Evaluation of the Health Effects of Climate Change and Contaminant Exposure Pueblo de San Ildefonso

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Executive Summary

The Pueblo de San Ildefonso (Pueblo) is facing changing climate conditions, including increasing average temperatures as well as more frequent and/or intense incidences of extreme heat, drought, wildfires, storms, and floods that are typical of the U.S. Southwest region. These changing climate conditions are expected to negatively impact human health (e.g., increased heat can cause heatstroke, hyperthermia, and even death; and wildfires can result in adverse effects to respiratory and cardiovascular systems).

Simultaneously, the Pueblo also faces potential human health impacts due to its proximity to the Los Alamos National Lab (LANL). Historical laboratory activities, including development of the atomic bomb, have left a legacy of plutonium and other radionuclides in the local environment. Extreme events such as wildfires, extreme rainfall, and flooding may increase the risk of mobilization and exposure to contaminants on the Pueblo from the LANL.

Climate change may adversely affect the health of Pueblo members directly (e.g., heat stress, adverse respiratory effects due to low air quality) or indirectly, by causing increased exposure to contamination (e.g., increased release/transport and exposure to contaminants during wildfires and extreme storm events). Additionally, there is concern about Pueblo members being simultaneously exposed to direct and indirect effects of climate change, particularly if the effects of the former exacerbate the latter. In other words, individuals who are already suffering from the effects of extreme heat or reduced air quality may be more susceptible to the effects of contaminant exposure than they otherwise would be. Understanding the combined impacts of extreme events and contamination on human health is important for identifying points of vulnerability as well as identifying opportunities for building resiliency.

In this paper we present a health impact assessment to understand the vulnerability of Pueblo community members to direct, indirect, and combined effects of climate change. We first evaluated the direct health impacts associated with climate change. We developed climate health load indices for two key climate hazards (heat and wildfire), based on recently published scientific literature on climate impacts and health, and locally available climate projections. We then characterized the indirect impacts of climate change, focusing on the potential for extreme events to increase contaminant exposure and human health risks, through an exemplar case study. Finally, we qualitatively discuss the combined effects of direct and indirect climate change impacts and contamination on human health, through a review of proxy literature.

To evaluate the direct health impacts associated with climate change, we developed Pueblo-specific quantitative projections for extreme heat and wildfire and integrated these projections to develop an overall climate load health index for the Pueblo. The climate load health index can be used as a proxy for understating the severity of climate-related health impacts in the future. A higher climate load health impact value indicates a higher likelihood of negative climate-related health effects for members of the Pueblo in the future. We projected that the overall climate load health index could be 90 times worse for the Pueblo by 2050 and nearly 300 times worse by 2090 compared to current conditions.

To characterize the indirect impacts of climate change, we compared pre- and post-storm conditions from 2013 as an illustrative example of how climate impacts may affect contaminant exposure levels and health risks. We found that excess cancer risk was greater with post-flood

surface water and sediment exposures compared to pre-flood surface water and sediment exposures. However, we do note that it is difficult to predict how burn-flood events will contribute to contaminant transport from LANL toward the Pueblo on broader spatial and temporal scales.

Our review of the literature demonstrates that, for populations experiencing negative health effects from multiple stressors, the total health impacts from these multiple stressors may be greater than those predicted for a single stressor, because the health impacts of these stressors may be additive or, in some cases, synergistic (i.e., greater than the sum of individual health impacts). Specifically, we provide examples where specific aspects of climate change that have been integrated into our estimate of climate load (e.g., particulate matter and heat, radionuclide exposure and smoking, coronavirus disease 2019 and wildfire smoke) have been documented to interact with other heath stressors.

The paper provides an overview of the cumulative health effects of contaminant exposure and climate-related health risks to members of the Pueblo. To build resiliency against these climate-related impacts, members of the Pueblo can target mitigation strategies in areas that may result in increased contaminant transport due to burn-flood events. Members of the Pueblo can also prepare for climate change-related health impacts by understanding that climate hazards, such as extreme heat, can negatively impact human health and try to mitigate their heat exposure accordingly.

