Plutonium-239 and Chromium-6 Contamination at Los Alamos National Laboratory: Analyzing Contaminant Migration and Assessing Remediation Options

An Interactive Qualifying Project submitted to the faculty of Worcester Polytechnic Institute in partial fulfilment of the requirements for the degree of Bachelor of Science by:

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Abstract

Work on nuclear weapons at Los Alamos National Laboratory has resulted in widespread contamination on site since its inception in the 1940s. We assessed the presence and migration of plutonium and chromium using publicly available environmental sampling data to inform ongoing debates about remediation approaches. Chromium concentrations at laboratory borders are increasing and continue to pose a risk to the adjacent Pueblo. Plutonium is present at deep depths and in areas off property. Our analysis revealed inconsistent sampling and reporting of data to enable reliable conclusions about migration trends. We recommend a re-evaluation of current characterization and clean-up efforts, improvements in sampling strategies, and funding for independent assessments.

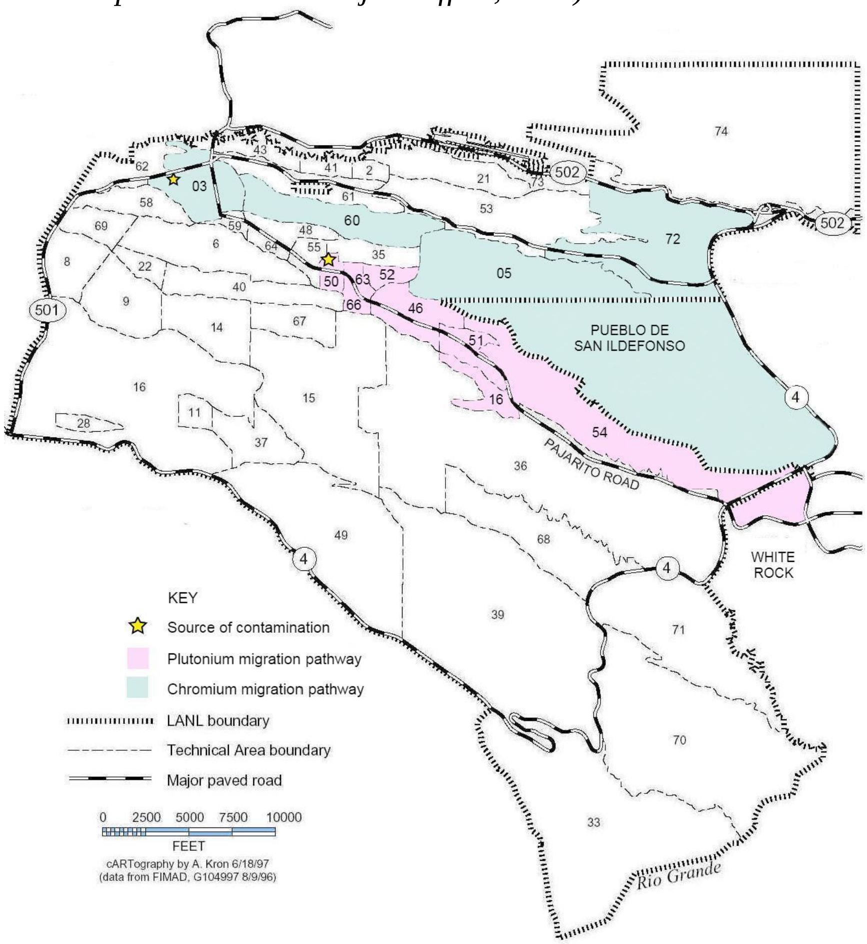
Executive Summary

Introduction

Los Alamos National Laboratory (LANL) in northern New Mexico has played an essential role in the nuclear weapons complex and has practiced poor waste disposal techniques in the past, making it a major source of groundwater contamination (DOE, 2001). The contamination has the potential to impact public health and also brings up issues of environmental justice. LANL is on land that is part of a large Sacred Area that has historically been home to Pueblo tribes and whose natural resources are now at risk of major pollution (Clapp & Silver, 2006; Masco, 2006). There are multiple conversations between the Department of Energy (DOE), the New Mexico Environment Department (NMED), and affected stakeholders about how portions of the property should be remediated, two of which concern plutonium contamination in Material Disposal Area C (MDA-C) and a chromium plume in Technical Area 5 (TA-5) (DOE Office of Environmental Management, 2019). Upcoming decisions will be critical to future land-use at these sites.

Figure ES1.

Migration Pathways of Plutonium and Chromium Across Technical Areas (Adapted from Site-Wide Environmental Impact Statement Project Office, 1997)



MDA-C is a 12-acre plot in TA-50, as shown in Figure ES1, that served as a primary toxic waste dump for LANL and contains significant quantities of plutonium waste. The presence of plutonium threatens regional aquifers that provide drinking water to nearby communities through migration (Marty et al., 1997). The DOE will finalize key actions for remediation upon the release of a corrective measures evaluation in early 2021, which is an opportunity for the community to voice input and concerns. Whether or not plutonium from MDA-C is migrating off the site will help them decide to simply cover the area with an impermeable cap or to relocate the radioactive material to a repository where it will be permanently stored (Nuclear Watch New Mexico, 2020).

TA-5 is the location of a subsurface plume of chromium-6, as shown in Figure ES1 (Amigos Bravos & Concerned Citizens for Nuclear Safety, 2006; Los Alamos Study Group, n.d.). The chromium was a consequence of waste disposal practices on top of Sandia Canyon, from where chromium traveled across and percolated underground into the regional aquifer. Chromium threatens the Pueblo de San Ildefonso and has potential to continue migrating through groundwaters, posing widespread exposure risk (Oswald, 2015; Andersen, 2018). The DOE has enacted an interim measure to control the contamination and will propose a final remedy in 2021, which will be subject to public comment and analyzed for approval by the NMED (DOE, 2015; N3B Los Alamos, 2019). Collecting more sampling data to gain an updated picture of the extent and shape of the plume will help them create a viable treatment plan (Chamberlain, 2019).

The goal of our project was to assess the presence and migration of plutonium-239 from MDA-C and chromium-6 from TA-5 using available environmental sampling data to inform ongoing debates about remediation approaches on the property. Our analyses serve the purpose of supporting our sponsor, Nuclear Watch New Mexico (NukeWatch), in their safety and environmental protection efforts. NukeWatch has long lobbied for remediation at LANL and calls for more transparency in operational activities at the laboratory. The team delivered on our goal for NukeWatch by:

1. Collecting data about plutonium-239 and chromium-6 contamination in Los Alamos National Laboratory property and surrounding areas available from a publicly accessible database.
2. Assessing migration of plutonium-239 and chromium-6 in soil and waterborne samples over time.
3. Assessing the feasibility and resilience of remedial options for Material Disposal Area C and the chromium plume.

Methods

The data for our project was sourced from Intellus, a publicly-accessible database that contains environmental records from LANL. We collected chromium-6 contamination data from the plume's origin in TA-3 as well as Technical Areas 5, 60, and 72 and the Pueblo de San Ildefonso. These locations were chosen based on the general flow of groundwater in the region towards the Rio Grande, which is chromium's likely migration path. For plutonium, we collected data for plutonium-239 as well as its isotopes plutonium-238 and plutonium-240 since they indicate previous presence of plutonium-239. We pulled data from all across the laboratory property and off-site locations near the property, but we largely focused on TA-50 and downstream technical areas, as shown in Figure ES1. There is some data that exists from 1970, but available data depends on when sampling began in certain locations. A major challenge we experienced was the numerous gaps and inconsistencies in the data taken from Intellus, hindering the extent of our independent assessment.

Using this data, we created visual representations of the chromium and plutonium contamination using graphing and mapping functions in Excel. Specifically, we made concentration graphs, groundwater elevation graphs, sample depth graphs, number of samples graphs, and heat maps depicting concentration levels over time at various locations. Our visuals as a result of our independent assessment of Intellus data offer Nukewatch tools and visual aids to be used in future public events regarding remediation of MDA-C and the chromium plume. As a result of our data analysis, we developed the following results and recommendations.

Results and Recommendations

Plutonium

Our first finding about plutonium contamination is that plutonium is detected beyond LANL boundaries. This is concerning since plutonium was disposed of in MDA-C and MDA-G, but nowhere off-site, meaning plutonium could have migrated across the laboratory. To explore this further, we looked into Cochiti Lake, which is located about ten miles south of the laboratory. Any contamination showing up here would be evidence of significant migration.

Figure ES2.

Plutonium Concentrations in Cochiti Lake Sediment

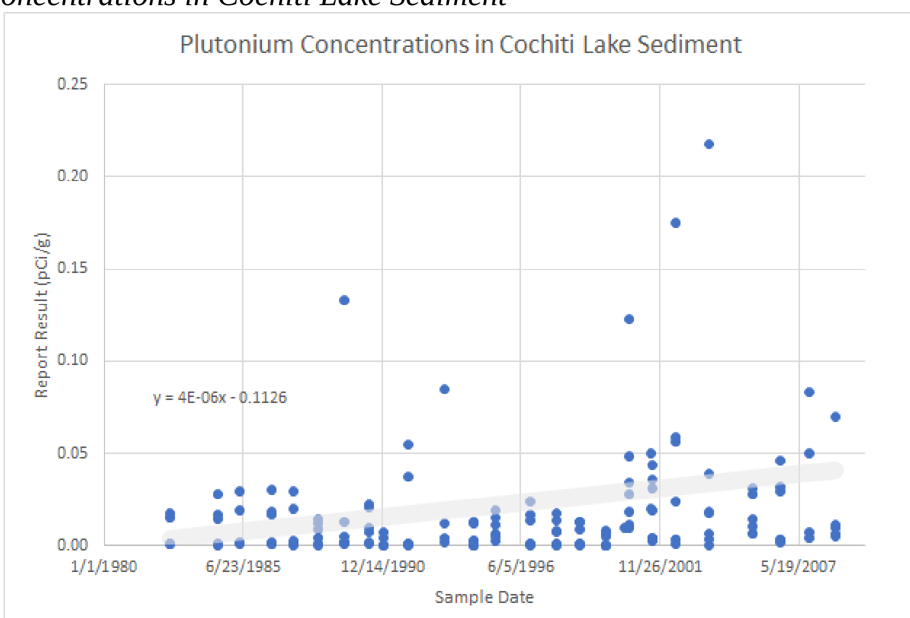


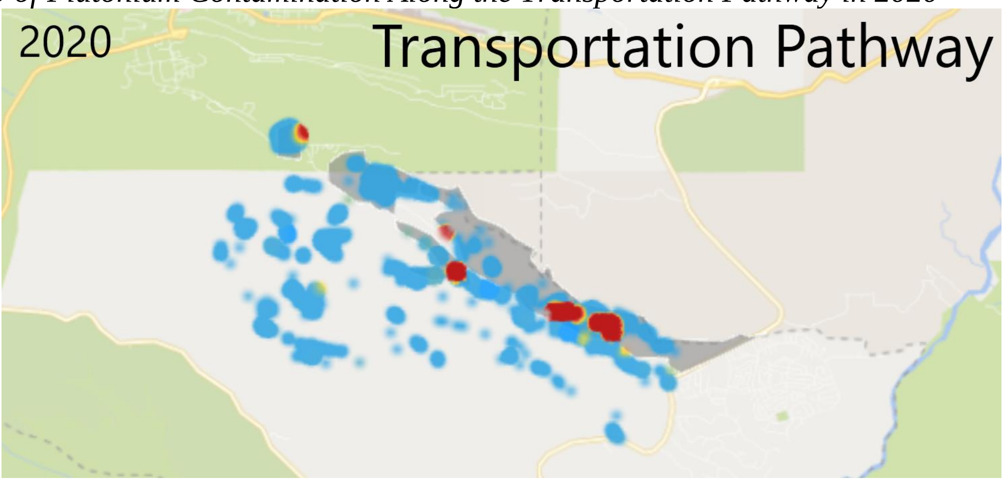
Figure ES2 reveals a slight upward trend in plutonium concentrations in Cochiti Lake sediment over the past twenty-six years. Concentrations range from background levels of 0.01 picoCuries per gram (pCi/g) to higher than upper levels of 0.1 pCi/g (Agency for Toxic Substances and Disease Registry, 2011). This warrants concern because Cochiti Lake lies near populated regions such as the town of Albuquerque. Therefore, its contamination could pose risk to many people.

The long and consistent testing period at Cochiti Lake allows for more meaningful analysis than what we have experienced while analyzing data on-site. If testing across wells beyond LANL boundaries was conducted in this manner, a more complete picture of contaminant migration off-site would be available, which would aid in the remediation discussion.

Because the technical areas along the transportation pathway were not tested each year, we could not see how plutonium concentrations were changing. Data trends may be misleading and can be attributed to new wells being tested that were never tested before, not the discovery of plutonium that was not there before. In an attempt to assess migration, we removed data points that were sampled only once, a few times over a short window of time, or sampled sporadically with large gaps between samples. However, even when only mapping the data that was sampled over longer spans of time, there still was not consistency.

Figure ES3.

Heat Map of Plutonium Contamination Along the Transportation Pathway in 2020



Note. Shown are plutonium contamination heat spots in the technical areas that are part of the transportation pathway, as outlined in black. Blue spots indicate safe levels whereas red spots indicate significant contamination.

Figure ES3 shows multiple areas with higher concentrations of plutonium that raise concern for LANL and the surrounding communities. Some of these areas are outside both MDA-C and MDA-G, therefore providing high probability that plutonium migrated from its original source. However, analyzing the data over time does not yield any concrete results in terms of migration trends. To address information gaps as well as our limited findings about the plutonium contamination at LANL, we propose two recommendations:

1. LANL should design and implement more consistent sampling practices across locations to allow identification of trends in contamination data.
2. The DOE and the NMED should consider factors of climate change and future land-use in analyses of proposed remedial options for MDA-C, which will entail asking questions such as:
    a. Will decreased percolation of rainwater through soil reduce likelihood of downwards migration, thus mitigating the need for relocation of contaminants?

b. Does increased reliance on the regional aquifers beneath LANL justify the implementation of more thorough remediation that would remove the sources of plutonium?
c. Will degradation over time of landfill caps and leachate collection systems be accelerated by harsher storms and increased frequency and size of wildfires?

Chromium

In 2017, the DOE conducted treatment tests at regional wells R-28 and R-42 located in the center of the plume where chromium was highly concentrated as an interim measure effort. These tests show that the treatments were successful, providing evidence in support of a final remedy involving in situ treatment via chemical application. Although the data proves its short-term viability, it is unclear if complications will arise in the long-term.

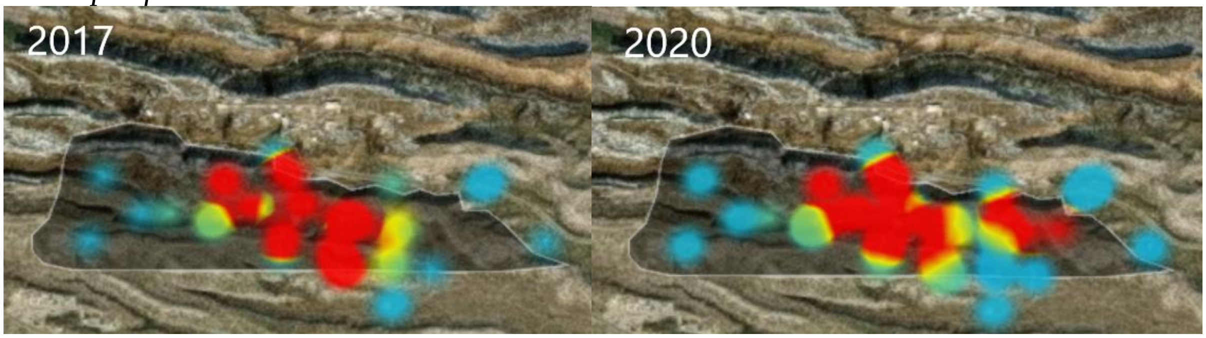
Another interim measure effort that the DOE implemented was an extract-and-inject system at the southern edge of the chromium plume in which contaminated groundwater is pumped to the surface, treated, and re-introduced into the aquifer. Data of chromium levels at the injection wells show concentrations close to zero. Additionally, a graph of chromium levels at the well in Pueblo property shows that concentration levels are below the legal limit of 50 ppb. Our analysis supports the claim that the extract-and-inject system is currently preventing migration of the plume across the border that LANL shares with the Pueblo. However, there are two areas of concern that could become challenges for the extract-and-inject system at the southern edge of the plume:

1. Contamination from the plume center (CRPZ-2) could migrate directly south or southeast in the direction of groundwater flow because chromium levels at this well have been dangerously above the Environmental Protection Agency drinking water standard of 100 ppb since 2018, and there is a recent increase in concentration.
2. There is still probability that contamination could cross into Pueblo property, proving that the extract-and-inject system is unlikely to be effective by itself to control migration in the long-run because chromium levels at extraction wells along the Pueblo border (CrEX-1 and CrEX-2) remain over 100 ppb, and those at regional wells along the border (R-50 and R-61) have recent values nearing 50 ppb.

Two more important findings about the plume shape are that it has slightly expanded to the west and it is starting to break off and form a second contamination oval to the east. The first is evidenced by the chromium levels in a western monitoring well (MCOI-6) that have lingered above 50 ppb since 2010, suggesting that the plume is wider than the DOE believed it to be in 2019 (Submittal of the Completion Report for Conversion of CrIN-6 to CrEX-5, 2019). The second is evidenced by high chromium levels above 200 ppb at relatively new wells in the east (R-70 and CrEX-5) and gradually increasing levels approaching 50 ppb at the southeast edge, suggesting expansion of the right side of the plume. Figure ES4 shows heat maps depicting the intensity of contamination at various sampling locations of the plume in 2017 and 2020. Comparing these images reveals that the plume has drawn back from the southern border and is elongating, suggesting that interim measure efforts at the bottom of the plume might be redirecting contamination east.

Figure ES4.

Heat Maps of the Chromium Plume in 2017 and 2020



Note. Shown are chromium contamination heat spots in Technical Area 5, which is outlined in black. Blue spots indicate safe levels, yellow spots indicate levels 50 ppb and above, and red spots indicate levels 100 ppb and above.

Evidently, concentrations at the plume center remain high and some levels at plume borders are increasing. Additionally, without knowing the future impacts of climate change and how groundwater levels could change in the coming decades, mischaracterizing the plume and underestimating chromium migration could pose risk to the widespread community should contamination spread to the Pueblo or Los Alamos water supply wells. Therefore, we propose four recommendations:

1. For LANL to continue the extract-and-inject method of controlling the plume until full-scale remediation is planned and deployed,
2. For the DOE to install new monitoring wells in Pueblo territory along the border with TA-5 to ensure chromium contamination is not continuing to migrate off LANL property,
3. For the DOE to install additional monitoring wells surrounding R-70 that will aid in characterizing the northeast area of the plume, and
4. For LANL to take sample depth and groundwater table data for TA-5 to aid in projection of plume migration over time due to changing water tables in the region.

