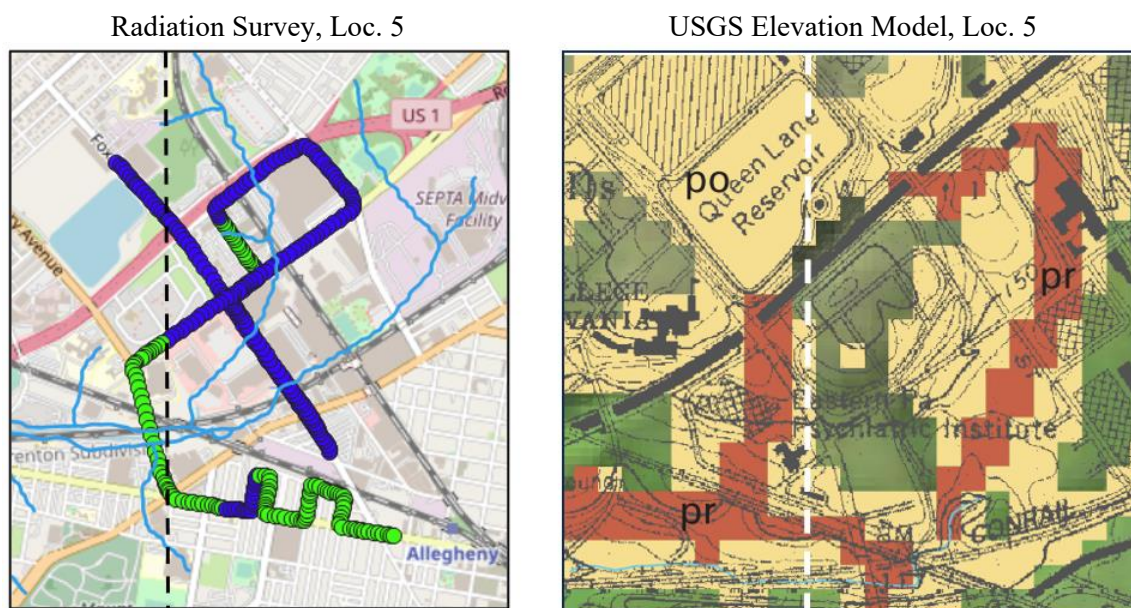


**Fig. 6.** Comparison of the Radiation Survey Data with the USGS Model Data for Loc. 3.



Featured above, Figure 6 shows there is a general alignment between the two maps although the USGS estimate of the CCP location, highlighted in red, lies west of the dotted reference line while the highest levels of activity (8.2 to 9.1 CPS) are east of the dotted reference line in the radiation survey. The radiation map is perhaps more accurate since the highest activity readings correlate with the historic Wingohocking Creek Bed which, being the lowest point in Location 3, would have received the most CCP. A well-defined correlation between the creek bed and radiation levels was also found in location 4 as indicated in Figure 3

Location 5, shown in figure 7, is about 1.8 km southwest of the Logan neighborhood and corresponds to an area with a high potential for buried coal according to the USGS map. The presence of several historic creeks indicates the need for fill material and, yet, the activity readings range from 2.2 CPS (blue-colored circles on the map) to 3.5 CPS (green-colored circles) which is in the range of background radiation suggesting that CCP is not present in any significant volume.



**Fig. 7.** Comparison of the Radiation Survey Data with the USGS Model Data for Loc. 5.

### Discussion.

While subsidence caused serious problems in Logan, the primary concern for CCP is the risk of toxicity from this widespread industrial waste stream. In China, alone, the total accumulation of fly ash exceeds 3 billion tons [10]. The Annual, worldwide production of CCP in 2019 was 1221.9 MT [11]. Top producers include China, Europe, India, and the United States. Apart from documented storage sites, there are unknown quantities of CCP in abandoned landfills, dumps, and Municipal Solid Waste (MSW) sites. CCP can also be found in some historic reclamation projects such as Flushing Meadows in New York City where at least 831 sq. km. was filled with MSW that contained significant amounts of coal ash [12].

Radiation surveys of CCP sites offer benefits in terms of lower costs and minimal logistics that are not conferred by other methods such as drilling, Ground Penetrating Radar (GPR), Electrical Resistivity Tomography (ERT), and topological analysis. Although drilling represents a standard of accuracy because it provides tangible samples of subsurface material, this approach is not practical for surveying large areas because of cost and complicated logistics.