Acronyms and Abbreviations

COVID-19	coronavirus disease 2019
Cs	Cesium
CSO	cancer slope factor
DGVM	Dynamic Global Vegetation Model
EPA	U.S. Environmental Protection Agency
Facility	Los Alamos National Lab
GCM	global climate model
HHRA	human health risk assessment
LANL	Los Alamos National Lab
NCA	National Climate Assessment
PM	particulate matter
Pu	Plutonium
Pueblo	Pueblo de San Ildefonso
RCP	Representative Concentration Pathway
SARS	severe acute respiratory syndrome
Sr	Strontium
TRA	Tribal Risk Assessment
U	Uranium
USGS	U.S. Geological Survey

1. Introduction

The Pueblo de San Ildefonso (Pueblo), located in northern New Mexico, is facing changing climate conditions, including increasing average temperatures as well as the more frequent and/or intense incidences of extreme heat, drought, wildfires, storms, and floods that are typical of the U.S. Southwest region (USGCRP, 2018). These changing climate conditions are expected to negatively impact human health. For example, increased heat can cause heatstroke, hyperthermia (i.e., condition of having a body temperature greatly above normal), and even death; and wildfires can result in adverse effects to respiratory and cardiovascular systems (Anderson and Bell, 2011; Mills et al., 2015; Lay et al., 2021).

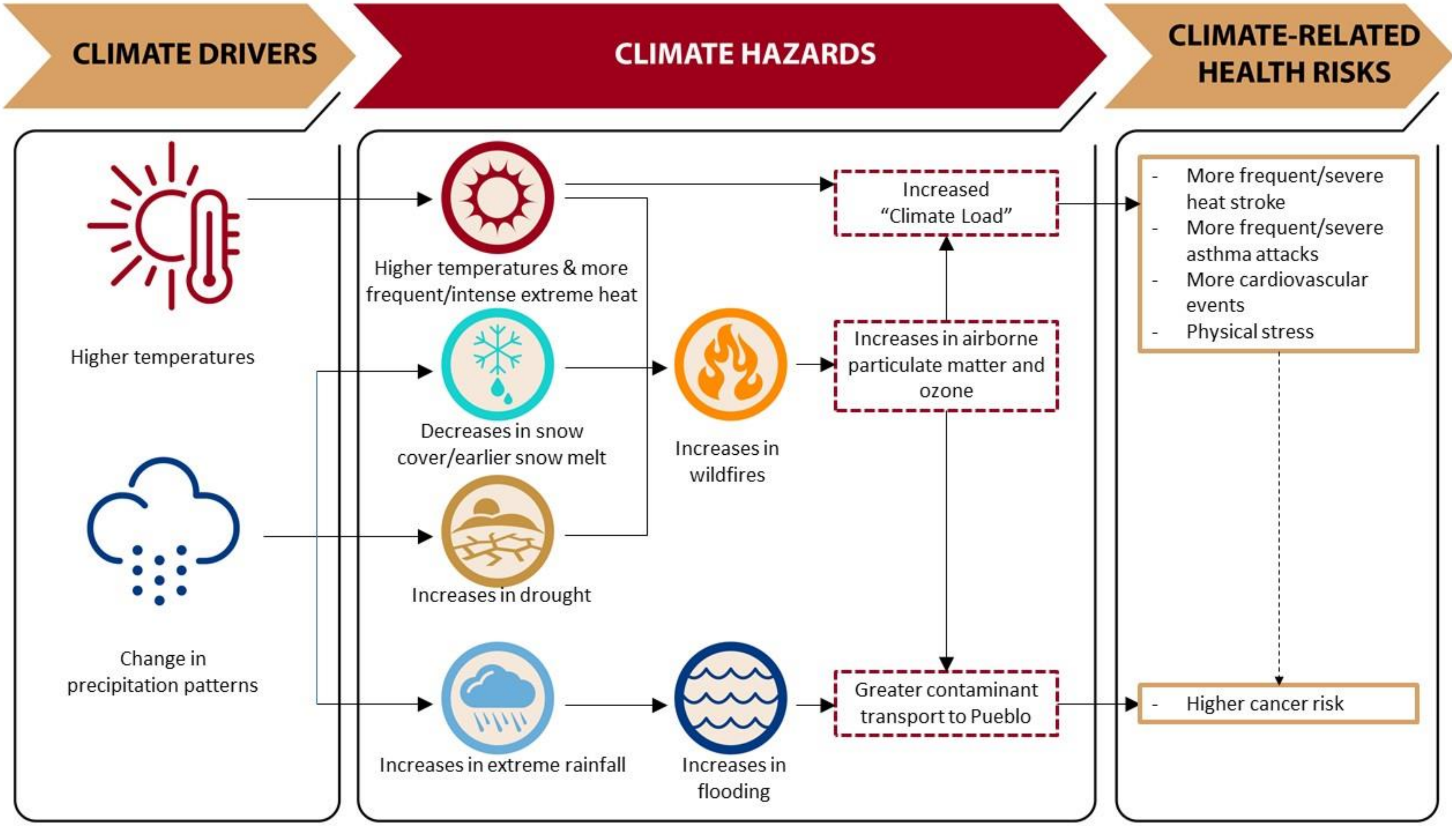
Simultaneously, the Pueblo also faces potential human health impacts due to its proximity to the Los Alamos National Lab (LANL or the facility). Since operations began in 1943 with the development and testing of nuclear weapons, activities at LANL have resulted in the release of radiological and other hazardous contaminants into the environment (U.S. DOE, 2021). Extreme events such as wildfires, extreme rainfall, and flooding may increase the risk of mobilization and exposure to contaminants on the Pueblo from the facility. Heavy rains that fall within the site on drought-affected soils or soils that have been mineralized by wildfires may erode the soil and transport it downstream toward the Pueblo, carrying along any contaminants attached to soil particles. For example, the increased mobilization of contaminants during storm events was documented after the large Cerro Grande Fire wildfire occurred in 2000 (Englert and Ford-Schmid, 2011), and the Pueblo is concerned that these trends of increased contaminant transport may increase in the future with changing climate conditions.