The Value of Independent Assessments to Improve Transparency

Independent assessments are of high importance for a DOE facility such as LANL. LANL's own reports regarding findings on contamination data can be susceptible to bias (Tuler & Kasperson, 2013). Independent assessments done by us, watchdog organizations, and any other third-party would reduce this bias and are more reliable to the community. Funding for organizations that do this work will allow for different groups to provide their own assessments, and increase social trust in the laboratory itself (Tuler & Kasperson, 2013). Because of its ability to improve the conditions, we recommend more financial support from the DOE to enable watchdog organizations and others to do independent assessments of environmental data in New Mexico. These funds can promote public interest and involvement with decision-making processes regarding remediation of contaminated sites as well as to promote best practices for remediation of contaminated sites.

Conclusion

The difficulties in proper clean-up reside in mischaracterizing contamination, budgetary concerns, and limited public awareness (Bridges et al., 2005). Consistent data sampling, public confidence in data analysis, more funding for independent assessments, and public involvement in future land-use discussions are necessary to overcome these problems (Tuler & Hersh, 2012; Tuler & Kasperson, 2013). For these reasons, the quality of long-term stewardship measures will be improved if these solutions are put into place. Environmental decision makers, in our case the DOE and the NMED, must also find a fine balance between addressing the contamination with haste, considering climate change uncertainties, and taking precaution on the grounds of ethics (National Research Council, 2000; Kasperson, 2008).

Acknowledgements

Our project had several helping hands along the way. We would like to acknowledge and thank the following individuals for their help during the duration of this project. Without their guidance, our project would have not been a success. We would like to begin by thanking our primary advisor, Seth Tuler, who is the WPI Santa Fe Project Center Advisor. Seth helped us with structuring and revisional changes with the report, as well as counseling us with painting a clearer picture about the overall issue at Los Alamos National Laboratory (LANL). Scott Kovac is the NukeWatch Operations and Research Director and our sponsor for the project. Scott has been the catalyst for this project, constantly offering background information about current events and history at LANL, as well as helping the team to decide what the core meaning of this project was. We are truly grateful for his help. Carol Stimmel was our ID 2050 Advisor and taught us many interpersonal communicative skills to aid in the conduction of our project. Some of these skills included working in a team setting and how to conduct surveys or interviews. Marco Kaltofen is an Associate Research Engineer in the Nuclear Science and Engineering Program at WPI. Marco counseled the team on the issue of climate change and contamination migration at LANL and helped us to make conclusions for these topics based on our data. Fabio Carrera oversees the Santa Fe, New Mexico project center for WPI. We appreciate his coordination to make this project possible. We would once again like to thank those listed previously for their time and commitment to our project.

Authorship

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2.3 Migration of the chromium plume beneath Sandia and Mortandad Canyons calls for its full remediation	Caran	Caran
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Glossary

Aquifer	An underground layer of permeable rock containing or transmitting groundwater.
Biologic uptake	When environmental chemicals and substances are incorporated into a living organism.
Consent order	An agreement to a dispute, agreed upon by both parties, governed by federal and state laws.
Corrective measures evaluation	A study to determine the correct action to be taken at a facility.
Department of Energy (DOE)	A cabinet-level department concerned with energy and safety with regards to nuclear material.
Environmental Protection Agency (EPA)	A U.S. government independent executive agency focusing on environmental assessment, research, and education.
Erosion	When surface processes such as water or air flow move soil or rock away from its original location to another location.
Half-life	The time it takes for an isotope to decrease to half of its radioactivity.
In situ treatment	A type of contamination remediation performed directly on the site without excavating or disturbing the soil.
Insolubility	A chemical's inability to be dissolved in a certain substance.
Interim measure	A set of actions that have a high probability of meeting environmental protection goals until a final remedy is implemented.
Ion exchange	The exchange of ions of the same charge between an insoluble solid and a solution in contact with it that is used in purification and separation processes.
Isotopes	Different forms of the same element with different numbers of neutrons and therefore different atomic masses.
Leachate	Water that has percolated through a solid and has drained out some of the constituents.
Los Alamos National Laboratory (LANL)	A Department of Energy lab that was originally where the Manhattan Project's nuclear testing took place during WWII and is currently a major science and technology institution.

Low-level waste (LLW)	Nuclear waste below an intermediate level, not actually defined by its radioactivity.
Material Disposal Area	An area designated by LANL for disposal of certain wastes ranging between LLW, transuranic waste, etc.
Micrograms	One millionth of a gram.
Mobile colloids	A mixture of non-settling, suspended particles dispersed throughout the surface of a solution.
New Mexico Community Foundation (NMCF)	A grant-making foundation that supports underserved communities and strengthens nonprofits in New Mexico.
New Mexico Environment Department (NMED)	An organization that provides regulatory oversight for hazardous waste generators, treatment, storage, and disposal, among other missions.
Nuclear Watch New Mexico (Nukewatch)	A watchdog organization, and also our sponsor, that aims to reduce the use of nuclear weapons and testing and to advocate for nuclear waste cleanup.
Plume	A concentrated area of polluted water in an aquifer.
Pueblo	A settlement of American Indians in the southwest of the United States, mostly consisting of multistory adobe houses.
Pueblo de San Ildefonso	A self-governing, federally recognized Pueblo tribe located in Santa Fe County.
Radionuclides	Unstable atoms that have excess nuclear energy.
Regional aquifer	An aquifer that supplies at least 50% of the drinking water for its service area that has no reasonably available alternative drinking water sources.
Saturated thickness	The vertical thickness of the defined aquifer in which the pore spaces of the rock forming the aquifer are filled (saturated) with water.
Sorption	Absorption and adsorption considered as a single process.
Sub-micrometer	Having a scale less than one millionth of a meter.
Subsurface	A layer or a series of layers of rock in the ground below the surface of the Earth.

Technical Area	A portion of LANL property with boundaries designated by the laboratory based on site operations and intersecting roads and rivers.
Transuranic waste	Waste that has been contaminated with alpha-emitting transuranic radionuclides having a higher atomic number than uranium (92), possessing half-lives greater than 20 years, and in radioactivity concentrations greater than 100 nanocuries per gram.
Watchdog organizations	Non-governmental organizations whose common mission includes monitoring governmental organizations for fraud, abuse, corruption, and the like.

Chapter 1: Introduction

Over the course of the twentieth century, development, experimentation, and testing of atomic weapons have spread toxic waste through the United States' land and waters (U.S. Congress, Office of Technology Assessment, 1991). This issue has manifested in Department of Energy (DOE) managed sites such as the Hanford Site, Rocky Flats, and the Nevada Test Site, which served as the testing ground for over 1000 nuclear weapons detonations (Kersting et al., 1999; Moore, 1998; Office of River Protection: DOE, 2020). After years of waste disposal, nuclear fallout, and contaminant migration in groundwater, the DOE continues to struggle to characterize, clean-up, and remediate lands in consideration for future use (Kersting et al., 1999; Moore, 1998; Office of River Protection: DOE, 2020).

Los Alamos National Laboratory (LANL) in northern New Mexico has played an essential role in the nuclear weapons complex and has historically practiced poor waste disposal techniques, making it a major source of groundwater contamination (DOE, 2001). The contamination has the potential to impact public health and raises issues of environmental justice. LANL is a part of a larger Sacred Area that has historically been home to Pueblo Tribes whose public health and natural resources are now at risk of major pollution (Clapp & Silver, 2006; Masco, 2006). Currently, there are multiple efforts between the DOE, the New Mexico Environment Department (NMED), and affected stakeholders about how portions of the property should be remediated, two of which concern Material Disposal Area C (MDA-C) and the chromium plume in Technical Area 5 (TA-5) (DOE Office of Environmental Management, 2019). Upcoming decisions anticipated in 2021 will be critical to future land-use at these sites.

The first site of concern is MDA-C, a 12-acre plot that served as a primary toxic waste dump for LANL and contains significant quantities of radioactive and chemical waste (Department of Energy: Office of Environmental Management, 2019), including plutonium which can be dangerous for the next half million years (Wolchover, 2011). The presence of plutonium threatens regional aquifers that provide drinking water to nearby communities through migration (Marty et al., 1997). The DOE will finalize key actions for remediation upon the release of a corrective measures evaluation in early 2021, which is an opportunity for the community to voice input and concerns. Whether or not plutonium from MDA-C is migrating off the site should inform the choice of options, ranging from simply covering the area with an impermeable cap or relocating the radioactive material to a repository where it will be permanently stored (Nuclear Watch New Mexico, 2020).

The second site of concern is a subsurface plume of chromium-6 in the northern section of the property (Amigos Bravos & Concerned Citizens for Nuclear Safety, 2006; Los Alamos Study Group, n.d.). Chromium threatens the Pueblo de San Ildefonso and has the potential to migrate to Los Alamos County water supply wells, posing widespread exposure risk (Oswald, 2015; Andersen, 2018). The DOE has enacted an interim measure to control the contamination and will propose a final remedy in 2021, which will be subject to public comment and analyzed for approval by the NMED (DOE, 2015; N3B Los Alamos, 2019). This decision should be informed by a good understanding of sampling data in order to gain an updated picture of the extent and shape of the plume (Chamberlain, 2019).

An important factor that bears on choices of the final remedies are long-term resilience and adaptivity to the changing climate in New Mexico. The Third National Climate Assessment expects the region to experience significantly drier and hotter days due to reduced late-winter and spring snowpacks and increased average annual temperatures. These changes are predicted to lead to earlier snowmelt and promote severe droughts. Although there is expected less precipitation overall, the assessment predicts that the limited amount of rainfall events will become more intense (Garfin et al., 2014). Assessing groundwater remediation approaches at LANL should therefore involve determining the system's exposure to these climate effects and their potential impacts, including decreased percolation through soil, groundwater level decline, degradation of system components, and altered mobilization of contaminants (EPA, 2019; Maco et al., 2018). Having foresight will be essential to prevent system failures, insufficient treatment, and unexpected costs (EPA, 2019).

The goal of our project was to assess the presence and migration of plutonium-239 from MDA-C and chromium-6 from TA-5 using available environmental sampling data to inform ongoing debates about remediation approaches on the property. Our analyses will serve the purpose of supporting our sponsor, Nuclear Watch New Mexico (NukeWatch), in their safety and environmental protection efforts. NukeWatch has long lobbied for remediation at LANL and calls for more transparency in operational activities at the laboratory. The team delivered on our goal for NukeWatch by:

1. Collecting data about plutonium-239 and chromium-6 contamination in Los Alamos National Laboratory property and surrounding areas available from a publicly accessible database.
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3. Assessing the feasibility and resilience of remedial options for Material Disposal Area C and the chromium plume.

We were able to confirm that the inject-and-treat efforts at the bottom of the chromium plume were working, but the plume shape is rapidly changing in multiple ways. We looked deep into the plutonium data, finding many examples of inconsistent sampling. Subsequently, there was little to say about migratory trends, but samples showed plutonium at concerning depths in TA-50 and an increasing contamination trend at Cochiti Lake. We learned to use Intellus, dodge its flawed conventions, and deliver to our sponsor on their desired datasets. We made recommendations using our research into remedial technologies to put our data into context and aid Nukewatch in preparing for their next steps. The team hopes that these results inspire further investigation into the remedial efforts ongoing at LANL.

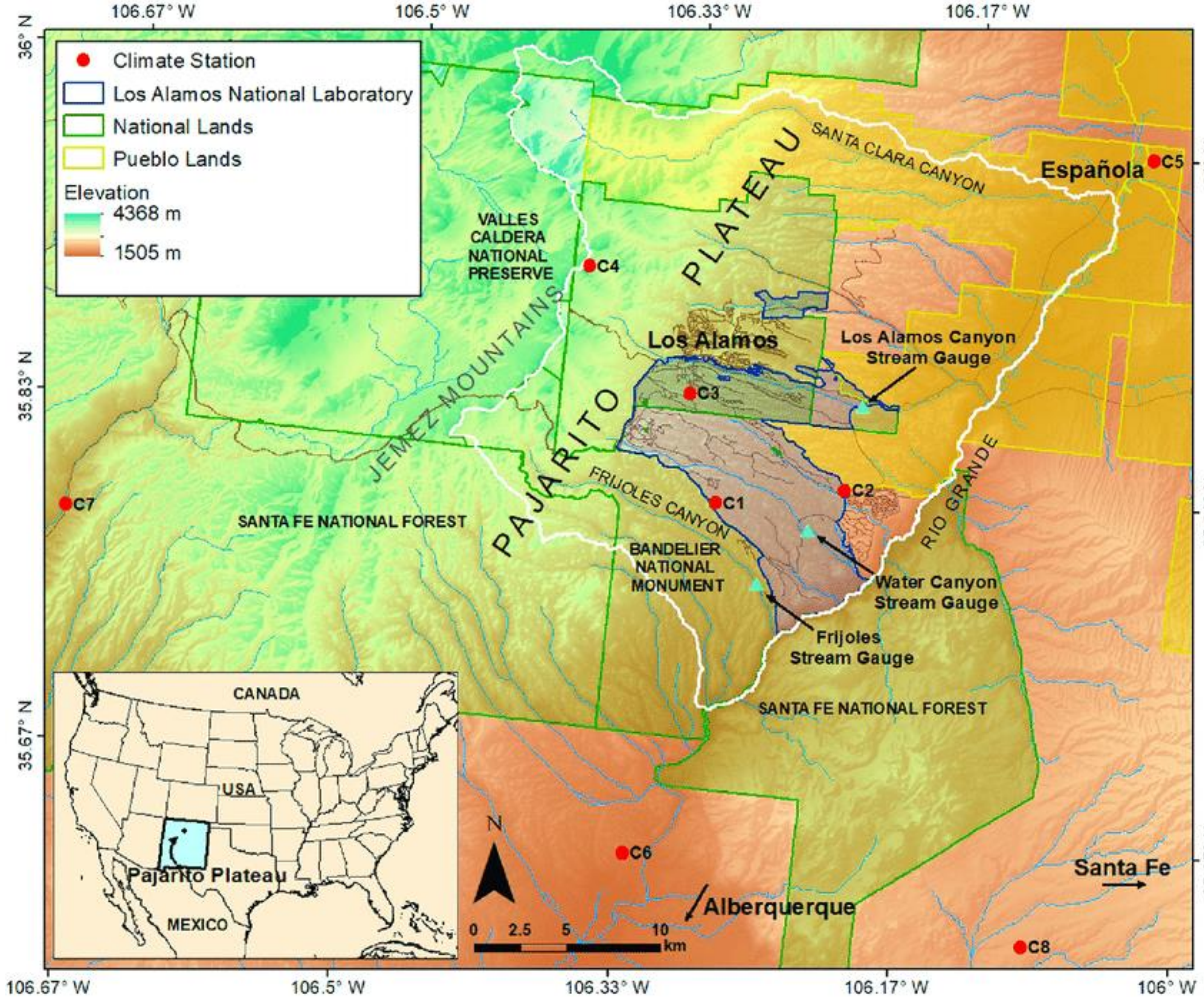
Chapter 2: Background

2.1 LANL has a history of problematic toxic waste disposal methods

LANL is located twenty-five miles northwest of Santa Fe, New Mexico. The site spans forty square miles and is dissected by canyons that are several hundred feet deep and drain into the Rio Grande river, shown in Figure 1. The aquifer beneath the plateau is the sole water supply for the lab and the communities of the Los Alamos region (Lauf & Buchheister, 2019).

Figure 1.

Physical Map of LANL in Northern New Mexico (Pajarito Plateau Study, 2020)



Note. This map depicts northern New Mexico known for its canyons and desert environments. LANL is depicted in relation to the nearby Pueblo.

It was at LANL that the United States conducted nuclear weapons research during World War II. With whispers that the Nazi regime in Europe was working on a nuclear device to use against the allies, several concerned physicists, including the famed Albert Einstein, wrote to then-president Franklin Delano Roosevelt, urging him to create a program to research nuclear weapons. Months later, a well-known nuclear physicist, J. Robert Oppenheimer, was tasked with leading the research efforts. LANL was established by the U.S. Department of Energy (DOE) in 1942 to serve as a key center for the named Manhattan Project (Lauf & Buchheister, 2019). The project took only twenty-seven months to research, produce, and test the world's first nuclear weapon. From the Cold War and up to present day, LANL has been conducting research and production of vital elements of nuclear weapons (Belfer Center, 2013).

Since the conclusion of the Manhattan Project at Los Alamos, the laboratory continued to ramp up their research efforts as the Cold War intensified. As scientists raced to develop more devastating weapons, the waste products that they created were neglected. Two of these materials were chromium-6 and plutonium-239. These wastes were simply buried in shallow pits or trenches, leaving them to migrate through groundwater. Furthermore, there are major discrepancies in the materials accounts specifically for plutonium at LANL because disposal of plutonium wastes (stored, buried, or discharged) was not consistently documented. Radioactive isotopes can be dangerous even in tiny quantities, so special care must be taken to monitor and safeguard these sites (Gray, 1995). They can also be dangerous for long periods of time. For example, plutonium-239 isotope has a half-life of over 24,000 years. This can cause a number of issues when attempting to store it for long periods of time.

NukeWatch is a watchdog organization that has been lobbying for LANL to remediate their contamination for years. They have influenced many of the laboratory's decisions in the past, and they continue to educate the public about nuclear waste hazards in New Mexico. Their primary focus is on global nuclear de-weaponization and the de-escalation of nuclear programs. NukeWatch accomplishes their mission by presenting relevant data, infographics, and activist memos that argue against nuclear testing, faulty cleanup procedures, and the continuing spread of contaminants. They compile information on nuclear contamination in the Los Alamos area and endeavor to make data more accessible to the everyday citizen. Through these efforts to make data more understandable and available, NukeWatch helps educate both politicians and the public on the risks of instances of contamination (NukeWatch, 2020).

There are two main areas of high concern at LANL that are currently up for remediation proposal:

1. The first area is TA-50, which contains a disposal region called MDA-C where plutonium-239 and other hazardous materials were dumped through the 1960s (LANL, 2005). This area was used prior to the creation of the Environmental Protection Agency (EPA) in the 1970s, thus no environmental safety measures were taken to ensure the safe disposal of radioactive material in the area.
2. The second area is TA-5 where chromium-6 contamination from cooling towers in TA-3 has migrated and pooled on top of the regional aquifer. The chromium-6 was used as an anti-rusting agent in the cooling towers prior to its migration to TA-5 (N3B Los Alamos, 2019).

LANL is due to propose remediation plans for both of these areas between 2021 and 2025.

2.2 Transuranic groundwater pollution within Material Disposal Area C warrants more concern in the remediation conversation

MDA-C served as the main disposal site for LANL before Material Disposal Area G (MDA-G) and was in operation between 1948 and 1974. At MDA-C, more than 3,000,000 cubic feet of transuranic waste has been disposed of within the nearly 12-acre area across 7 pits and 108 shafts at depths up to 25 feet (Los Alamos Study Group, n.d.; U.S. DOE: Office of Environmental Management, 2019). The transuranic wastes of concern include plutonium, uranium, americium-241, sodium-22, cobalt-60, strontium-90, uranium-233, and other fission products (Los Alamos Study Group, n.d.). The nature of this waste ranges from extremely radioactive products such as plutonium-239 that pose immense danger to humans and animals to contaminants with minimal toxicity such as mercury, copper, cobalt, boron, beryllium, and silver (Iryna, 2017). Remediation at MDA-C is an important precursor to an eventual clean-up of

MDA-G which is home to more than double the amount of waste that is buried at MDA-C (S. Kovac, personal communication, 2020).