Some power companies use GPR as a cheaper option for mapping the boundaries of CCP landfills near their generating plants [13], however, GPR is not effective for sites containing heterogeneous fill, especially if construction material or metal objects are present. The wheel mounted GPR unit offers good mobility on moderately flat areas but will have difficulty navigating rough terrain. Not every location is suitable for GPR since clay soils, salinity, and water content can create electromagnetic interference. Training and experience are required to correctly interpret the subsurface features presented by GPR scans

Electrical Resistivity Tomography provides imaging above and below the landfill liners (both geosynthetic and clay liners) to identify karst features, water seepage pathways, and other potential structural problems. Although logistics, cost, and training limit the use of ERT, this method can produce detailed, 3-

dimensional maps of subsurface conditions to a depth of 30 meters [14]. ERT is practical only in circumstances where the location of the landfill is known with a high level of confidence since it is time-consuming to set up the required monitoring equipment.

Computational methods, such as those used by the USGS, utilize topological data to identify sites with significant differences between historic and current elevations on the assumption these would be candidate sites for CCP fill. Unfortunately, this produces false positives where clean fill was used to level areas of low elevation. This approach was effective in Logan since CCP fill was abundant but not in the broader area of Philadelphia. Unique historical circumstances explain why CCP was transported to Logan as opposed to other locations in the city and, for this reason, a model that considers only changes in elevation has limited applications.

Gamma-ray measurements for CCP surveys represent a new application of a method that is widely used in geology for mineral exploration and lithological investigation. It is efficient and well-suited for mapping CCP sites since surveys can be performed either on foot or in a vehicle. Mapping results are generally accurate but, unlike drilling, radiological surveys cannot provide detailed subsurface data. Radiation surveys do not have any soil interferences except for naturally occurring radioactive minerals (NORMS) and anthropometric sources of radiation.

CCP landfills are often covered with a layer of soil to reduce wind transport which makes it necessary to understand if radiation can penetrate the expected overburden. Measurements of the overburden from the area presented in Figure 3 confirmed that radiation from CCP penetrated up to 47 cm of clean fill. Since soil is an efficient moderator of gamma radiation, the average penetration depth might be in the range of only tens of centimeters depending on site-specific parameters such as photon energy of the source, build-up factor, soil density, moisture content, and chemical composition [15], [16].

### **Conclusion**

Gamma radiation from CCP was sufficiently energetic to be detected above background radiation levels in the survey area. Furthermore, a clear gradient of increasing radiation levels was measured when approaching increased concentrations of CCP. Although radiation measurements do not yield the high spatial resolution of drilling or GPR, they provide results suitable for surveying large territories and mapping the boundaries of CCP deposits. Future work is planned for additional radiation surveys to test the generality of radiation survey methods and help assess the influence of various soil parameters on the absorption of gamma radiation.

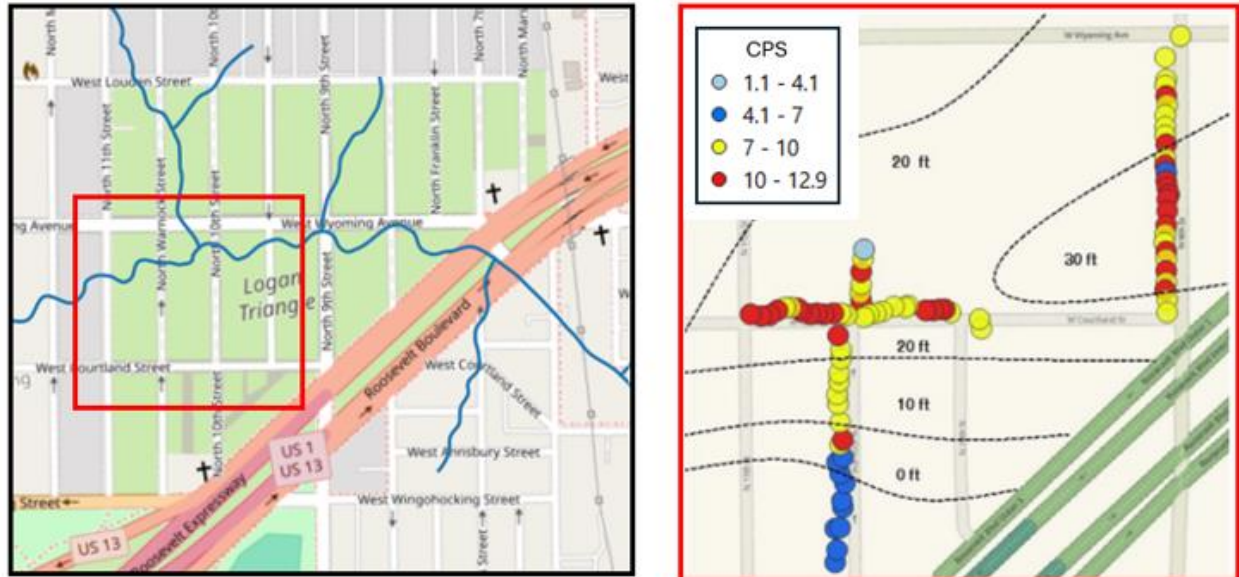
Radiation methods have broad application for discovering and mapping buried CCP. Appropriate target areas include coal powered, thermal energy plants, cities with a history industrial development and, more generally, countries with large CCP waste streams such as India, China and the United States.