Consequently, climate change may adversely affect the health of Pueblo members directly (e.g., heat stress, adverse respiratory effects due to low air quality). In addition, the Pueblo is concerned that climate change may also adversely affect human health indirectly by causing increased exposure to contamination (e.g., increased release/transport and exposure to contaminants during wildfires and extreme storm events). Finally, there is concern about Pueblo members being simultaneously exposed to direct and indirect effects of climate change, particularly if the effects of the former exacerbate the latter. In other words, individuals already suffering from the effects of extreme heat or reduced air quality may be more susceptible to the effects of contaminant exposure than they otherwise would be (Figure 1).

Understanding the combined impacts of extreme events and contamination on human health is important for identifying points of vulnerability as well as identifying opportunities for building resiliency. It is also a very challenging endeavor, with limited scientific studies that directly quantitatively assess the combined effects of climate change and contamination on human health.

The purpose of this paper is to present a health impact assessment to understand the vulnerability of Pueblo community members to the direct, indirect, and combined effects of climate change. Recognizing the state of available science, we take the following approach to this assessment. We first evaluate the direct health impacts associated with climate change. We develop climate health load indices for two key climate hazards (heat and wildfire), based on recently published scientific literature on climate impacts and health, and locally available climate projections. We then characterize the indirect impacts of climate change, focusing on the potential for extreme events to increase contaminant exposure and human health risks, through an exemplar case study, specifically, a large storm event that occurred in fall 2013.

Figure 1. Process diagram illustrating how climate change can impact the health of members of the Pueblo.



Next, we qualitatively discuss the combined effects of direct and indirect climate change impacts and contamination on human health, through a review of proxy literature.

The remainder of this report is organized as follows:

- Section 2 provides background information on the Pueblo
- Section 3 describes relevant climate drivers and hazards, and associated health risks
- Section 4 presents a climate load health index for two climate hazards – heat and wildfires
- Section 5 presents an approach to quantifying the indirect health effects of climate change, focusing on contaminant exposure and human health, using an exemplar case study
- Section 6 qualitatively discusses the combined health effects of contaminants and different climate change impacts based on a review of available literature
- Section 7 presents a summary of our findings
- This is followed by references cited in the text.