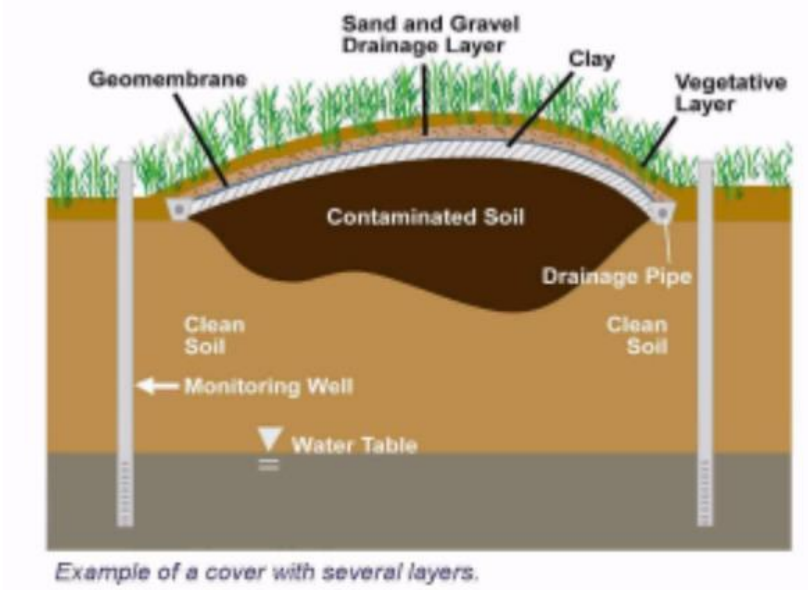
Environmental sampling has demonstrated that Plutonium has leaked into the surrounding soil and groundwater over time. This has created a toxicity problem, one that now shows evidence of faster-than-anticipated migration (Marty et al., 1997). Plutonium appears to have now migrated into the Espanola Basin, which is becoming an increasingly important water source for 270,000 people across the towns of Espanola, Santa Fe, and Los Alamos (NukeWatch, 2020). Furthermore, plutonium has also been observed at depths that exceed 1,300 feet and threaten the regional aquifer (Nuclear Watch New Mexico, 2020). This migration raises concern for human health since its path could extend in the direction of nearby communities and the Rio Grande, a source of drinking water for millions of people (International Boundary & Water Commission, n.d.). For example, the town of White Rock, is directly in the path of the migration pathway. The town's aquifer lies directly under LANL property and is supplied through the Pajarito Canyon. This groundwater transportation pathway runs through White Rock and into White Rock Canyon where it empties into the Rio Grande River (Color Plates, n.d.).[1] Plutonium contamination in this water pathway has the potential to spread into the drinking water of thousands of New Mexicans.[2]

In 2012, the DOE proposed to remedy the problem at MDA-C with a cap-and-cover approach, which would entail covering the contaminated area with an impermeable barrier and monitoring for migration via nearby wells. Contaminants have already migrated far from the source at MDA-C, and this proposed method is not usually intended to be used with the hazardous radioactive waste types that are present at MDA-C (U.S. EPA, 2012). Below, a schematic of a cap-and-cover system labeled Figure 2 can be seen. In this approach the pit that holds the contaminated soil is unlined and therefore not completely sealed, so there is still risk for potential contaminant migration. Over time, the cap can wear and break down due to weather events and plant intrusion, which could limit the lifetime of the remedy and create the need for more maintenance. Due to contaminants remaining near the surface, institutional controls will be necessary and limit safe future land-use of the area. Institutional controls are not reliable over the long term because they, "...will require extensive monitoring, maintenance, and oversight. This means that the technical performance of the remedy is dependent on non-technical factors over which DOE and federal regulators have little influence. For example, the performance of a remedy can depend on the vigilance and willingness to enforce restrictions by local government officials who may be overworked and under-funded. They are also dependent on factors over which federal regulators do have some influence, but are not very good at ensuring; these include long-term budgetary commitments and institutional vigilance" (Tuler & Hersh, 2012).

[1] See Figure D2 in Appendix D.
[2] See Appendix A for more information on plutonium-239 contamination at LANL.

Figure 2.

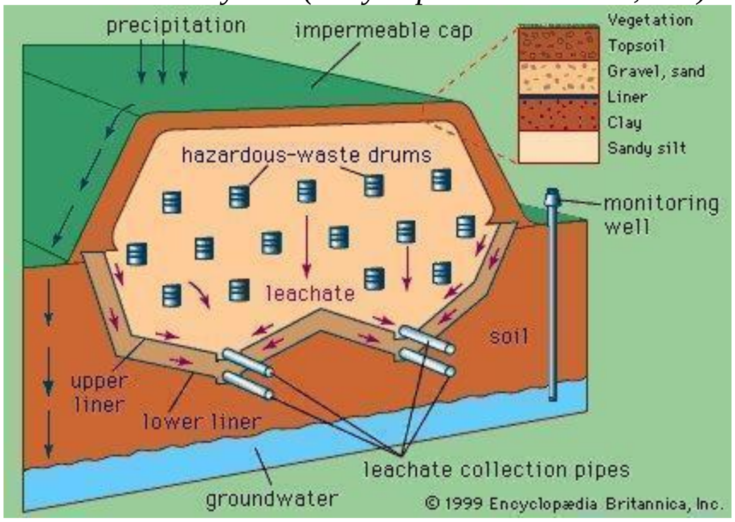
Schematic of a Cap-and-Cover System (EPA, 2012)



Note. This schematic displays a cap-and-cover system with various layers and monitoring wells to monitor for migration of contaminants away from the source.

On the other hand, NukeWatch recommends a full, comprehensive, job-producing cleanup in which LANL characterizes the buried waste at MDA-C, sends the highly radioactive transuranic waste (including plutonium) to the WIPP, and lines the landfill with a leachate collection system to safely collect other contaminants. A leachate collection system, as shown in Figure 3, would slowly diffuse the toxicity of the leftover low-level waste (LLW) still stored at LANL (Waste Management, 2020). While this process would cost the DOE far more money and take more time to complete than a simple cap-and-cover approach, it has advantages. Deep underground repositories such as the WIPP allow for multiple barriers that are both engineered and natural such as rock, salt, and clay. The isolation of the contaminants mitigates risk to humans and the environment and is intended to limit the obligation of facility maintenance by future generations (World Nuclear Association, 2020).

Figure 3.
Schematic of a Leachate Collection System (Encyclopedia Britannica, n.d.)



Note. This schematic depicts a leachate collection system. As can be seen, the hazardous waste is securely buried in a lined landfill that allows for the leachate from the waste to percolate down to the collection pipes in which it can then be removed and properly disposed of. This allows for a slow detoxification of LLW.

As the discussion regarding remediation of MDA-C continues, climate change is an important factor that may impact long term functioning of remedies because of the increasing role that environmental factors are playing in the execution of remedial options (EPA, 2019). Looking ahead, New Mexico is expected to experience higher average annual temperatures and less rainfall on average, and when it does rain, it is expected to come in the form of strong and violent storms. This will likely cause a decrease in the amount of water available to percolate down through the soil into the regional aquifers and instead the majority of rainwater will rapidly wash through and create dangerous flash floods. This effect coupled with a shallower and shorter lasting spring snowpack in the mountains will create a greater reliance among the people of New Mexico on the regional aquifers, which due to the drier climate will have slower recharge rates. Over time, this will cause the level of the aquifers to decrease (Union of Concerned Scientists, n.d.; Gonzalez et al., 2018). For this reason, proper remediation to ensure that groundwater resources are not contaminated is all the more important. New Mexico will also continue to see worse storms and more frequent wildfires; issues that LANL is already coping with (DOE, 2015). The potential effects of such weather events on engineered remedial solutions will need to be considered (Maco et al., 2018).

2.3 Migration of the chromium-6 plume beneath Sandia and Mortandad Canyons calls for its full remediation

Groundwater sampling data from monitoring wells at LANL indicate the presence of chromium-6 contamination resulting from historical discharge of wastewater from Technical Area 3 (TA-3), which was active from 1956 until 1972 (N3B Los Alamos, 2019). A non-nuclear power plant with cooling towers located in TA-3 was the source of the contamination. The pipes of the cooling towers were coated with a corrosion-inhibiting and anti-rusting chemical called potassium dichromate, which dissociates to produce chromium-6 (Katzman, 2017). Workers periodically released chromium-contaminated wastewater from these towers into the head of Sandia Canyon (NukeWatch, 2017). About ninety percent of the chromium-6 converted to non-toxic chromium-3, while the remaining chromium-6 (estimated to be at least 2,000 kg) traveled down Sandia Canyon via surface water and seeped through the underlying rock layers into the regional aquifer below Mortandad Canyon to become the existing plume (Chamberlain, 2019; N3B Los Alamos, 2019). Figure 4 displays the pathway of the wastewater from the source to the aquifer.

Figure 4.
Chromium Contamination Pathway (Katzman, 2017)

In December 2005, LANL reported to the NMED that there was a chromium plume located 900-1,000 feet below the canyon bottom and within the top 100 feet of the aquifer (Katzman, 2017; N3B Los Alamos 2019). It measured approximately 1 mile long by 0.5 miles wide by 50 feet in depth (Katzman, 2017). Plume concentrations exceeded the New Mexico groundwater standard of 50 parts per billion (ppb) and the EPA's drinking water limit of 100 ppb and reached levels as high as 1,240 ppb in the center (DOE Environmental Management Los Alamos Field Office, 2015; Agency for Toxic Substances and Disease Registry, 2012; Longmire, 2015). Fortunately, TA-3 has ceased operations and there is no other active source of chromium-6 that could further contaminate the area (N3B Los Alamos, 2019).

With historical evidence that chromium migrates at speeds matching surface water and groundwater flows, chromium contamination is currently the laboratory's highest priority in on-site clean-up (Longmire, 2015; S. Kovac, personal communication, 2020). A Chromium Plume Control Interim Measure (IM) is currently being enforced by the DOE. The IM is a series of actions fully implemented in 2019 that LANL must make in order to meet environmental protection goals until the DOE can implement a final remedy to the contamination (N3B Los Alamos, 2019). The primary goal of the IM is to control expansion and limit downgradient migration of the plume as the DOE investigates options for a final remedy (DOE Environmental Management Los Alamos Field Office, 2015).

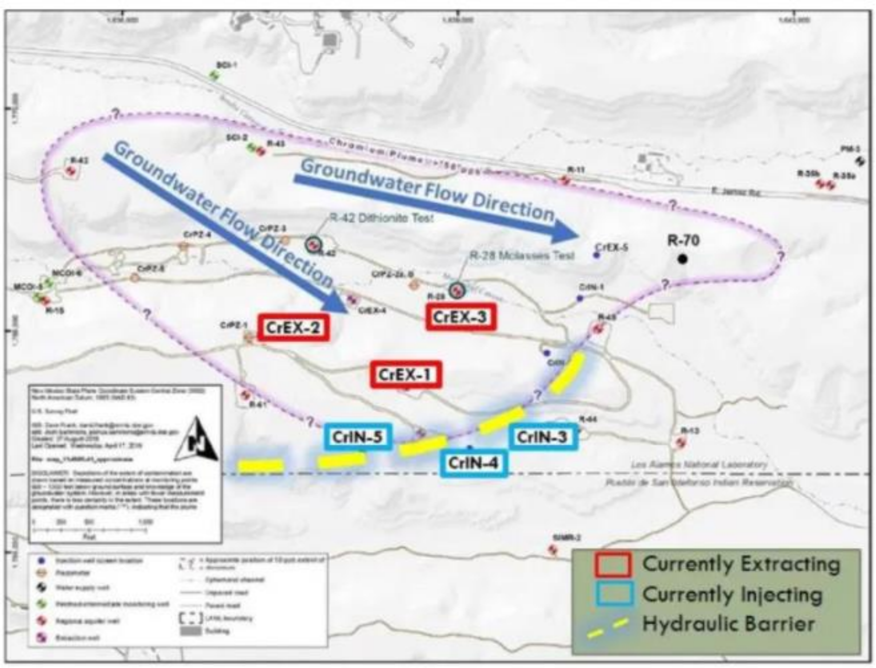
Through the enforcement of the IM, LANL has installed a network of wells in and around the chromium plume:

1. monitoring wells where samples of chromium concentration data are taken,
2. extraction wells that pump contaminated groundwater from the aquifer, which is then piped to a treatment system at the surface that uses a technology called ion exchange to remove chromium and bring the concentration below 50 ppb, and
3. injection wells that return the treated water to the aquifer at the edge of the plume (N3B Los Alamos, 2019).

Figure 5 pinpoints the locations of currently active injection and extraction wells and indicates general directions of groundwater flow. Over time, this extract-and-inject process will hydraulically control groundwater flow and ideally reduce the chromium concentrations at the plume edge, thereby gradually reducing the plume's size (N3B Los Alamos, 2019). A measurable goal from the IM is to pump 230 million gallons of contaminated plume water annually (DOE Environmental Management Los Alamos Field Office, 2015).

Figure 5.

Chromium Extraction and Injection Wells (Chamberlain, 2019)



In addition to operating this network of wells, the IM calls for LANL to characterize the plume center through a series of tests such as pumping and measuring water levels. The results from these tests will help the DOE evaluate the effectiveness and feasibility of either an in situ treatment or the continuation of a pump-and-treat method throughout the whole plume. An in situ treatment would involve the forced reduction of chromium-6 to chromium-3 through the introduction of chemicals directly into the aquifer. These chemicals undergo a reaction with chromium-6, thereby immobilizing it and eliminating its toxicity (Department of Energy Environmental Management Los Alamos Field Office, 2015). Through the IM, the NMED and the DOE have conducted a couple pilot-scale tests that introduce sodium dithionite to well R-42 and molasses to well R-28 in the plume center. Some advantages of this approach are that the contaminated media is not brought to the surface, so there would be no potential cross-media contamination, and there would be no disposal requirements or transportation costs of the treated water. This option seems the simplest but the most invasive as the chemicals may disrupt the surrounding environment in ways that cannot be holistically predicted. For example, the introduction of chemicals may yield unwanted byproducts. Therefore, it would be inefficient if the exact location of the plume is not determined. After the IM is completed, the DOE can determine and propose the final remedy, which will be subject to public comment and analyzed for approval by the NMED (DOE Environmental Management Los Alamos Field Office, 2015).

The locations of the injection wells on the border were chosen based on the belief that they were located where detection samples are below the New Mexico groundwater standard. They essentially formed the boundary of what legally requires treatment. However, NukeWatch discovered data from an injection (CrIN-6) in July 2017 of a chromium concentration level five times greater than the standard, characteristic of the plume center. This value suggests that the size of the plume was either underestimated or has expanded since the implementation of the network of wells and knowledge of the current boundaries of the plume are unclear. A consequence could be that this well meant to inject treated water back into the aquifer at the plume edge was actually injecting treated water somewhere within the plume and pushing the contamination further east (Nuclear Watch New Mexico, 2017; Chamberlain, 2019). After this discovery, CrIN-6 was converted to extraction well CrEX-5 in June 2018 and a new well, R-70, was installed 700 feet east of CrEX-5 in May 2019 to help characterize the northeastern plume area (Hintze, 2019). Boundary approximations have increased to 1.7 miles long by 0.7 miles wide, and the lateral and vertical extent of the plume and the complex groundwater flow paths are still not completely defined. Further migration can reach the Los Alamos County water supply well PM-3 northeast of the plume or cross the boundary that LANL shares with Pueblo de San Ildefonso south of the plume, as shown in Figure 5 (Andersen, 2018).

Alarmingly, the monitoring well closest to the Pueblo (R-50) has data of chromium concentrations between 80 and 120 ppb, a range that exceeds the state standard (Oswald, 2015). Chromium is naturally occurring at low levels, but higher concentrations like these can damage the liver and kidneys and cause cancer (Clean Water Action, 2020). Therefore, Pueblo de San Ildefonso is an important stakeholder regarding remediation of the chromium plume since they have high exposure risk. Additionally, an environmental change to LANL property creates a widespread cultural impact to Pueblos because it is located on a Pueblo Sacred Area (DOE Environmental Management Los Alamos Field Office, 2015). Pueblo representatives explained that all resources within the Sacred Area are connected to one another, so any remediation of the plume would result in a holistic impact to the resources and their associated practices (DOE Environmental Management Los Alamos Field Office, 2015).

Given the available information and uncertainties, various stakeholders are asking that the DOE and the NMED rethink their treatment plan before they make a decision on the final remedy. The fact that the chromium plume is expanding or migrating adds a layer of complexity that must be taken into consideration. It would not be effective if they prematurely treat the plume without properly characterizing its heterogeneous shape. Therefore, evaluation of the IM and selecting and approving the final remedy could take a number of years (N3B Los Alamos, 2019)

Chapter 3: Methods

The goal of our project was to assess the presence and migration of plutonium-239 from MDA-C and chromium-6 from TA-5 using available environmental sampling data to inform ongoing debates about remediation approaches on the property. Our analyses will serve the purpose of supporting our sponsor, Nuclear Watch New Mexico (NukeWatch), in their safety and environmental protection efforts. NukeWatch has long lobbied for remediation at LANL and calls for more transparency in operational activities at the laboratory. The team delivered on our goal for NukeWatch by:

1. Collecting data about plutonium-239 and chromium-6 contamination in Los Alamos National Laboratory property and surrounding areas available from a publicly accessible database.
2. Assessing migration of plutonium-239 and chromium-6 in soil and waterborne samples over time.
3. Assessing the feasibility and resilience of remedial options for Material Disposal Area C and the chromium plume.

3.1 Objective #1: Collecting data about plutonium-239 and chromium-6 contamination in LANL property and surrounding areas from a publicly accessible database.

The core of this project involved extracting information from the publicly accessible Intellus New Mexico database. Intellus is a system curated by LANL to be more transparent. It has data from over fifty years on the contamination of the site and is our primary source when it comes to samples on the property.[3]

Our team relied on Intelius for pulling all data related to plutonium-238/239/240 and chromium-6 located throughout numerous technical areas at LANL. In searching the database, the team utilized a variety of search terms and groupings to narrow down the results provided by Intellus. The team developed standards for our data collection in order for the data to easily be combined and divided as needed and for simplicity and comparison.[4]

The data we retrieved from LANL had many characteristics for each data point (twenty-five in total). Table 1 outlines the characteristics most often used in our data analysis.

[3] See Appendix B for more information on Intellus.

[4] See Table B1 in Appendix B for our data collection standards and our reasoning for them.