### Appendix A. Pilot Test Results

A pilot test was conducted to determine if radiation from CCP could be detected above the background level. A small number radiation readings were collected in the portion of Location 1, outlined in the red square in Figure 8. The test was designed to determine how closely the Ludlum instrument could track changing levels of radiation in the survey area. The resulting measurements displayed in Figure 7 correlated well with the depth of CCP reported by the LEA survey which indicated that a larger survey could also provide useful results.

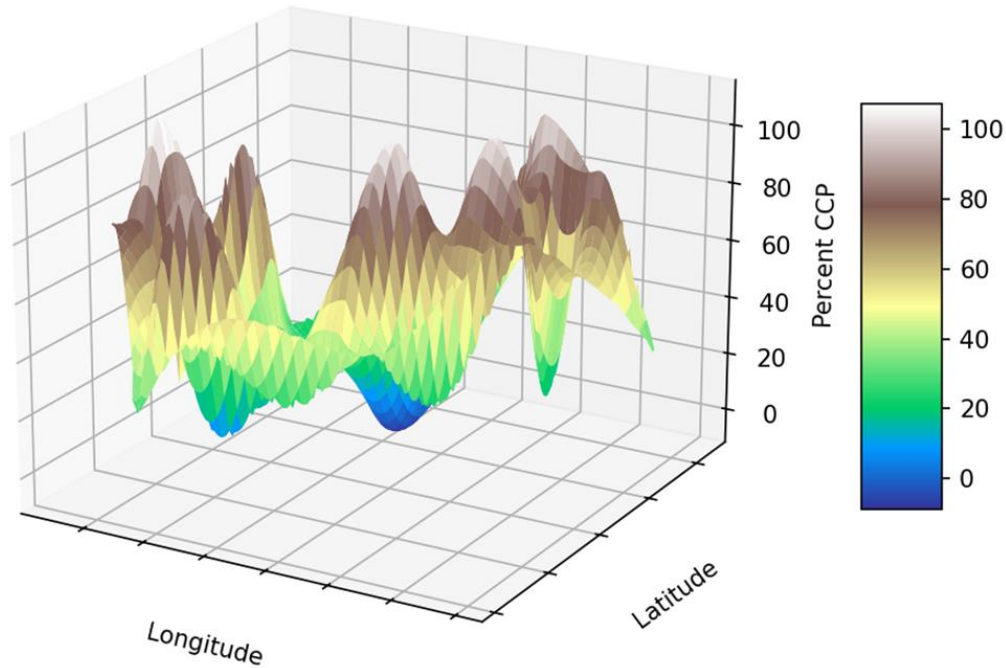
Map adapted from LEA Survey



**Fig. 8.** Radiation Survey Points Collected During Pilot Test.

### Appendix B. Percent by volume of CCP at the 30 cm Soil Horizon

Most of the work performed to level the Wingohocking Creek was done without modern earth-moving equipment which helps to explain why the CCP fill was laid down in an inconsistent pattern. This plot shows the percentage of CCP present in a soil horizon located 30 cm below grade. The Z axis indicates the increase in the concentration of CCP within the soil horizon as the colors move up the scale from blue to brown. The area displayed in the plot is the nine square block section in Location 1 where 900 homes were damaged by soil settlement and subsequently demolished.



**Fig. 9.** Percent CCP Fill Present at the 30.5 cm Soil Horizon. Graphics software Tools [17]

**Research Data:** All data used in this paper is available at: <https://github.com/juliangrauer/Radiation-Survey-Data>

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