2. Brief Overview of the Pueblo de San Ildefonso

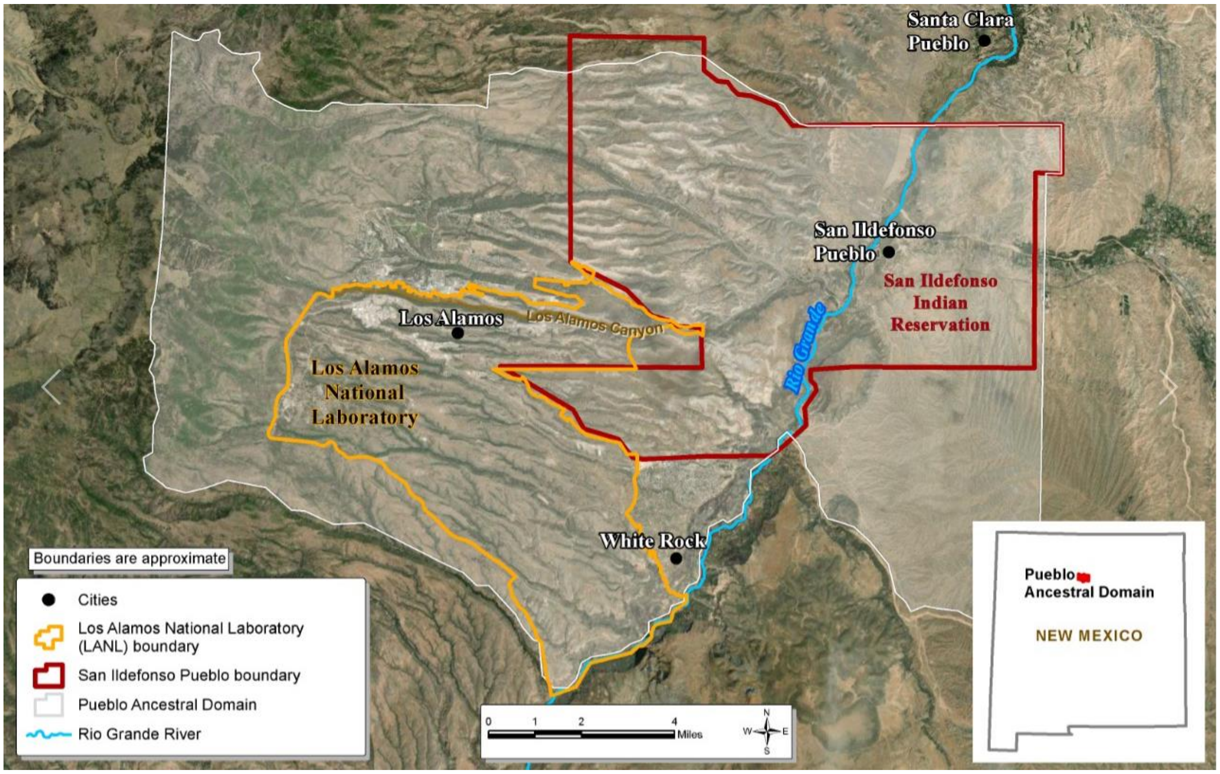
The Pueblo de San Ildefonso – or Po' Woh Geh Owingeh, which means "where the water cuts through" in the Pueblo's Tewa language – is located along the Rio Grande at the foot of Black Mesa in north-central New Mexico. The Pueblo has a semi-arid climate, characterized by low precipitation and low humidity. Changes in precipitation differ across seasons with some of the of the annual precipitation occurring during summer thunderstorms, which can result in significant surface water runoff flows in local canyons.

Inhabitation began in the 1300s, when people from Bandelier, who earlier had come from the Mesa Verde area in southern Colorado, moved down to the Rio Grande (Pueblo de San Ildefonso, 2021). The Pueblo currently encompasses approximately 30,000 acres, sitting within a larger Ancestral Domain of more than 60,000 acres (Figure 2). The Pueblo was traditionally an agricultural-based society, growing a variety of crops including corns, beans, and squash, known as the Three Sisters. They later added melons, cilantro, and chili using water-conserving, dry farming techniques, such as "waffle gardens" (https://www.sanipueblo.org/farm-program.aspx). More recently, the Pueblo has engaged youth in agricultural practices through a youth farming program (see photograph panel). Large game hunting is also traditionally important to the Pueblo. With a recent

Top left: Pueblo youth farm program; top right: black-on-black pottery created by Pueblo artisans; bottom left: large game on the Pueblo; bottom right: traditional cultural site within the Ancestral Domain. All photographs from https://www.sanipueblo.org/.

resurgence of traditional arts, the Pueblo is well-known for black-on-black, high-polished pottery (see photograph panel). The Pueblo is listed in the National Register of Historic Places, recognized for its historic and cultural significance, and its important role in the revival of Pueblo ceramics. The Pueblo has an enrollment of approximately 750 people and is one of 6 Tewa-speaking Pueblos in New Mexico (NPS, 2016; Pueblo de San Ildefonso, 2021).

Figure 2. Location of the Pueblo in proximity to LANL.