Table 1.
Intellus Data Categories

Intellus Category	Their Importance.
Latitude and Longitude	The location of the data point is important. Longitude and latitude data are compatible with most graphing softwares like Excel, allowing for easy superimposing of the data onto maps.
Report Results	This contains the value of the sample taken. It is usually a number relating to the amount/concentration of contamination in an area.
Report Units	This gives the data clear meaning by telling the units that report results are in.
Sample Type	This indicates the medium of the sample. An example would be W for Water and SED for Sediment.
Sample Date	This is important to know in order for us to detect changes in sample results over time. This helped us to isolate certain time frames for the data we collected.
Sample Depth	Sample depth includes the following sub-categories: sample start depth, sample end depth, and sample depth units. These come together to give us a picture of where this sample was taken and its height. Some data lacks this information, which can mean that it was faultily imputed, so the depth was assumed to be the depth of the well in consideration.

Intellus has other features that were useful to the team, including its mapping functions. These functions were useful for finding specific wells of interest or looking at very exact data and the full reports associated with these data sets. While these could be useful for context or answering technical questions, they are not central features to their project as they were not easy to extract data from and do not provide neutral commentary, respectively.

Data on chromium-6 was pulled from the plume's origin in TA-3 in the direction towards the Bandelier National Monument. This area also includes Technical Areas 5, 50, 72, and the property of the Pueblo de San Ildefonso. This transportation pathway follows the general flow of water in the region. This is the likely path that the chromium plume will continue to migrate in as it makes its way towards the Rio Grande.[5]

For plutonium, we collected data for plutonium-239 as well as its isotopes plutonium-238 and plutonium-240 since they indicate previous presence of plutonium-239. We extracted data related to the migration pathway between MDA-C in TA-50 and MDA-G in TA-54 towards the direction of the Rio Grande. This follows the general path of the watershed.[6] We considered how rapidly plutonium is migrating through viewing data points that were sampled within this area.

[5] See Figure D1 in Appendix D for the chromium transportation pathway.
[6] See Figure D1 in Appendix D for the plutonium transportation pathway.

We did this in order to make an assessment on the potential for resource contamination as well as a proper mode of containment or remediation.

Upon downloading the CSV spreadsheet from Intellus, the team converted the file into a Macro-Enabled Excel Worksheet. This is where we performed the bulk of the analysis, calculations, and visualizations for analytical work and displaying data. Our team used functions on the data, including a log function that aids in the visual clarity of the data when displayed on a map or graph. We used $\log_{10}$(result*10,000). Downloading this data was often challenging due to various issues with the Intellus database, as outlined in section 4.3.

3.2 Objective #2: Assess migration of plutonium-239 and chromium-6 in soil and waterborne samples over time

We created methods of displaying the contamination data using the graphing and mapping functions in Excel to create visual representations of the chromium and plutonium contamination at LANL and surrounding areas. When displaying the information, we considered that:

1. for information to convey a certain message and be easily understood, it must use clear and plain language, respect the audience and its concerns, and seek strictly to inform the viewer or reader, and
2. clarity is essential when creating effective visualizations. Images must be carefully chosen, vivid, and concrete, and the use of personalized examples can further enhance understanding (National Research Council Committee on Risk Perception and Communication, 1989).

Especially since our project involved technical details and quantitative data complexity, we tried to communicate key information in simple terms through interactive maps and graphs. These forms of information were made simple enough for anyone to explore, regardless of their educational background or professional occupation.

Chromium

The NMED and the DOE have spent the past several years trying to determine the size and extent of the plume. Due to its constant movement, it has been difficult to track the ever-changing boundaries of the plume, making its containment a challenge. We produced the following visuals using Excel graphing and mapping functions to develop our own understanding of the plume:

1. Concentration over time graphs and heat maps for individual monitoring wells in TA-5 where the plume is located.
2. Concentration heat maps depicting the changing shape of the chromium plume in TA-5 from 1970 and 2020 and from 2017 and 2020.
3. Concentration over time graphs and a heat map of the technical areas in the chromium migration pathway.[7]

[7] See Figure D1 in Appendix D for the chromium transportation pathway.

First, we created a graph of chromium concentration levels over time for each regional, intermediate, injection, and extraction well in TA-5 within or surrounding the plume. These graphs depict whether the contamination is changing or staying static at specific locations. Then, we created heat maps for each well, which show the intensity of the contamination over time using a color scale by value. We used different colors to indicate if sampling data exceed the New Mexico standard of 50 ppb or exceed the EPA standard of 100 ppb (DOE Environmental Management Los Alamos Field Office, 2015; Agency for Toxic Substances and Disease Registry, 2012). These graphs allowed us to visually compare contamination between individual wells.

After focusing on individual wells, we zoomed out by creating one concentration heat map of the plume from the years 1970 to 2020 to depict the historical and current state of the plume. Then, we mapped data within a shorter time frame between the years 2017 and 2020. The starting year was chosen because it was the earliest year in which data exists for all of the plume wells. This eliminated the influence that monitoring at some wells did not happen before 2017. This map allowed us to accurately picture the changing shape of the plume and will be especially useful in the future when new data is taken for comparison. To make both of these heat maps, we used the data we collected for individual wells and combined them into one spreadsheet.

Thirdly, we zoomed out further and looked at the contamination across the chromium migration pathway by creating concentration over time graphs and a heat map of TA-3, the entirety of TA-5, TA-60, and TA-72. The graphs helped us to see if there are any high chromium levels outside of the plume. The heat map helped us to visualize how the chromium has historically moved down the technical areas in the pathway.

It is important to note that we also planned to graph sample depth values over time as well as groundwater levels over time to understand groundwater flow paths that transport chromium. Although monitoring the plume intensified in 2005, the majority of concentration sampling data lacks corresponding depth measurements, and groundwater elevation values are absent for TA-5. Due to lack of data required, we were unable to deliver these graphics.

Plutonium

Possible migration of plutonium out MDA-C and MDA-G is cause for concern. Using Excel mapping functions, we created visual displays of the data that better represents the contamination than the map built into Intellus. We created the following maps that visualize the data in the clearest ways possible in order to promote easier and more reliable analysis:

1. Water level measurements within TA-50, one of the sources of plutonium contamination, is displayed in scatter plots.
2. The depths of samples collected, as well as the depths of positive plutonium contamination readings was displayed in scatter plots.
3. Map showing areas close to LANL boundaries and all available off-site samples.
4. Map specific to water samples off-site at Cochiti lake.
5. Maps and bar charts depict testing over time to visualize the number of samples and locations of samples.

The EPA has defined that the standard safe level for Alpha particle activity in drinking water is 15 picoCuries per liter (pCi/L) (EPA, 2018). We analyzed the levels of all of these boreholes and compared them to EPA standards. High levels of contamination in these areas are the largest cause for concern.

3.3 Objective #3: Assessing the feasibility and resilience of remedial options for Material Disposal Area C and the chromium plume

Using our analysis of plutonium and chromium contamination, we drew attention to relevant trends and gaps in existing information so that NukeWatch and other interested parties can advocate for proper next steps in remediation of MDA-C, the chromium plume, and future sites.

Chromium

The final remedy of the chromium plume can either be a pump-and-treat system or an in situ treatment. Results of the IM, which implemented the extract-and-inject system at the plume borders and pilot treatments at two regional wells at the plume center, will help the DOE determine the viability of each approach. After collecting chromium data from these wells and creating graphs and maps to visualize the changing concentration levels over time at these locations, we developed a better understanding of how feasible the remedies were on a small-scale and how they impacted certain characteristics of the plume.

First, we used the analysis of chromium concentrations over time to give us ideas of how chromium may be migrating to different locations:

1. whether extraction and injection wells at the southern border of the plume are hydraulically controlling the plume to prevent contamination from entering the Pueblo de San Ildefonso.
2. if treatment has been eliminating chromium-6 in regional wells R-42 and R-28. Evaluating the success of reducing contamination at these wells will guide discussions on the best approach for complete remediation of the plume.
3. if there are other problem areas of contamination that should be brought to attention.

Second, we analyzed plume concentrations to assess the changing shape of the plume and identify its boundaries. This information will be important when considering possible reevaluation of the IM if the plume has changed significantly. These maps gave us a picture of the lateral extent of chromium contamination.

Nevertheless, the vertical extent of contamination remains unknown due to the lack of sampling depth measurements and groundwater elevation data where the plume is located (Andersen, 2018). This leaves us to wonder where the plume lies in the aquifer and what the groundwater flow paths in the aquifer look like. This information would have been valuable insight into how the plume might react to different groundwater conditions and how remedies might respond to climate change effects. For example, a falling groundwater table could decrease access to the contamination, but it could also decrease contaminant transport, promoting containment of the plume. Alas, we were unable to make climate response predictions in the absence of needed data. Fortunately, the remedial options in consideration are short-term projects and will hopefully not experience many complications from extreme weather patterns.

Plutonium

In the case of MDA-C, the remediation method can either be a cap-and-cover approach or a comprehensive clean-up (NukeWatch, 2020). As a result of objective 2, we created maps to visualize the extent of plutonium contamination across LANL property and gather information on the groundwater levels over time. Coupling this information with background research on climate change and the remedial methods in consideration, we assessed the two options as they relate to efficacy in preventing contamination migration, extent of current migration, climate change, and future land-use.

First, we analyzed any trends in depths of plutonium samples over time in TA-50 to identify how soon the aquifer would be contaminated. Large gaps between sampling periods and uncertainty regarding how consistent the testing regimen was, motivated further testing to confirm the validity of the results.

Second, we assessed the extent of plutonium migration as it moves towards the Rio Grande. During analysis of the map, the reality that not all sample locations were consistently tested arose, and expectations for what could be shown with the available data required adjustment. One of the sites that showed contamination, Cochiti Lake, is downstream of LANL along the Rio Grande and thus warranted special attention as a marker of extensive migration.[8] We observed trends over time in plutonium concentrations at Cochiti Lake to gain an understanding of downstream contamination.

These graphs and maps painted a picture of the scale of the plutonium contamination at LANL. If our analysis found that plutonium had not migrated at a threatening rate towards the aquifer and it is not threatening surrounding communities, a conservative cap-and-cover approach may be appropriate, but in this case, the effects of climate change and questions of future land-use will still need to be considered and discussed. On the other hand, if after analysis plutonium appeared to be threatening the surrounding area, either through aquifer contamination or migration off property, a comprehensive approach on the scale of what is recommended by NukeWatch should be considered. Our final recommendations hinged on the x-factor of uncertain data inhibiting conclusive results.

Third, we analyzed the trend in groundwater elevation through graphing historical water levels in TA-50 and coupling this data with predictions from climate scientists. The graph depicting groundwater levels over time in TA-50 provided a historical data comparison to the predicted climate change effects (Gonzalez et al., 2018; Union of Concerned Scientists, n.d.). These trends will be integral in guiding discussion regarding how a shrinking aquifer and drier climate will affect remediation methods.

The subject of climate change as it pertains to remediation of MDA-C will require further discussion than simply consideration of water levels in the regional aquifers. Our review of the literature on climate change in New Mexico as well as how it pertains to the remediation methods in consideration with regards to MDA-C brought up concern for how severe storms and increased frequency of wildfires may affect the solutions being considered. We discuss these issues along with future land-use as they relate to remediation options at MDA-C in more detail in the results chapter of the report.

[8] See Figure D3 in Appendix D to see the relative position of Cochiti Lake to LANL.

Chapter 4: Results

This chapter discusses our results from in-depth data analysis. Investigating plutonium data yielded inconclusive results that raised many questions regarding how data is being obtained by LANL and uploaded to the Intellus database. We made minimal statements with certainty regarding the extent of contamination. While investigating chromium data yielded some conclusive results, areas of data were missing in the Intellus database that could have aided in further analyzing the state of chromium contamination at LANL.

When communicating key findings and recommendations that emerge from our project work, it is important that we communicate any uncertainties in order to be open, trusted, and credible (National Research Council Committee on Risk Perception and Communication, 1989). We recognize that there exists information and data gaps and a limited awareness of current knowledge of the plutonium and chromium contamination at LANL. We also recognize the presence of bias that could have led us to make distorted conclusions about plutonium and chromium migration to support the goal of our sponsor. Therefore, we considered uncertainty and consciously prevented the influence of bias when viewing the data.

4.1 Inconsistent sampling on behalf of LANL made forming concrete conclusions on plutonium migration trends impossible

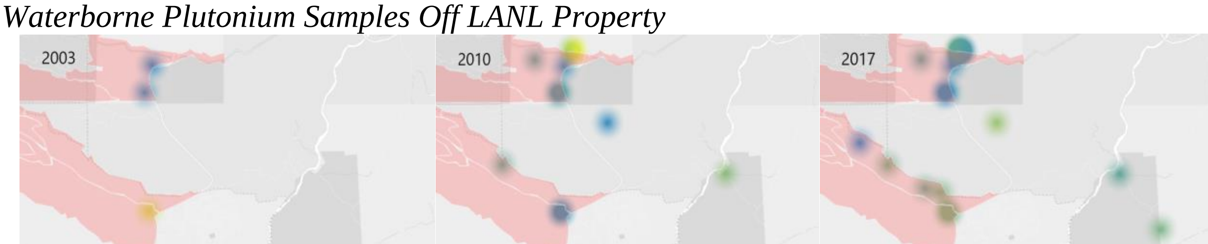
We developed the following findings concerning plutonium contamination at LANL through analyzing existing plutonium data gathered from Intellus.

1. Plutonium has shown up beyond LANL boundaries in waterborne samples, but due to the sampling routine in wells near or beyond the LANL boundary, migratory trends are not clear.

As we began our investigation of the plutonium contamination as a whole across the lab, we sought to examine if plutonium is appearing in larger concentrations over time near or beyond the LANL property boundary. The heat maps in Figure 6 depict the same region of northern New Mexico over a period of fourteen years. This figure shows the boundaries of LANL property shaded in red. Samples are seen offsite and in Technical Areas 36, 54, and 72. These samples are unrestricted in terms of the depth at which they were sampled.

Figure 6.

Waterborne Plutonium Samples Off LANL Property



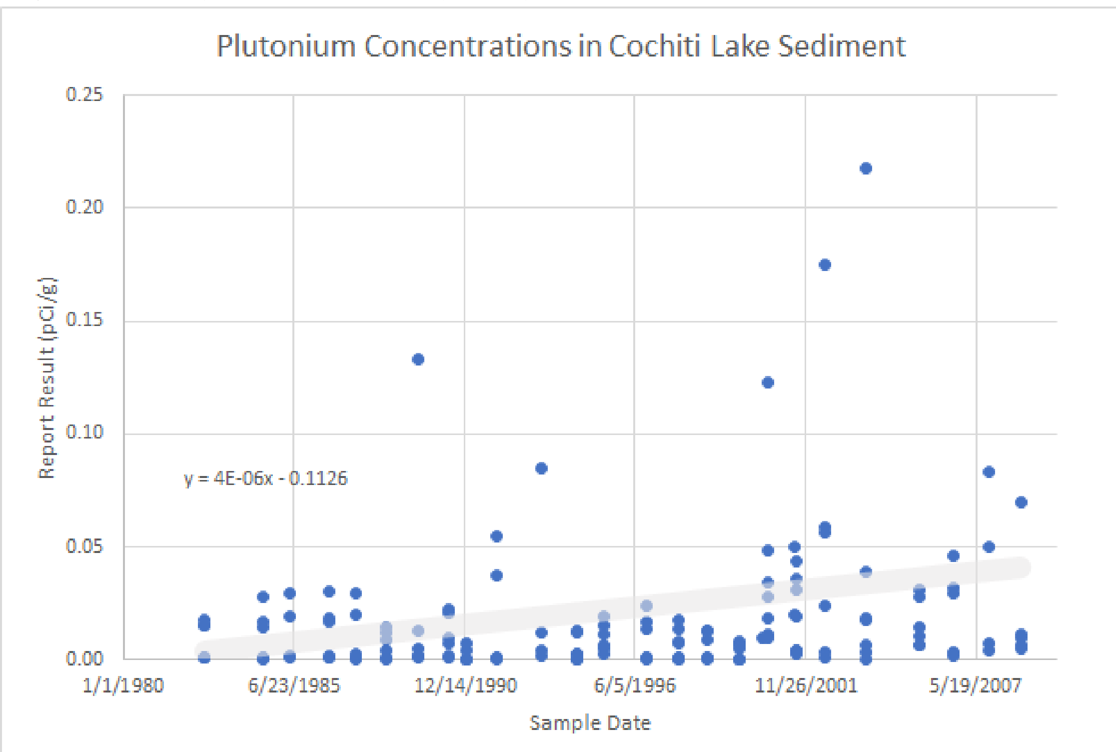
The colored orbs represent samples, with warmer colors showing samples with higher concentrations of plutonium. Blue spots indicate safer levels from 0 pCi/g and range to more orange spots indicating samples nearing 0.5 pCi/L. Neither of these values come close to the EPA limit for alpha particle activity in drinking water of 15 pCi/L, but they represent expected background levels (EPA, 2018). To create these maps, samples were taken only from locations that had been tested up to 2020. We hoped that a clear trend would become discernible, but not all locations were tested consistently throughout the time period, which made identification of such trends difficult. From 2010 to 2017 when most location IDs were at least tested somewhat consistently, one can see a slight trend towards warmer colors, but it is difficult to state this with certainty.

Figure 6 suggests that communities surrounding LANL, notably the town of White Rock, may be subject to an increasing threat of plutonium contamination of their drinking water. While it is impossible to say that there is a definite trend of increasing off-site contamination based on the available data, plutonium is detectable beyond the LANL property. At this time, these quantities do not approach EPA standards, but if nothing is done to remediate the contamination at the source, it is possible that in time we will see dangerous levels of plutonium in drinking water sources surrounding LANL.

On the other hand, an in-depth look at plutonium sampling at Cochiti Lake downstream of LANL along the Rio Grande reveals an upward trend in plutonium concentrations. The Cochiti Lake sediment sampling consists of three independent testing locations: Lower Cochiti, Middle Cochiti, and Upper Cochiti.

Figure 7.

Plutonium Concentrations in Cochiti Lake Sediment



Note. For better visualization, the scale was shrunk and removed one outlier value. This value was 0.966 pCi/g and was taken on 9/15/2000.