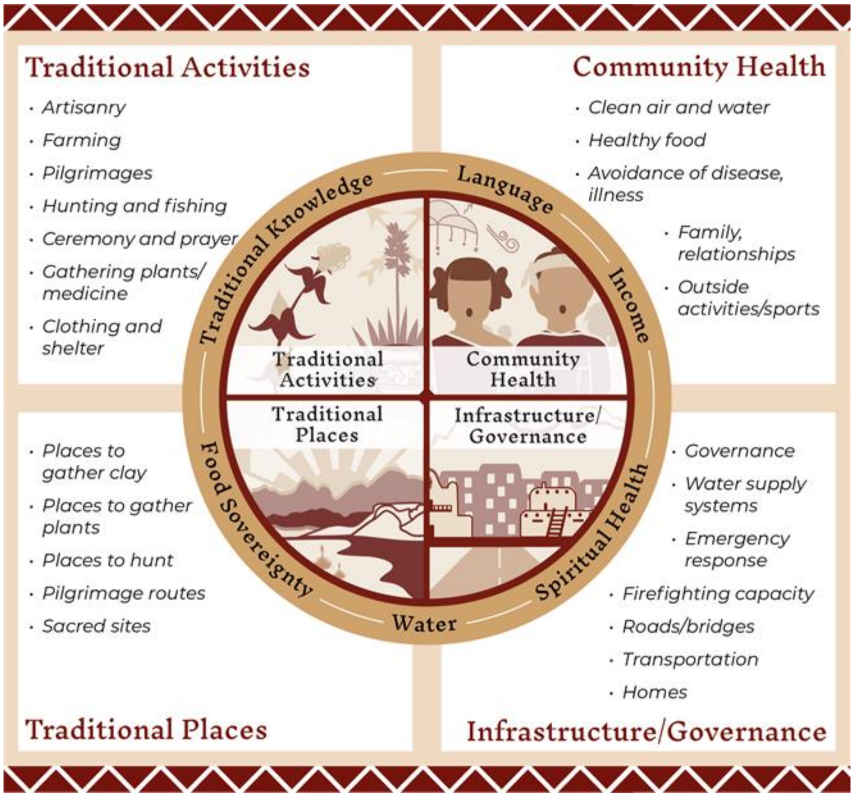
The Pueblo faces unique environmental challenges because of its proximity to the Department of Energy's LANL facility, where historical and ongoing activities, beginning with the World War II-era development of the atomic bomb, have left a legacy of radionuclides such as plutonium, as well as other contaminants in the local environment (Figure 3; U.S. DOE, 2021). The facility is located entirely within the Ancestral Domain of the Pueblo, and much of the Pueblo's current lands are located directly adjacent to and downgradient of the facility (see Figure 2). Traditional uses of natural resources are deeply rooted in the Pueblo's culture and members of the Pueblo use almost all of the natural resources (e.g., plants, soil/clay, water, animals) found on Pueblo lands and within the Ancestral Domain. However, members of the Pueblo are concerned with being able to continue their traditional practices due to the potential health risks associated with the use of contaminated natural resources (see Section 5.1). Simultaneously, the Pueblo is also experiencing dramatic climate change-related impacts. For example, average temperatures near the Pueblo (recorded at LANL) have increased over the past 15 to 25 years, and 5 of the hottest summers on record at LANL have occurred since 2002 (Bruggeman, 2017). A further discussion of climate change impacts affecting the Pueblo is provided below in Section 3.

Figure 3. Photograph of the center of Los Alamos (Technical Area 1 of LANL) taken on December 4, 1946.

Source: https://www.lanl.gov/museum/manhattan-project/.

As a result of these concerns, the Pueblo has recently engaged in a climate resiliency planning process. The first step in this planning was to articulate the Pueblo's community vision, which identifies key aspects of community life (Figure 4). The Pueblo is now developing adaptation strategies to preserve and sustain the key aspects of its community vision. As shown in Figure 4, a key aspect of community life is community health, which is broadly defined to encompass healthy family and community relationships; access to clean uncontaminated air, water, and other resources; and avoidance of disease and illness. The assessment presented in this report is focused on characterizing the direct, indirect (i.e., climate-induced increased exposure to contamination from LANL), and combined impacts of climate change on the health of Pueblo community members. The results of this assessment will help to identify points of climate-related health vulnerability, as well as identify opportunities for building adaptation and resiliency into the community's health.

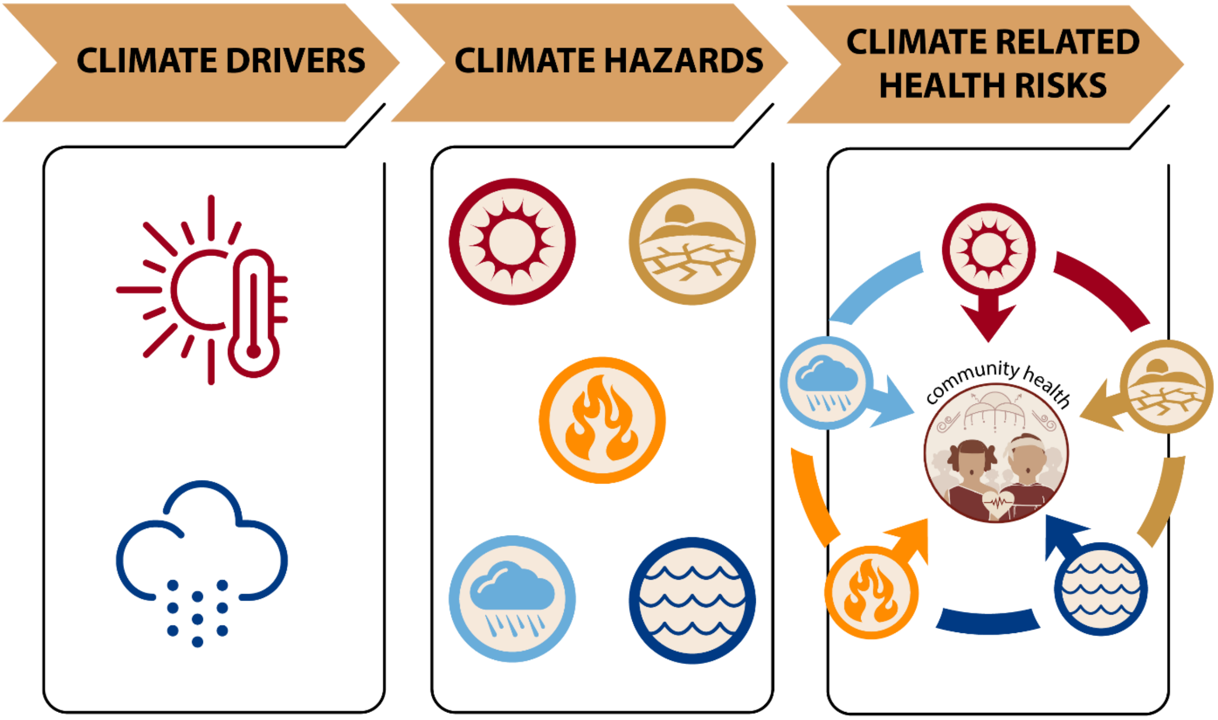
Figure 4. The Pueblo's community vision. These are the key aspects of community life for which the Pueblo is developing climate adaptation measures to preserve and sustain them for future generations.



3. Anticipated Climate Change Impacts

In this section we discuss anticipated climate change impacts for the Pueblo, with a specific focus on impacts that have potential implications for human health. This summary draws directly from the Pueblo's Climate Change Action Plan, which Abt Associates helped draft. Below, we describe (1) key climate drivers for the Pueblo and the U.S. Southwest region, and (2) related climate hazards that could result from projected changes in temperature and precipitation. We then summarize the climate-related health risks that could be associated with these climate hazards (Figure 5).

Figure 5. Key components of our climate-related health risk assessment.



3.1 Climate Drivers

Situated in the Southwest, the Pueblo has a semi-arid climate characterized by abundant sunshine, light precipitation totals, and low humidity. Some of the annual precipitation comes during summer thunderstorms, which can result in significant surface water *(or Poe)* runoff flows in the canyons.

Climate – the long-term, average weather in an area – is largely determined by temperature and precipitation. In this report, we refer to temperature and precipitation as climate drivers.

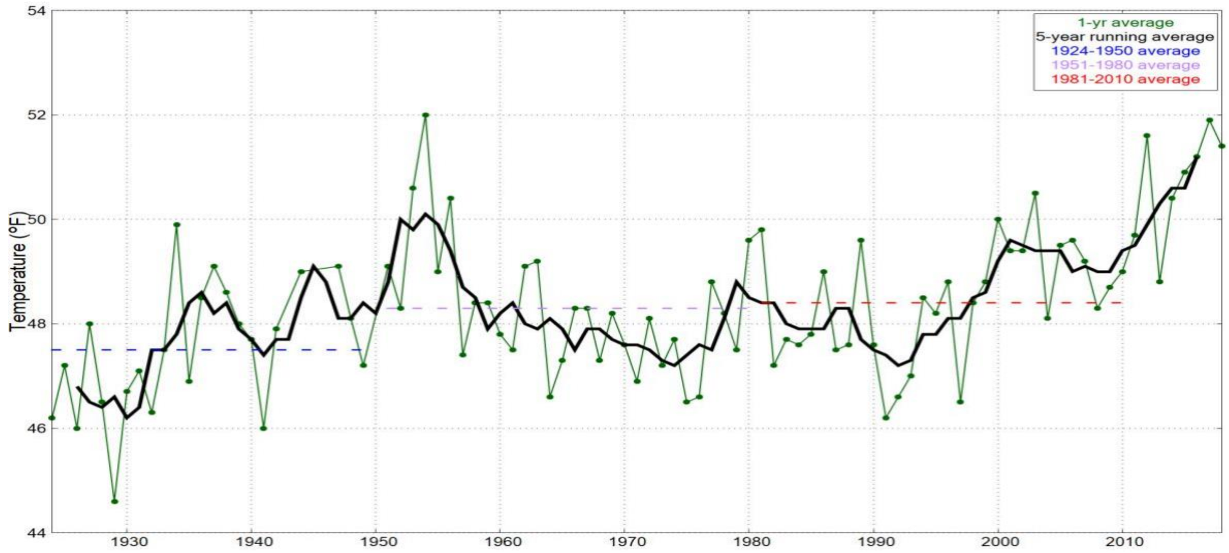
3.1.1 Temperature

In the southwestern United States, the average annual temperature increased 1.6°F between 1901 and 2016 (Vose et al., 2017; Gonzalez et al., 2018). Moreover, the region recorded more warm nights and fewer cold nights between 1990 and 2016, including a 4.1°F increase for the coldest day of the year (Gonzalez et al., 2018). Parts of the Southwest recorded their highest temperatures since 1895 in 2012, 2014, 2015, 2016, and 2017 (Gonzalez et al., 2018). Annual average temperatures for the Southwest are predicted to rise 3.4–4.3°F by mid-century (2036–2065) and 4.4–7.7°F by late century (2071–2100; Vose et al., 2017).