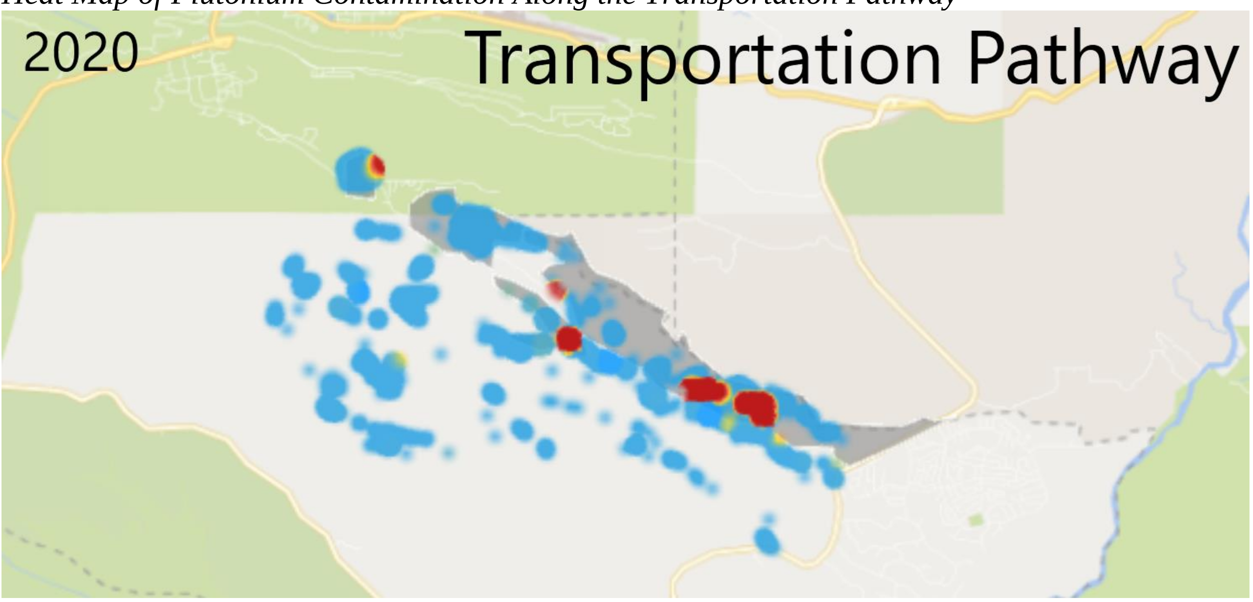
Plotting the plutonium concentrations in picoCuries per gram (pCi/g) over time produced the results shown in Figure 7. This plot revealed a slight but evident upward trend in plutonium concentrations over the past twenty-six years. The concentrations range from below the lower end of background levels of 0.01 pCi/g to higher than the upper end of 0.1 pCi/g (Agency for Toxic Substances and Disease Registry, 2011). The trend here is concerning; Cochiti Lake is more than seven miles downstream from LANL and lies in the direction of more populated regions such as the town of Alburqurque. Thus, contamination here could pose risk to many people. Unfortunately, after 2008, consistent testing at Cochiti Lake came to a halt and subsequently, this data set will lose its value as time passes.

The long and consistent testing period at Cochiti Lake allows for more meaningful analysis than what is seen in Figure 7. If testing across wells beyond LANL boundaries was conducted in this manner, a more complete picture of contaminant migration offsite would be available, which would aid in the remediation discussion.

The available contamination data does not help to support the idea that plutonium contamination is migrating. When played over time, our map of the theorized transportation pathway shows new wells pop up every year with differing concentrations. Because the technical areas along the pathway were not all tested each year, we could not see how plutonium concentrations changed. Trends that may be seen in the video can be attributed to new wells being tested that were never tested before, not the discovery of plutonium that was not there before. This ends up being very misleading.

Figure 8.

Heat Map of Plutonium Contamination Along the Transportation Pathway



In an attempt to assess plutonium locations over time, we eliminated the data points that do not show trends over time. We removed data points that were sampled only once, a few times over a short window of time, or sampled sporadically with large gaps between samples. However, even when only mapping the data that was sampled over longer spans of time, there still was not consistency.

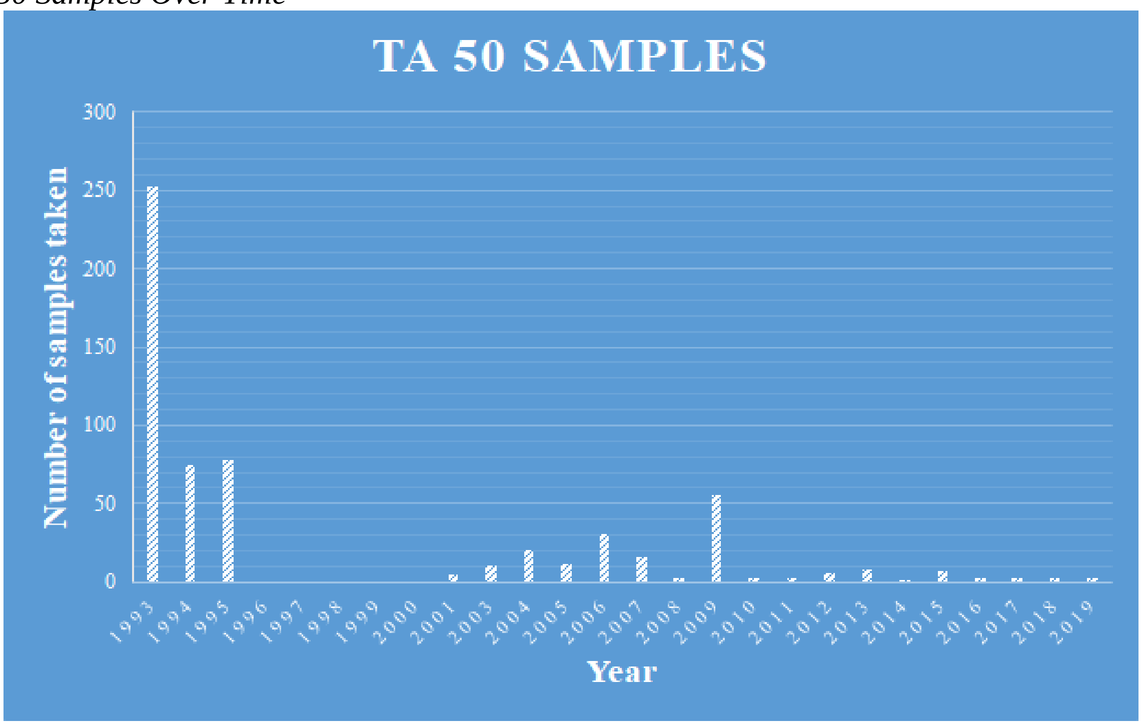
Figure 8 shows areas with higher concentrations of plutonium shown in red that should be cause for concern for LANL and the surrounding communities. These areas are outside of both MDA-C and MDA-G, therefore proving that plutonium has migrated from its original contamination area. However, analyzing the data over time does not yield any concrete results in terms of migration or times for newly contaminated areas. It only proves that there is contamination outside of the source locations, but there is no proof as to how it got there or where it came from.

2. Plutonium has been observed at depths up to 653 feet in TA-50, but the sampling routine has been inconsistent or lacks historical continuity, which made forming conclusions regarding migration difficult.

Figure 9 depicts the number of samples taken in TA-50 every year. There were no samples taken in TA-50 before 1993. The Manhattan Project took place in the 1940s, which leaves a fifty-year gap before this particular technical area was sampled after initial use of plutonium on LANL property. In order to fully analyze how plutonium has migrated, samples taken over the entire lifetime of the contamination would be required.

Figure 9.

TA-50 Samples Over Time

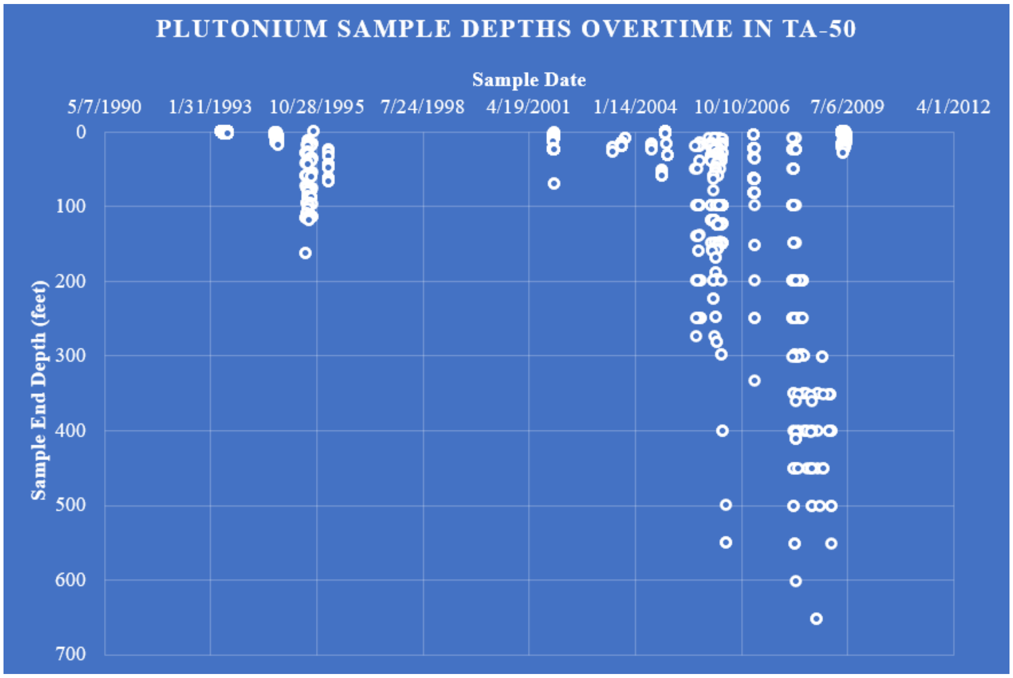


Another weakness of the dataset results from inconsistent sampling. One example is that there were over 250 samples taken in 1993, but fewer than half that many samples were taken in any year thereafter. Another is there was no testing done between 1996 and 2000 in which migration may have taken place. And in the last four years, there have only been 2-3 samples taken annually. All of these different instances of inconsistent sampling prevent a clear and full understanding of plutonium migration at TA-50 as a whole. It is very troubling considering TA-50 is one source of the plutonium contamination on LANL property.

Although inconsistent data prevented more conclusive analysis of the migration of plutonium at TA-50, data was uncovered that depicted plutonium reaching depths up to 653 feet. Initially, Figure 10 appears to show rapid migration of plutonium down towards the aquifer. In 1995, discernible samples of plutonium were not found deeper than 163.1 feet, and just ten years later, plutonium was being detected at depths of up to 653 feet. If this were truly the case, it would be extremely concerning as it would mean plutonium has been migrating at a rate of about 38 feet per year. Therefore, plutonium would theoretically reach aquifer depths in seventeen years or less.

Figure 10.

Plutonium Sample Depths Over Time in TA-50



This information would raise many red flags, but it became apparent that the analysis was not that simple. As shown in Figure 9, there are gaps in plutonium data for TA-50. Samples were not taken before 1993, there was a pause in sampling between 1996 and 2000, and there was a lack of relevant samples taken after 2009.

Furthermore, we sought to determine if the downwards migration shown in Figure 10 was a true depiction of what was happening in TA-50. We plotted sample depths of plutonium during this period without restriction-meaning that negative, zero, null, and positive result values were taken into consideration, unlike the above plot which contains only positive result samples. Figure E1 in Appendix E depicts the same trend as in Figure 10. This means that the migratory trend may only be a result of testing being performed at deeper depths over time rather than relevant samples showing up at depths where plutonium was not previously detected.

Even so, it is evident that there is some sort of downward migration at LANL. Plutonium was found in significant quantities hundreds of feet below ground, and it was not disposed of at these depths. Unfortunately, due to the testing regimen in TA-50, we cannot quantify the rate at which the plutonium is migrating.

3. A progressively drier and hotter climate in New Mexico will increase reliance on aquifers in the region and lead to more frequent destructive storms and wildfires.

Land remediation at MDA-C will inherently have long lasting effects due to the 24,200 year half-life of plutonium, and thus climate change and future land-use must be thoroughly discussed as they pertain to the decision making process of choosing a remedial option at MDA-C (Lenntech, n.d.).

To reiterate, New Mexico is expected to experience higher average annual temperatures and less rainfall on average, which will develop a much drier climate in New Mexico as time passes. Regions of northern New Mexico could experience up to 40 more days of extreme heat (temperatures above 90°F), and when these heat waves coincide with drought, which is becoming a common aspect of life in the Southwest as evidenced by Lakes Mead and Powell reaching their lowest levels in history since filling began in 1936 and 1963 respectively (Gonzalez et al., 2018).

Consistent rainfall is expected to decline in northern New Mexico and stronger and more violent storms will become commonplace. Due to dry, hardened soil as a result of drought and high temperatures, the majority of rain from these storms will rapidly wash through and create dangerous flash floods with minimal percolation into groundwater reservoirs (Union of Concerned Scientists, n.d.). Over time, this trend of less available shallow groundwater, surface water, a shrinking spring snowpack, and shrinking reservoirs will lead to increased reliance on the regional aquifers, and subsequently a decrease in saturated thickness. Using groundwater data from Intellus for TA-50, we graphed the groundwater elevation over time. The results of this analysis can be seen in Figure 11.

Figure 11.
Groundwater Elevation Over Time in TA-50

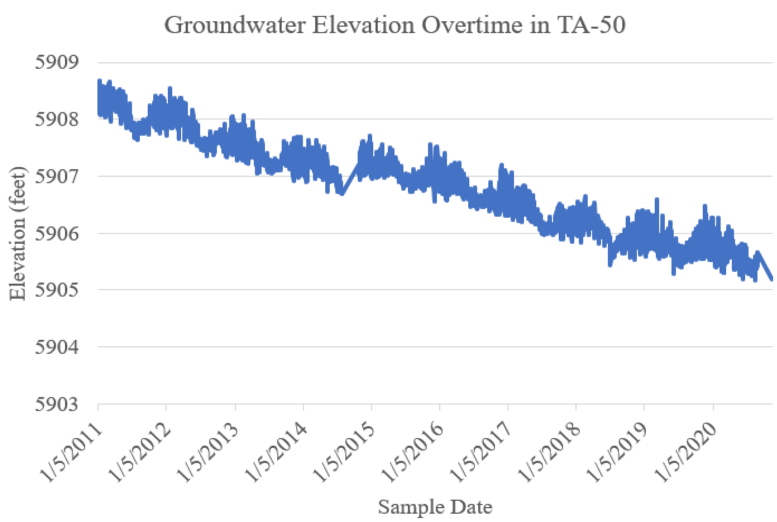


Figure 11 depicts an already shrinking aquifer over the past decade, which supports the predictions of climate scientists, and shows increased use of the aquifer. If this trend is to continue, it reinforces the need to ensure that plutonium and other contaminants will not continue to pose a risk to the aquifer in the area. Relocation of the waste to the WIPP would guarantee that no more contaminants that have not already migrated from the source at MDA-C would be at risk of migration towards water resources. On the other hand, although the cap-and-cover system can help to slow down vertical migration, without proper landfill lining, there is still a risk of leakage from the burial site.

The drier predicted climate in New Mexico will likely lead to worse storms and more frequent wildfires, a trend that has already been seen as wildfires have drastically increased in acreage burned from 1954 to 2011. The Las Conchas fire in the summer of 2011 burned 154,000 acres, destroyed 63 buildings, and cost an estimated $160 million. LANL dealt with the damage caused by such fires, and has subsequently put in measures to mitigate damage of future fires (DOE, 2015). The destruction caused by such wildfires and storms could accelerate degradation of man-made remediation systems such as a landfill cap or a leachate collection system (Gonzalez et al., 2018; Maco et al., 2018).

4.2 Findings related to characterization of the chromium-6 plume

By analyzing existing chromium-6 data gathered from Intellus, we gained the following insights concerning the plume.

1. The pilot-scale in situ treatments at the center of the plume worked, but the long-term viability is unclear.

In 2017, the DOE conducted treatment tests at the center of the plume where chromium was highly concentrated (regional wells R-28 and R-42) as an outcome of the Chromium Plume Interim Measure (IM). The DOE injected sodium dithionite at R-42 and molasses at R-28. Figures 12 and 13 show that the tests successfully decreased chromium to insignificant levels.

Figure 12.
R-42: Chromium Levels Over Time

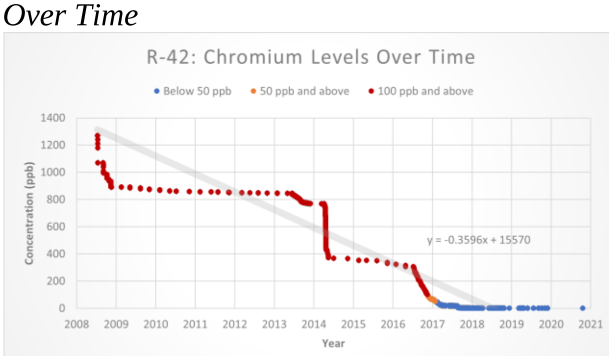
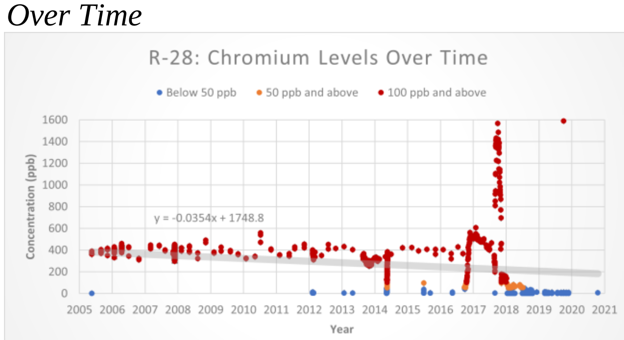


Figure 13.
R-28: Chromium Levels Over Time



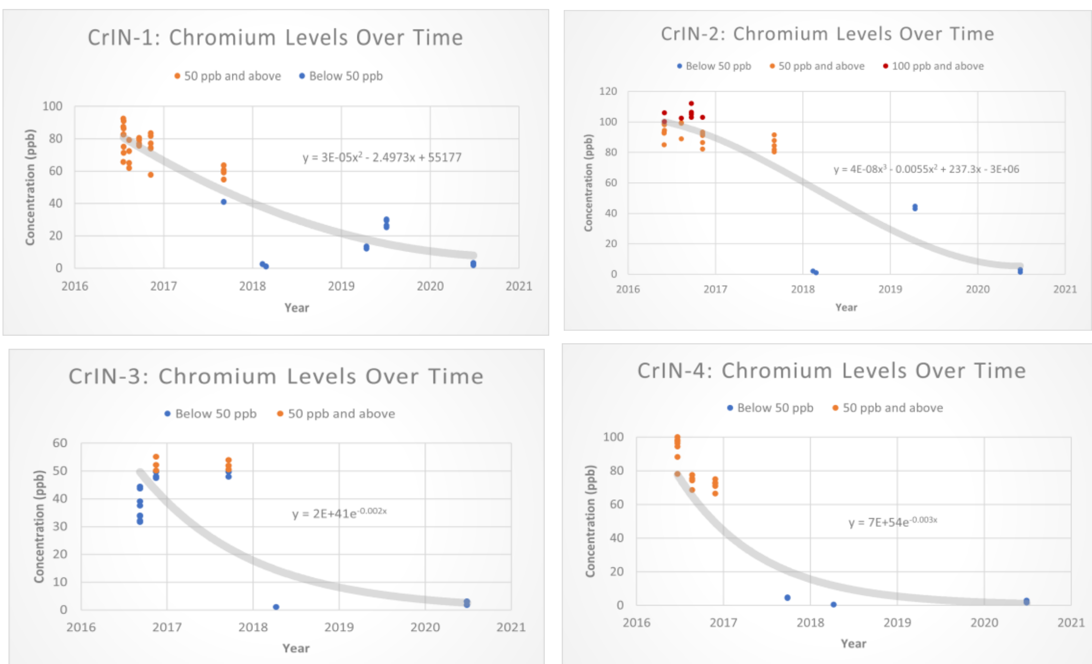
However, there is one extreme outlier value of 1600 ppb post-molasses treatment (Figure 13). This raises the question of whether this value was falsely reported in Intellus or there is a perceptible presence of chromium in R-28. Either the data entry practices at LANL or the effectiveness of dithionite in the complete treatment of chromium are doubtful. Nevertheless, recent data this year shows that no chromium was measured, mitigating the chance that chromium could migrate northeast in the direction of a Los Alamos County supply well (to extraction well CrEX-5).[9] These graphs support the short-term viability of in situ treatment, but it is unclear whether or not concentration levels will remain close to zero in the long-term.

2. The extract-and-inject system at the Pueblo border is working, but is unlikely to be effective by itself to control chromium migration in the long-run.

Another outcome from the IM is that the extract-and-inject method that LANL is currently implementing is successfully keeping the contamination off Pueblo property. The injection wells are located along the TA-05 border with the San Ildefonso Pueblo.[10] Figure 14 reveals that the injection of treated water significantly reduced chromium concentrations below the legal limit at the southern border of the plume.

Figure 14.

Concentration Graphs of the Injection Wells

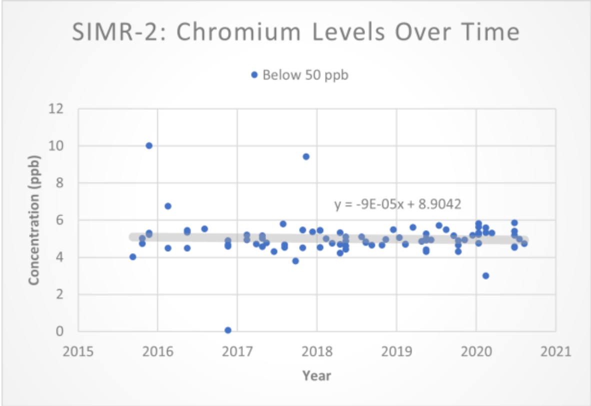


This claim is further supported by data taken from well SIM-2 within the Pueblo territory, as displayed in Figure 15. The chromium concentration levels in this well have remained fairly stable around 5 ppb since 2015, well below the limit of 50 ppb. In combination with Figures 14 and 15, the argument can be made that the methods that LANL is currently taking to prevent the spread of the chromium plume are working and that the plume has not migrated into the Pueblo.

[9] See Figure D4 in Appendix D to see the locations of CrEX-5 and Los Alamos County supply well PM-3.

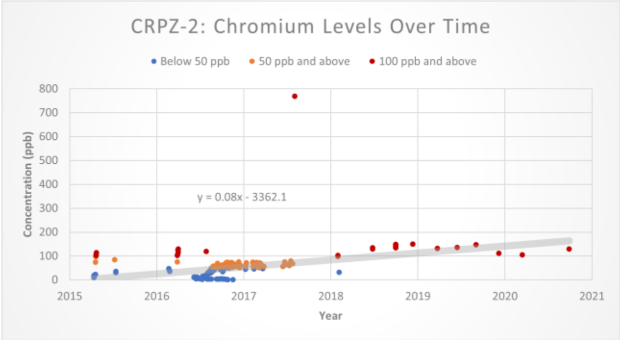
[10] See Figure D4 in Appendix D to see the placement of injection wells near the border.

Figure 15.
SIMR-2: Chromium Levels Over Time



However, there are a few areas of concern that have the possibility of creating issues along the Pueblo border in future years should LANL carry on current IM methods of remediation. The first of these areas is CRPZ-2.[11] This well is located directly to the left of regional well R-28 and extraction well CrEX-3. Figure 16 suggests that chromium-6 concentration levels are increasing and have remained over 100 ppb since 2018. However, levels at R-28 and CrEX-3 located directly to the right of CRPZ-2 have decreased over the past years. The treatment at R-28 is likely the cause of the chromium decreased in both wells. This brings up the question of where the chromium from CRPZ-2 could be traveling.

Figure 16.
CRPZ-2: Chromium Levels Over Time



A second area of concern is around regional wells R-50 and R-61. Both of these wells are located along the border with the San Ildefonso Pueblo. Just to the north of these regional wells are CrEX-1 and CrEX-2.[12] While levels at both wells have been decreasing over the past years, they still remain over 100 ppb and 200 ppb, respectively, as shown by Figures 17 and 18.

[11] See Figure D4 in Appendix D to see the placement of well CRPZ-2.
[12] See Figure D4 in Appendix D to see the placement of the extraction wells along the plume border.

Figure 17.
CrEX-1: Chromium Levels Over Time

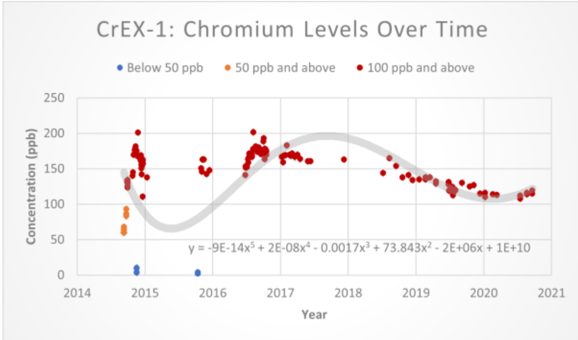


Figure 18.
CrEX-2: Chromium Levels Over Time

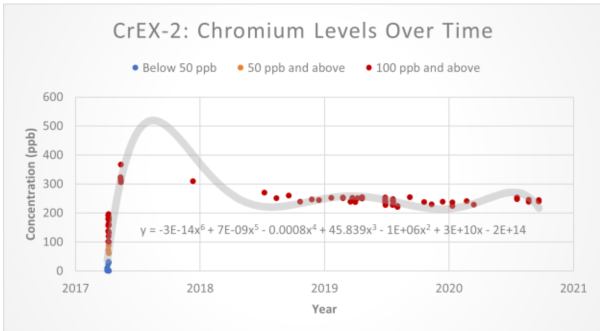


Figure 19 shows that the chromium concentration levels in regional well R-50 have decreased sharply over the past two years but are still lingering just under 50 ppb. Figure 20 shows that those in R-61 have been increasing slowly over the past few years and approaching 50 ppb.

Figure 19.
R-50: Chromium Levels Over Time

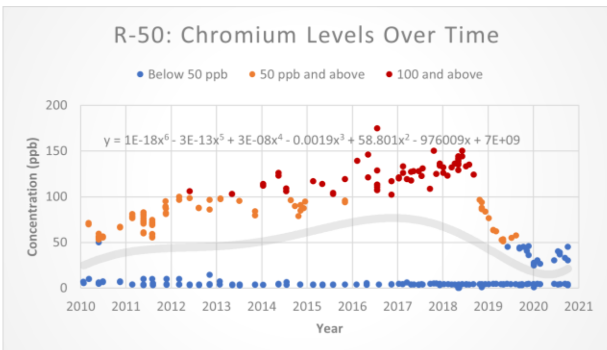
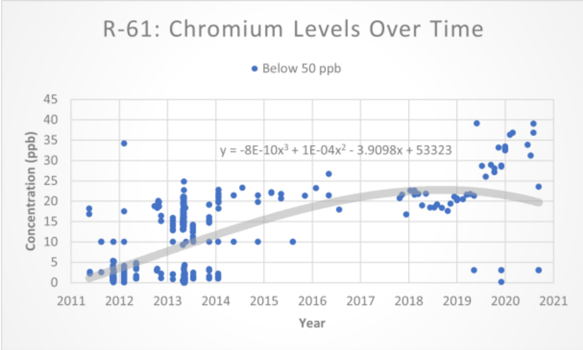


Figure 20.
R-61: Chromium Levels Over Time

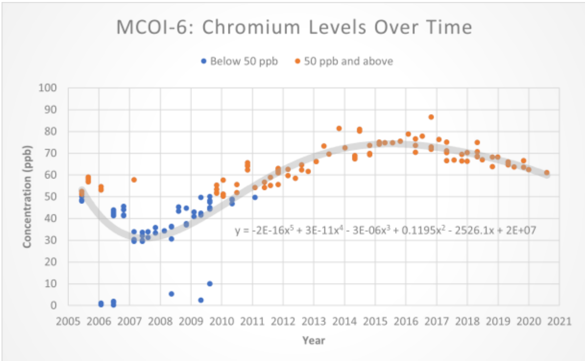


These trends are of great concern due to the wells' close proximity to Pueblo property. It is concerning that the recent trends of these two wells could indicate that the plume might be spreading towards the west and down into the Pueblo. It is also concerning that there is only one monitoring well in the Pueblo.[13]

3. The plume has slightly expanded to the west where chromium levels are now decreasing, probably because of southeast groundwater flow.

Sampling data suggest that the plume has slightly expanded to the west. Based on the placement of the plume boundaries in Figure D4 in Appendix D, the DOE believed that the chromium contamination just reached the right side of monitoring well MCOI-6 in 2018. However, Figure 21 shows that concentrations at MCOI-6 remained above 50 ppb since 2010. Levels increased from 30 ppb to 70 ppb from 2007 to 2015, and the latest reading is 60 ppb.

Figure 21.
MCOI-6: Chromium Levels Over Time



In 2005, there were levels above 50 ppb, but they immediately decreased to 30 ppb in 2007. Suddenly, levels started to increase gradually, passing 50 ppb in late 2009, and reaching their peak in 2016 at 87 ppb. Levels have been decreasing for the past 4 years, which can probably be explained by the natural southeast groundwater flow that may be transporting chromium away from this well. Despite this trend, levels have remained above 50 ppb since 2009. The most recent sample was 61 ppb from August. This proves that the plume is wider than

[13] See Figure D4 in Appendix D to see the placement of this monitoring well named SIMR-2.

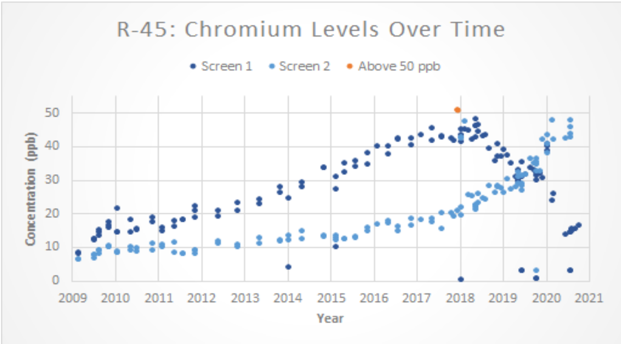
previously believed and there is potential that chromium could migrate further west against groundwater flow like it has in the past.

4. Another contamination oval is starting to form east of the plume.

Sampling data suggest that a contamination oval is starting to form east of the plume. This is evidenced by the high chromium level of 255 ppb at R-70 and 226 ppb at CrEX-5. Also, Figure 22 shows that concentration levels at regional well R-45, which is south of CrEX-5 and placed at the base of the oval, have been gradually increasing since 2009 and are approaching 50 ppb.

Figure 22.

R-45: Chromium Levels Over Time



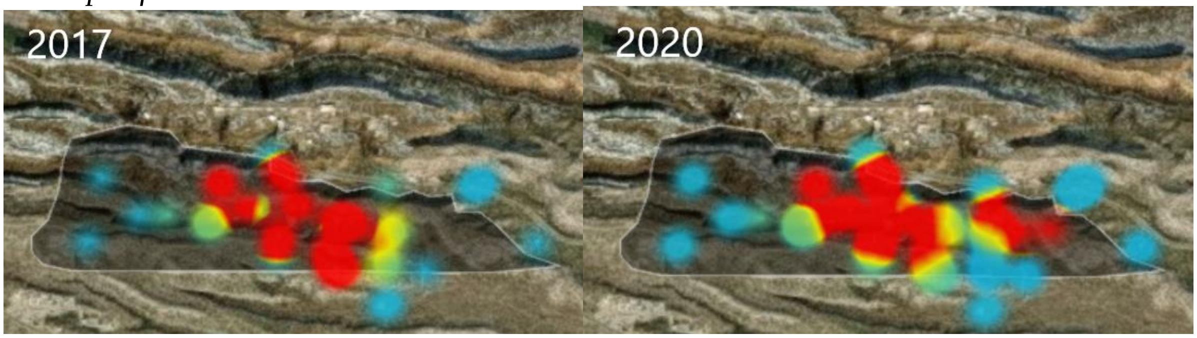
Note. Screen 1 (dark blue) and Screen 2 (light blue) are separate sampling segments of regional well R-45. All values, with the exceptional orange data point, were below 50 ppb.

This graph includes two sets of data from R-45. The first set called Screen 1 is samples taken at depths between 880 and 890 feet below ground surface. The second set called Screen 2 is samples taken at deeper depths between 975 and 995 feet below ground surface (Everett et al., 2009). Levels in Screen 1 began to decrease in 2018 after measuring 51 ppb and are now around 15 ppb. Levels in Screen 2, however, continue to increase and are nearing 50 ppb. Not only does this suggest that the contamination at R-45 is percolating deeper in the aquifer, but it also suggests that the southeast edge of the plume is projected to expand. If this trend continues, then the chromium level at R-45 could reach above 50 ppb, thereby expanding the right side of the plume.

Heat maps depicting the intensity of contamination at various sampling locations of the plume in 2017 and 2020 are shown in Figure 23. Comparing these maps shows how much the shape of the plume has changed in just a span of three years. Based on the data from CrEX-5, R-70, and R-45 and these maps, it seems that the plume is splitting into two separate ovals, and the smaller oval is breaking off right where R-45 is. This makes sense due to the treatment at R-28 and new sampling at CrEX-5 and R-70.

Figure 23.

Heat Maps of the Chromium Plume in 2017 and 2020



Note. Shown are chromium contamination heat spots in Technical Area 5, which is outlined in black. Blue spots indicate safe levels, yellow spots indicate levels 50 ppb and above, and red spots indicate levels 100 ppb and above.

These heat maps suggest that control efforts at the bottom of the plume are redirecting the contamination east, elongating the plume. While the objective of preventing the plume from crossing into Pueblo territory has so far been accomplished by the DOE, there is still concern that their current control efforts are just delaying the inevitable full-scale remediation response.

4.3 Intellus Database Issues

Throughout the duration of this project, our team has continuously struggled with the Intellus database. Our challenges using the database can be seen as we explain our process in extracting and analyzing data. Furthermore, there have been several occasions in which the team has had to reach out to technical support personnel at Intellus to clarify issues with the database. Some of these issues included:

1. Discrepancies surrounding how data is classified, such as the difference between “chromium” and “chromium-6”
2. Server problems where the database ceased to function
3. Missing data regions in the spreadsheets we downloaded because they were not recorded in the field during testing
4. Errors in latitude and longitude coordinates
5. Well sampling data uploaded without depth measurements
6. Incorrect location group labeling of samples
7. Obtuse and useless mapping functions due to lack of data integration

All of these issues draw into question the practices used at Intellus and LANL for data collection and uploading to the database, which was developed for increased transparency with the public. It is not always a matter of learning how to use the database, but Intellus itself does not contain certain functionalities and has various bugs. If these issues were addressed thereby improving the functionality of Intellus, then users of the database would not have to experience such a steep learning curve before having the ability to efficiently utilize the system. It is important to understand that not all problems that we have encountered during the course of the project are the fault of the Intellus database. Some of our encountered issues are a result of

LANL and N3B's inadequate sampling practices. Our recommendation regarding these issues are described in section 5.1 of the report.

Chapter 5: Recommendations

Based on our findings working with the contamination data at LANL, we recommend actions in three areas: plutonium, chromium, and independent assessments. Our recommendations are based on the data we collected from Intellus and the trends and findings that we discovered from this data and were developed to ensure that the communities surrounding LANL retain their right to clean land and water.

5.1 Plutonium

The availability and quality of data related to plutonium from LANL's sampling program around Area C makes conclusions difficult. In order for more successful data analysis and remediation decisions to be made in the future, we recommend:

1. LANL should design and implement more consistent sampling practices across locations to allow identification of trends in contamination data.

We are not recommending more sampling, but rather less, more refined sampling. Sampling across the entire facility should be done with consistency in relation to wells tested and frequency in which they are tested. This will allow for all of the data taken from now on to be useful in the future. This is the only way that any changes in contamination levels can be accurately and confidently detected.

According to the Harvard University paper "*Salience, Credibility, Legitimacy and Boundaries: Linking Research, Assessment and Decision Making,*" transferring information and managing boundaries between different groups of people require three attributes: salience, credibility, and legitimacy. Salience is how relevant the information is to the decision-making process; credibility is how believable and trusted the information is to the audience; and legitimacy is how fairly and unbiased the information considers appropriate values, concerns, and perspectives. If information is not credible, regardless of how salient it is, it will likely be ignored. Going a step further, regardless of how salient and credible information is, if the process of producing that information is not seen as legitimate, it will not be used (Cash et al., 2002). These attributes were largely undermined by our experience with Intellus. Throughout our collection and investigation of plutonium and chromium data, we exposed holes and pitfalls of the sampling done at LANL.

In order to determine migration trends, data over time must be analyzed, refined, and graphed and the sampling must have been historically consistent and continuous. The main result to come out of our plutonium research is that LANL and N3B have done a poor job of sampling data. While Intellus holds all of the contamination data for LANL, the lacking quality of the data makes it very difficult to glean any reliable conclusions.

The most beneficial sampling technique that we would recommend LANL adopt is more regularity and strict consistency in testing. In order to see if plutonium really is migrating from TA-50 southeast toward White Rock, bore wells in all of the technical areas along this transportation path should be tested every year. All of the selected wells in each technical area should be included each year, and new wells should not be added and old wells ignored.

Past TA-36 and TA-72, to the east of LANL, there is very little testing at all. While most places on-site need more consistent testing, off-site needs more consistency as well as more wells. There should be more wells along the border of LANL property, and more that go out further toward the town of white rock. Contamination from LANL leaving the property should be a major concern, and more offsite sampling will help for any contamination to be found quickly and therefore addressed and hopefully remediated quickly.

2. The DOE and the NMED should consider factors of climate change and future land-use in analyses of proposed remedial options for MDA-C.

Our findings based on research regarding climate change, future land-use, and institutional controls were discussed in section 4.1. Based upon the predictions from climate scientists and our own findings regarding groundwater elevation in TA-50, it is evident that the parties involved in determining the best remedial option should consider how a drier climate and shrinking aquifers, may affect their effectiveness. The following questions should be asked:

1. Will decreased percolation of rainwater through soil reduce likelihood of downwards migration, thus mitigating the need for relocation of contaminants?
2. Does increased reliance on the regional aquifers beneath LANL justify the implementation of more thorough remediation such as what would be obtained with a remedial process such as characterization and relocation of waste to the WIPP?
3. Will degradation over time of landfill caps and leachate collection systems be accelerated by harsher storms and increased frequency and size of wildfires?