New Mexico is the sixth-fasted warming state in the Nation, with average annual temperatures increasing 0.6°F per decade since 1970 and about 2.7°F over 45 years (Tebaldi et al., 2012). Average temperatures near the Pueblo (recorded at LANL) have increased over the past 15–

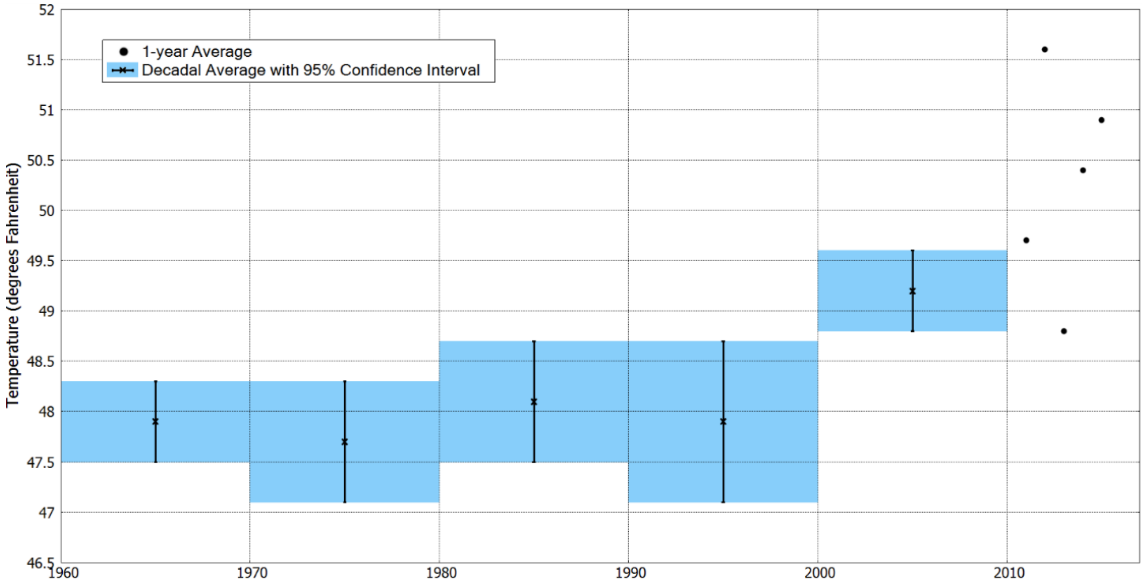
25 years. Although this is a relatively short period of observation, this increase in temperature is consistent with projections of the National Climate Assessment (NCA; Gonzalez et al., 2018) and the Intergovernmental Panel on Climate Change (IPCC, 2014; Figure 6). During the 2001–2010 decade, temperatures were approximately 1°F warmer than the previous 40 years, and from 2011 to 2018 temperatures were approximately 2.5°F warmer than 1960–2000 averages (Figure 7; Bruggeman, 2017; Hansen et al., 2019). Five of the hottest summers on record at LANL have occurred since 2002 (Bruggeman, 2017).

Figure 6. Temperature history for Los Alamos. One-year averages are displayed in green and five-year running averages are displayed in black. The dashed lines represent long-term averages (25 and 30 years).



Sources: Bruggeman, 2017; Hansen et al., 2019.

Figure 7. Decadal average temperatures and two times the standard error for Los Alamos from 1960 to 2015.