In addition, future studies should consider increased frequency of storms and wildfires; we did not assess their potential impacts. As future land-use is considered, it will be important to involve the community to ensure that all parties affected by remediation will be involved in the decision making process. Community involvement is promoted by the EPA, and increases effectiveness of long-term remedial systems (Tuler & Hersh, 2012). Thus, parties responsible for making the decision regarding remediation at MDA-C should encourage involvement of the community and local government. This involvement can take the form of deciding restriction levels for remediated land, envisioned future land-uses, and development of institutional controls. The willingness for the DOE, NMED, LANL, NukeWatch, and other interested parties to fully discuss these issues will determine the long-term effectiveness of remediation at MDA-C.

5.2 Chromium

With the chromium plume boundaries continually changing, it is becoming increasingly difficult for LANL and the DOE to characterize and control the plume and evaluate the most feasible remedy. Based on the data from Intellus, the team recommends the following steps in mitigating the plume:

1. For LANL to continue the extract-and-inject method of controlling the chromium plume until full-scale remediation is planned and deployed.

This recommendation is based on data collected in and around the plume in TA-5. As depicted by our concentration graphs for the injection wells, the extract-and-inject method is effective at controlling the plume along the boundary with the Pueblo. As depicted by our concentration graphs for the regional wells that received treatment, an in situ treatment would be favorable due to its feasibility and short-term application. However, as supported by our data taken from other wells, concentrations at the center remain high and some levels at the border are increasing, requiring full-scale remediation. Representatives at LANL may argue that if the contamination is kept inside their property, they should not have to remediate the plume. Without knowing the future impacts of climate change and how the groundwater levels could change in the coming decades, underestimating plume migration could spell disaster for future generations in the region should contamination spread to water supply wells or the Rio Grande. With this uncertainty, it is in the laboratory's best interest to fully remediate the plume.

2. For the DOE to consider the installation of new monitoring wells in Pueblo territory along the border with TA-5 to ensure chromium contamination is not continuing to migrate off LANL property.

Currently there is only one monitoring well along the TA-05 and San Ildefonso Pueblo border (SIMR-2). While this well is located along the water transportation pathway, it is possible for contamination to move around this well to the east or west. As highlighted in our concentration data from R-70 in the east, the plume is expanding in this direction. Similarly in the west, concentration data from R-50 and R-61 show increasing levels along the western border with the Pueblo. In order to be certain that plume is not entering into Pueblo territory, installing a new string of monitoring wells directly along the shared border inside Pueblo land will ensure that the leading edge of the plume is known. The team anticipates that this suggestion will not be widely embraced by Pueblo representatives. However, in order to ensure that the plume is not spreading into Pueblo drinking wells, it is important to install a new set of wells as a last defense.

3. For the DOE to install additional monitoring wells surrounding R-70 that will aid in characterizing the northeast area of the plume.

This recommendation will require the NMED to find additional funding for the DOE to install more monitoring wells that cost an estimated $3.5 million each (Oswald, 2015). These wells can help the DOE define the lateral and vertical extent of chromium contamination in the northeastern portion of the plume where the new contamination oval is forming. Better characterization of the plume can help the DOE prioritize certain areas for clean-up, thereby saving time, funds, and other resources. A challenge for this recommendation is that its implementation will likely affect the investigation for a final remedy in terms of project duration and cost as well as delay the entire process. Another challenge is the 2016 consent order between LANL and the NMED that allows LANL to avoid clean-up efforts by claiming they are expensive or impractical due to lack of funding with no opportunity for public input (NukeWatch, 2017). Despite these challenges, we hope that continued efforts consider uncertainties and make progress towards full remediation of the plume.

4. For LANL to take sample depth and groundwater table data for TA-5 to aid in projection of plume migration over time due to changing water tables in the region.

In order to more accurately predict how the chromium plume might migrate over time, we recommend taking sample depth and groundwater table data over time in TA-05. If the groundwater table looks like it is increasing over the coming years, this could be an indication that the plume may begin to migrate at a faster rate in the direction of the ground transportation pathway. Inversely, if the groundwater table looks like it is decreasing over time, there is less probability that contamination from the plume could migrate through the transportation pathway. This data could also reveal trends that suggest how climate change could impact the region in the coming decades. The projected drier climate could mean less movement of the plume but an increased issue with drinking water levels for the communities in the region. Analyzing groundwater table data could help the NMED address these possibilities.

5.3 The Value of Independent Assessments to Improve Transparency

The purpose of Intellus is to be a usable database holding all of the LANL contamination data for anyone to utilize (Los Alamos Monitor, 2012). Our project was an independent assessment of plutonium and chromium data from Intellus, but relied on methods outside of the tools that Intellus provides. Our assessment allowed us to create visuals and come to findings that we never would have been able to do using Intellus alone.

Independent assessments are of high importance for a DOE facility such as LANL. LANL's own reports regarding findings on contamination data can be susceptible to bias. For example, the laboratory might be hesitant to be fully transparent by revealing high levels of contamination due to risks to reputation and potential implications (Tuler & Kasperson, 2013). Independent assessments done by us, watchdog organizations, and any other third-party would reduce this bias and is more reliable to the community. Funding for organizations that do this kind of work will allow for different groups to provide their own assessments, and increase social trust in the laboratory itself (Tuler & Kasperson, 2013). Because of its ability to improve the conditions, we recommend more financial support from the DOE to enable watchdog organizations and others to do independent assessments of environmental data in New Mexico. This support can come in the form of more grants such as the Monitoring and Technical Assessment Fund that was the result of a settlement between the DOE and non-profit peace and environmental groups and the Community Involvement Fund that was established by the DOE-EM. These funds serve the purpose of promoting public interest and involvement with decision-making processes regarding remediation at DOE sites, and more funding in this manner will continue to promote the best practices for remediation of contaminated sites such as LANL.

Chapter 6: Conclusion

The unsupervised nuclear weapons industry has spread toxic waste through the United States' land and waters (U.S. Congress, Office of Technology Assessment, 1991). This issue has manifested in sites managed by the DOE, which continues to struggle to properly characterize, clean-up, and remediate such lands (DOE, 2001; Kersting et al., 1999; Moore, 1998; Office of River Protection: DOE, 2020). The difficulties in proper clean-up reside in mischaracterizing contamination, budgetary concerns, and limited public awareness (Bridges et al., 2005). Some of the useful information that could aid in guiding discussion on remediation at LANL, for example, can be gleaned from Intellus, but there still exists volumes of information that can simply not be obtained by using the Intellus database alone. Consistent data sampling, public confidence in data analysis, more funding for independent assessments, and public involvement in future land-use discussions are integral in overcoming these problems (Tuler & Hersh, 2012; Tuler & Kasperson, 2013).

For these reasons, the quality of long-term stewardship measures will be improved if these solutions are put into place. However, according to the National Research Council, the only safe assumption about long-term stewardship measures at sites where wastes are left in place is that they will fail because our current knowledge of the behavior of wastes in environmental media may eventually prove to be wrong (National Research Council, 2000). Therefore, deciding on waste clean-up efforts at LANL must involve making subjective judgements more than making objective estimates based upon past experiences of actual events and outcomes. Even with the presence of uncertainty, the Rio Declaration on Environment and Development of 1992 states that “where there are threats of serious or irreversible damage, the lack of full scientific understanding shall not be used as a reason for postponing cost-effective measures to prevent environmental deterioration” (Kasperson, 2008). So, the environmental decision makers, in this case the DOE and the NMED, must find a fine balance between addressing the contamination with haste, considering climate change uncertainties, and taking precaution on the grounds of ethics.

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Appendix A: Plutonium's Migratory History and Evidence for Migration at LANL

Due to poor storage techniques of radiological contaminants, the events of water infiltration, fires, erosion, biologic uptake, and degradation of pits and shafts can lead to a leakage of hazardous substances over time. At MDA-C, all of the above may have led to contaminant migration. Diffusion of gaseous substances happens through seepage of air into shafts and pits, which then diffuse back through porous rock and soil. This process is often driven by pressure changes. Biologic uptake is a complicated mode of contaminant migration that first entails plants pulling contaminants from the soil along with nutrients that they require to grow. Later, the substances return to surface soil through biomass decay where they are either driven into the soil by burrowing animals, water infiltration, or transported in surface runoff. Contaminants such as strontium-90 are particularly susceptible to these types of migration. Some metals and radiological contaminants are susceptible to migration by water infiltration due to snowmelt and rainfall through the stored waste, which then carry the contaminants slowly through the subsurface rock (LANL, 2005). Water-based migration is of particular concern due to the potential for the contaminants to be transported into aquifers deep in the subsurface and subsequently to drinking water sources such as the Rio Grande, just east of the LANL property.

When seeking to understand the extent of migration in relation to MDA-C and gaining perspective on the magnitude of the problem, it is important to consider contaminants that may be less mobile or have poorly understood mobility characteristics. It is even more logical to focus on the clean-up of a material that will remain toxic for thousands of years and potentially become a major health risk for anyone who could be exposed. When focusing on the various contaminants present at MDA-C, plutonium isotopes stand out as a top candidate with these characteristics. With a half-life of 24,200 years and causing high rates of cancer in individuals exposed through inhalation or ingestion of particles on the scale of micrograms, plutonium-239 must be further understood (Lenntech, n.d.).

In past investigations of incidents that concern migration of plutonium-239 in soil and groundwater, the rate of possible migration has been heavily debated. During investigation into the extent of plutonium-239 migration at Rocky Flats, Colorado, many experts dueled with the DOE in arguments over whether plutonium-239 in the soil was a risk to nearby communities. One such expert, Iggy Liator, initially published work in peer-reviewed journals while working for the DOE that suggested plutonium was an immobile contaminant once deposited in soil. He rescinded his claims when he discovered substantial migration of plutonium during a rainstorm in the wet spring of 1995. Bringing forth his discovery, Liator was promptly dismissed from his role (Moore, 1998).

Another shocking example of unexpected plutonium migration can be observed when reviewing the history of INL, a DOE laboratory located in southern Idaho. At INL during the 1950s and 1960s, toxic waste was disposed of in 55-gallon drums, cardboard boxes, and wooden boxes and then placed into unlined pits and shafts, all of which are severely inadequate storage practices. INL is located right above the Snake River Aquifer, the sole drinking source for 200,000 people. Therefore, any toxic waste disposed of at the INL site poses great risk. In 1965, it was estimated that it would take 80,000 years for plutonium to reach the aquifer, but in 1997, that estimate was revised to 30 years, and plutonium and other radionuclides and toxic chemicals were detected in the aquifer (Burns, 2002). The situation at INL draws stark comparisons to the situation at MDA-C in Los Alamos. For both situations, radiotoxic substances were disposed of improperly, and the pollution threatens water resources due to their close proximity.

Mobile colloids suggest a potential cause for faster-than-expected migration of substances like plutonium that are considered relatively immobile due to their water insolubility. Mobile colloids are suspended particles in the sub-micrometer size that exist naturally in groundwater. Colloids have the potential to enable a transportation pathway for non-soluble contaminants via sorption (Kersting et al., 1999). Evidence of colloidal migration reveals that people could be significantly underestimating the extent and potential for radionuclide migration.

Despite observed migration of plutonium and other radionuclides, these contaminants are still considered to be relatively immobile on their own in normal environmental conditions due to their insolubility in water. When analyzing contaminant migration at MDA-C, it will be particularly concerning if significant migration of plutonium isotopes is discovered. Plutonium migration suggests that more mobile contaminants such as chromium-6 will have traveled even further away from their source and deeper into the ground towards the regional aquifers. This is problematic as it entails greater risk to contamination of natural resources and subsequently threatens the health of communities surrounding LANL.

Appendix B: History and Use of the Intellus Database

In 2012, the NMED Hazardous Waste Bureau added a section to a consent order that "requires the maintenance of a publicly accessible database containing data from environmental media collected as part of environmental investigation and monitoring activities" (Los Alamos Monitor, 2012). This consent order requires the software Intellus New Mexico to hold all environmental data in the Los Alamos region and prompted the shift from the New Mexico Community Foundation (NMCF) to Intellus for LANL's records management. Intellus allows the laboratory to organize records in a way that anyone is eligible to access. Over twenty-eight thousand documents and reports that cover data for air, soil, sediment, biota, and water are accessible through maps using Excel tools and are updated nightly (Intellus, 2020).

NukeWatch points to concerns over the usability and usefulness of Intellus, particularly because LANL decided to no longer provide training in database software due to lack of funding (Severance, 2012). Because of this, the Intellus database is rife with problems that make it difficult to understand and use. Our preliminary research showed that the system lacked the ability to clearly compare and contextualize the data. Obvious questions like "Is my drinking water safe?" are hard to answer with Intellus. This is a significant problem for citizens and organizations in New Mexico who wish to advocate for themselves and their needs to the EPA and other governmental structures. The 2012 consent order requiring LANL to have a free public database of their environmental data was satisfied legally, but Intellus has still not been able to reach the public in the way that it was initially intended (NMED, 2020).

Table B1.
Intellus Data Retrieval Specifications Our Team Developed

Data Retrieval Specification	Reasoning
Select Los Alamos National Laboratory and NMED DOE Oversight Bureau as the data providers.	These provide an all-inclusive data retrieval.
When retrieving data, set the time frame from January 1st, 1970 to the present day.	This ensures us that we are comparing data from the same time frame and that no data is missed to the present.
When choosing the location, select both N3B (a data collection contractor) and LANL data.	These categorizations are seemingly arbitrary as there is N3B data from before they were hired by LANL, likely because they re-uploaded the data or because of some other organizational mishap. Even if the user is taking data from before the company existed, it is important to have them selected.
As well as the default time, place, amount, units, sample type, etc., also include sample start depth, end depth, and depth units.	This allows for better division of data by depth on a basic level, allows us to find change in depth over time, tells us how tall the sample was, and indicates if the sample is an aquifer sample.
When looking for data from the whole database, select LANL Property (both LANL and N3B) and all location groups labeled Offsite.	Intellus does not allow for more than 5 years of "All Locations" data to be taken at once. This would waste hours of downloading and combining different data sets considering the team is looking into fifty years of data. The use of labels we have developed to get a nearly complete data set requires some trust of the Intellus system not to leave data unlabeled. More specific data sets are retrieved by exact location.
Save datasets to the MyIntellus feature for future use and download them as CSV files for data analysis in Excel.	This allows for two backups of the spreadsheets we create in case there is data lost while the team organizes and graphs the data.

Appendix C: Chromium-6 and Plutonium-239 Health Effects to the Human Body

The two contaminants at LANL of high concern to NukeWatch that are the main focus of our project are chromium-6 and plutonium-239. Plutonium-239, a byproduct of nuclear weapons testing and production, and chromium-6, an anti-rusting chemical used in manufacturing, both have dangerous health effects caused by excessive exposure. Humans can be exposed to either chemical through ingesting contaminated foods, breathing contaminated air, or drinking contaminated water as a result of living near hazardous waste sites or industries that use those chemicals.

Drinking high levels of chromium-6 can lead to cancer, asthma attacks, and damage to the liver and kidneys (Clean Water Action, 2020). Breathing high levels of chromium-6, in particular, may cause respiratory irritation, breathing problems, a runny nose, and nose ulcers. Direct skin contact with chromium-6 can cause skin ulcers and allergic reactions (Agency for Toxic Substances and Disease Registry, 2012). For these health reasons, the EPA has determined a maximum contaminant level of 0.1 milligrams per liter or 100 ppb of chromium in drinking water (Agency for Toxic Substances and Disease Registry, 2012).

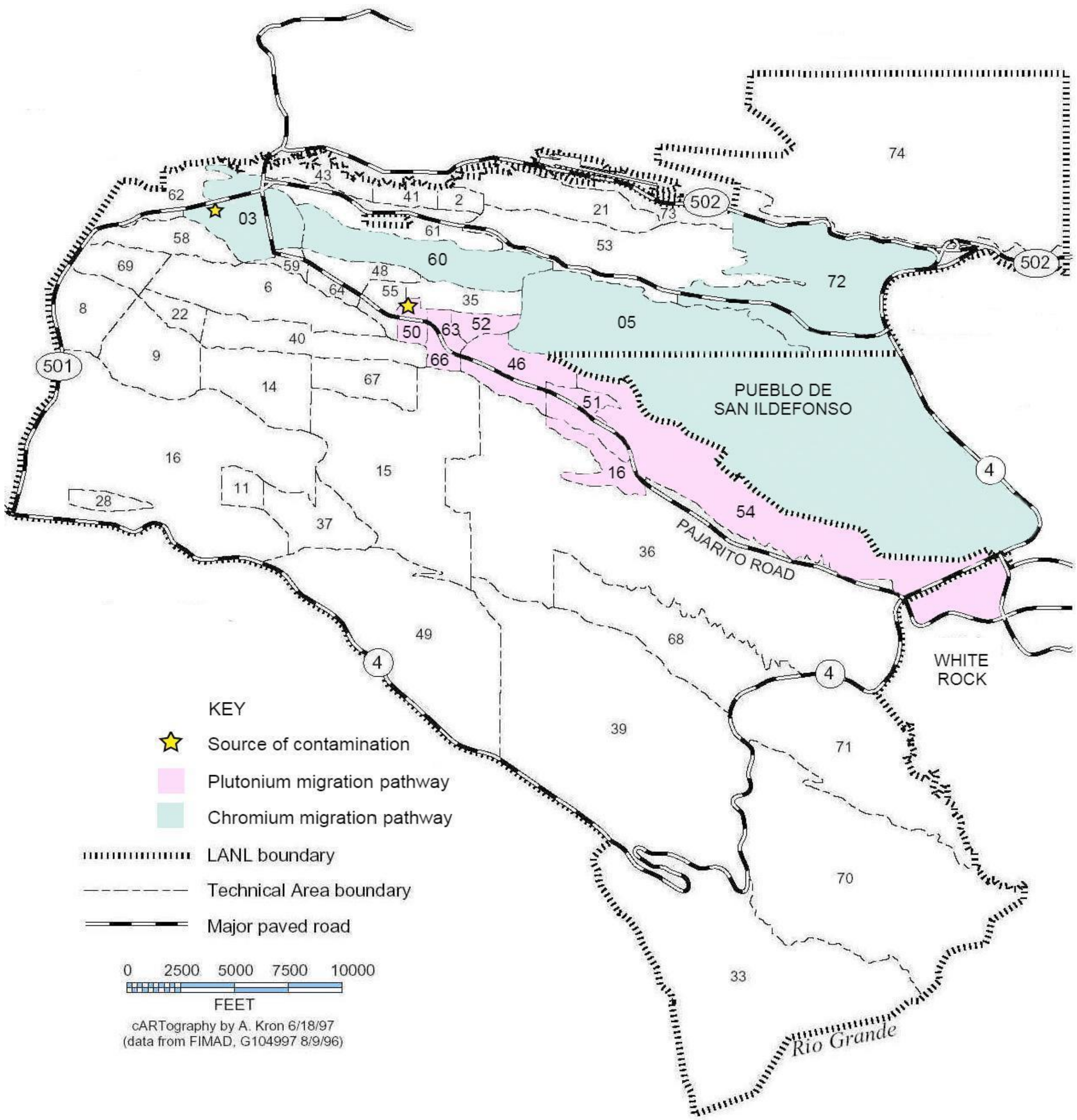
Plutonium-239, on the other hand, causes much more dangerous symptoms. Plutonium-239 is a solid material fashioned into spherical shapes for use in nuclear weapons. Tiny plutonium particles are released into the environment through production or testing of these nuclear weapons. These microparticles lodge in the lung tissue when inhaled, which can kill lung cells and therefore cause scarring, eventually leading to lung disease or cancer. Once it enters the bloodstream, it can travel to the kidneys and concentrate in the bones, liver, and spleen, posing the risk of developing cancer in those organs. Inhalation is the most common mode of exposure, while ingestion of contaminated food or water does not pose as much of a threat. The stomach cannot absorb plutonium easily, so the plutonium is not absorbed into the body and passes through the digestive system in the feces.

It is clear that both plutonium-239 and chromium-6 have hazardous health effects. For this reason, exposure to these chemicals is something that NukeWatch is advocating to limit or eliminate through promoting environmental awareness and pushing for remediation efforts.

Appendix D: Maps of LANL

Figure D1.

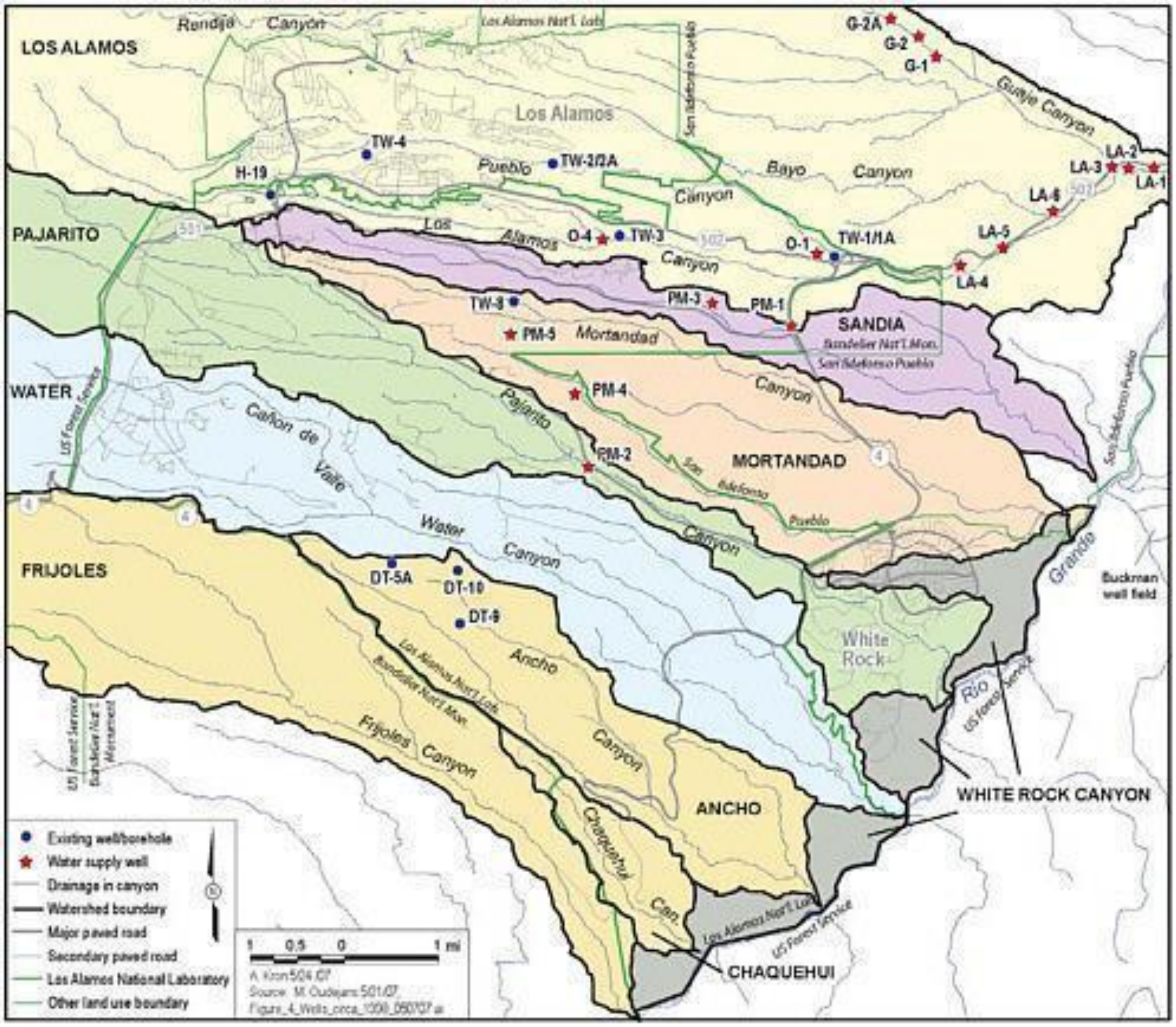
Migration Pathways of Plutonium and Chromium Across Technical Areas (Adapted from Site-Wide Environmental Impact Statement Project Office, 1997)



Note. Light pink-colored areas represent technical areas that plutonium-239 has contaminated or can potentially contaminate, and light green-colored areas represent those for chromium-6. These pathways are based on southeast downgradient groundwater flow. The original technical area that was the source of the contamination for each pathway is indicated by a star.

Figure D2.

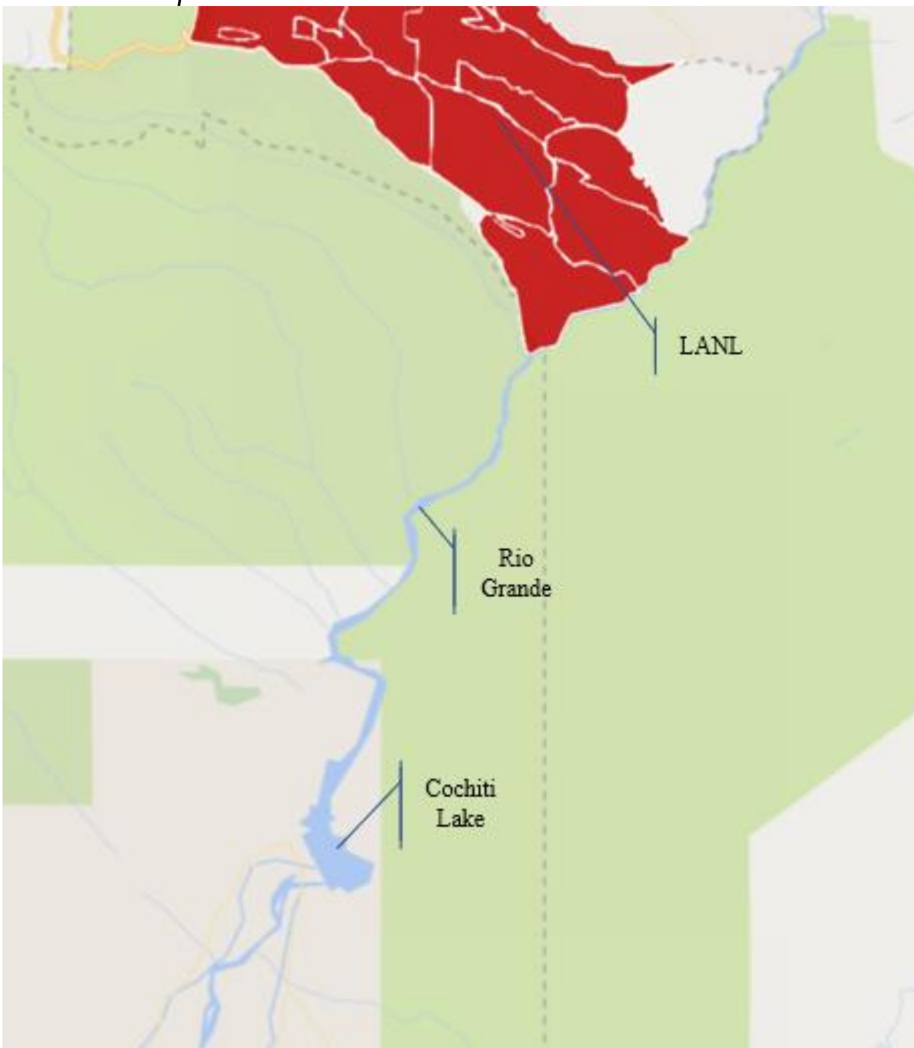
Various Groundwater Pathways Across LANL (Plans and Practices for Groundwater Protection at the Los Alamos National Laboratory, 2007)



Note. This map depicts the groundwater pathways and watershed boundaries on LANL property. The pathways follow the canyons that make up the geography of the area.

Figure D3.

Map of Cochiti Lake in Reference to LANL



Note. Our team created this map using the 3D mapping functions on Excel.

Figure D4.

Map Showing the Location of the Chromium Plume Wells (Submittal of the Completion Report for Conversion of CrIN-6 to CrEX-5, 2019)

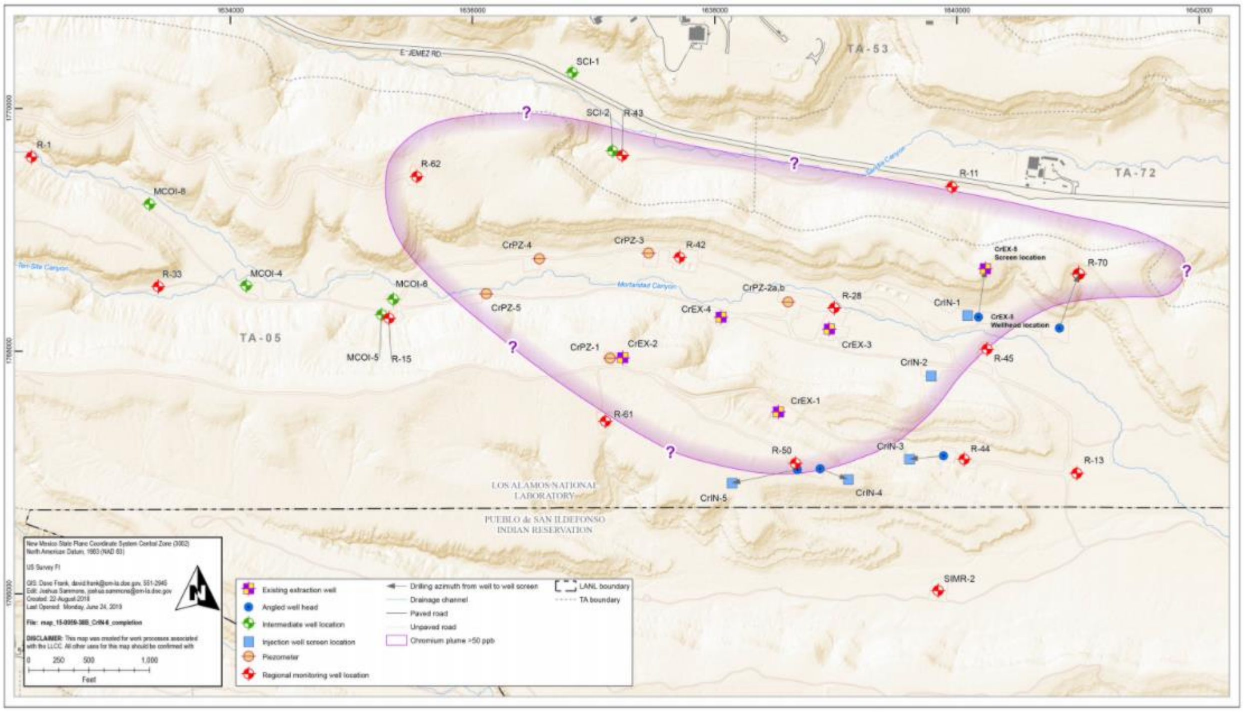


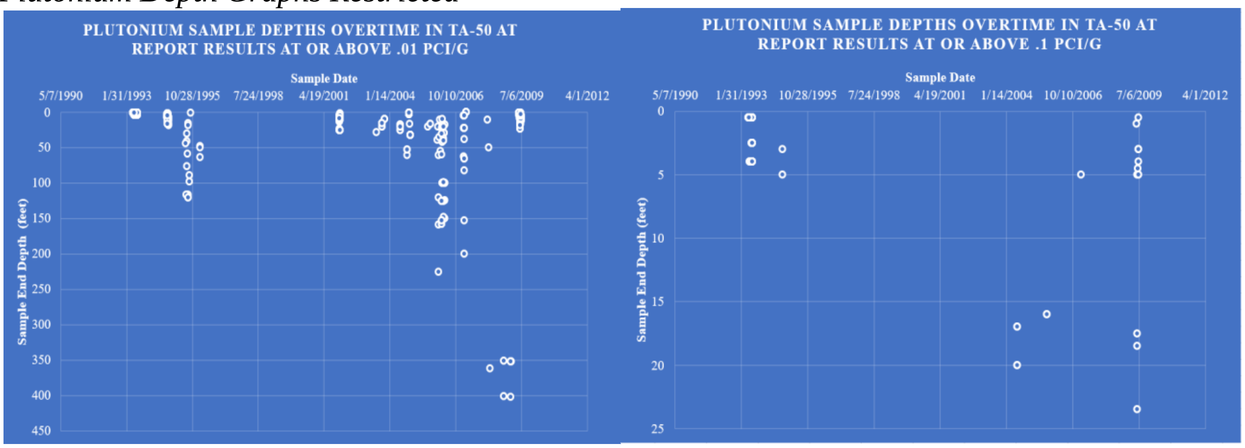
Figure 1.0-1 Project location map

Note. This map shows the location of various wells in and around the chromium-6 plume, including injection and extraction wells, regional wells, and other monitoring wells. The plume boundaries are noted and the southern border with the Pueblo is also outlined.

Appendix E: Supplementary Plutonium Depth Graphs

Figure E1.

Plutonium Depth Graphs Restricted

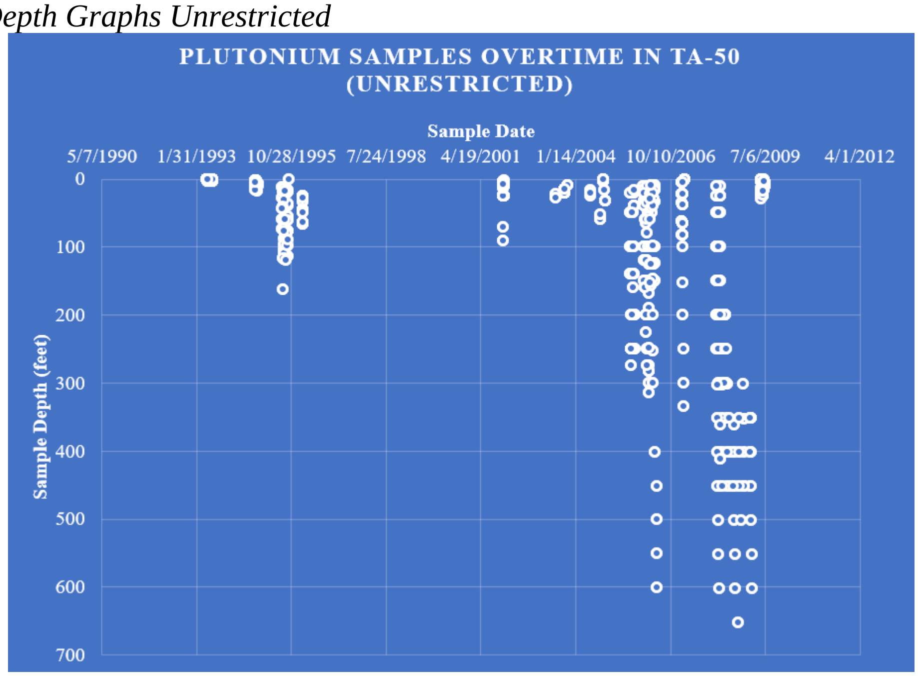


Note. These plots coincide with the plot labeled Figure 10.

The above two plots differ from Figure 10 because they isolate the same data above a certain level. The left plot shows plutonium samples in TA-50 at or above 0.01 pCi/g, while the plot above right shows samples at or above 0.1 pCi/g. These values represent the estimate for background levels due to fallout (Agency for Toxic Substances and Disease Registry, 2011). A similar trend as seen in Figure 10 is depicted: more samples found at greater depths over time. This trend is subject to scrutiny regarding sampling depths and testing gaps. It is also worth noting that as the data was limited to higher concentrations, the depths at which samples were found significantly decreased.

Figure E2.

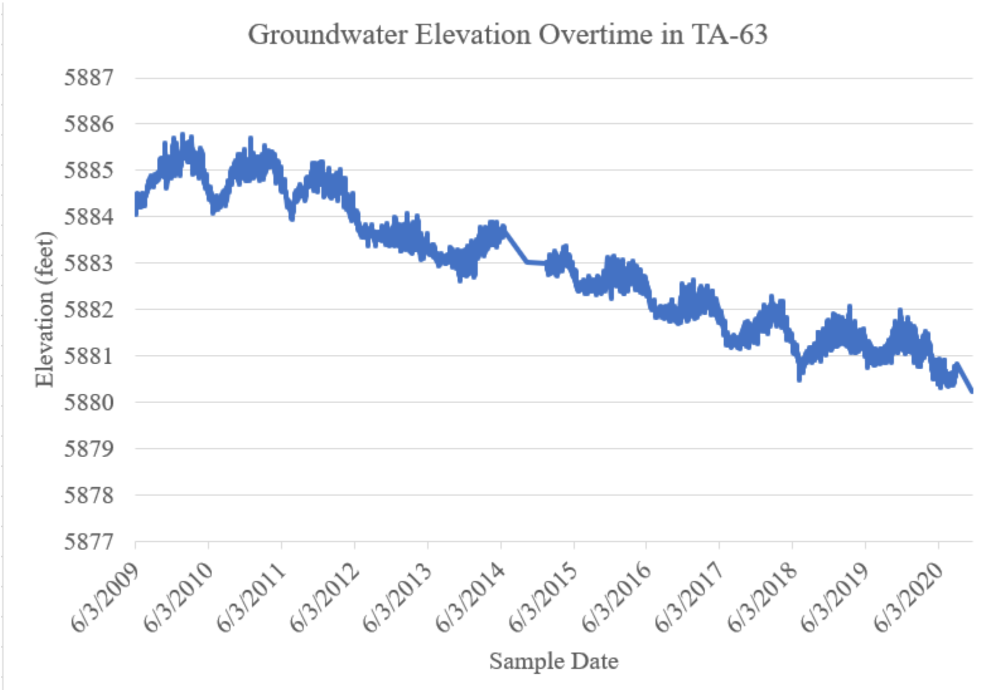
Plutonium Depth Graphs Unrestricted



The above plot was created in order to determine if the trends seen in Figures 10 and E1 were truly showing migration over time or if they were subject to increased testing at greater depths. The plot was created by taking all of the plutonium samples rather than limiting it to positive values and plotting the depths of the respective samples over time. The plot shows that the trend that was previously observed is subject to scrutiny as samples were not taken at all depths over the course of the sampling period, and the sampling gaps prior to 1993 and between 1996 and 2000 are also present when samples are unrestricted.

Figure E3.

Groundwater Elevation Over Time in TA-63



Note. A similar trend to TA-50 of a shrinking aquifer is seen here.