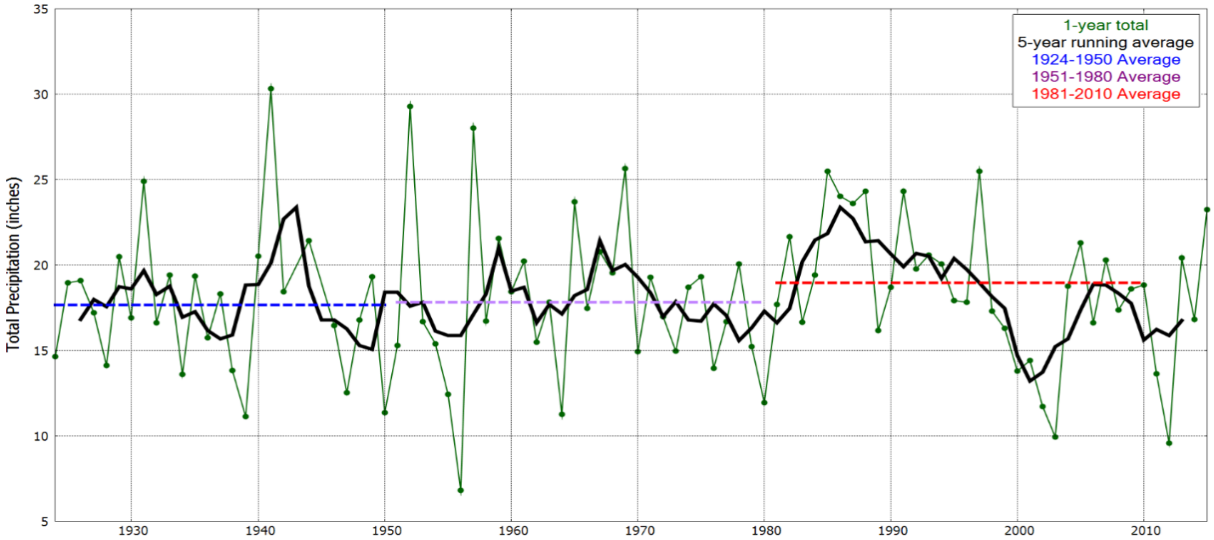
Source: Bruggeman, 2017.

3.1.2 Precipitation

Observed changes in precipitation differ across the seasons. The Southwest has seen a decrease in precipitation, with drying most pronounced during the spring season (Easterling et al., 2017). Similar to observed changes, precipitation is expected to decline in the future, particularly in the spring (Easterling et al., 2017). As temperature increases, winter and spring precipitation may also shift from snow *(or Pho')* to rain *(or Kwan)*. The NCA projects declines in various snow metrics in the western United States, including snow water equivalent, the number of extreme snowfall events, and the number of snowfall days (Gonzalez et al., 2018).

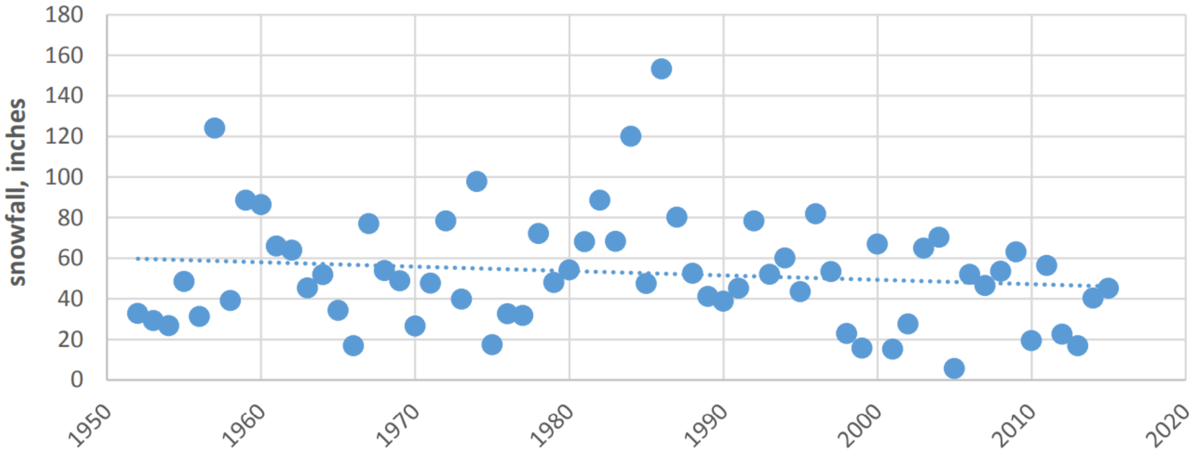
LANL data are generally consistent with NCA data. While precipitation overall does not show strong trends (Figure 8), the form of precipitation is changing. In particular, there has been a downward trend for snowfall from 1951 to 2015 (Bruggeman, 2017; Figure 9) and a decreasing length in the snow season (Bruggeman, 2017; Hansen et al., 2019). In addition, as discussed further below, when precipitation does occur as rainfall, the trend is for the rain to come in fewer but more intense storm events that can cause destructive flooding.

Figure 8. Precipitation history for Los Alamos. One-year averages are displayed in green and five-year running averages are displayed in black. The dashed lines represent long-term averages (25 and 30 years).



Source: Bruggeman, 2017.

Figure 9. Annual snowfall (July 1–June 1) for Los Alamos (1951–2015).



Source: Bruggeman, 2017.

3.2 Climate Hazards

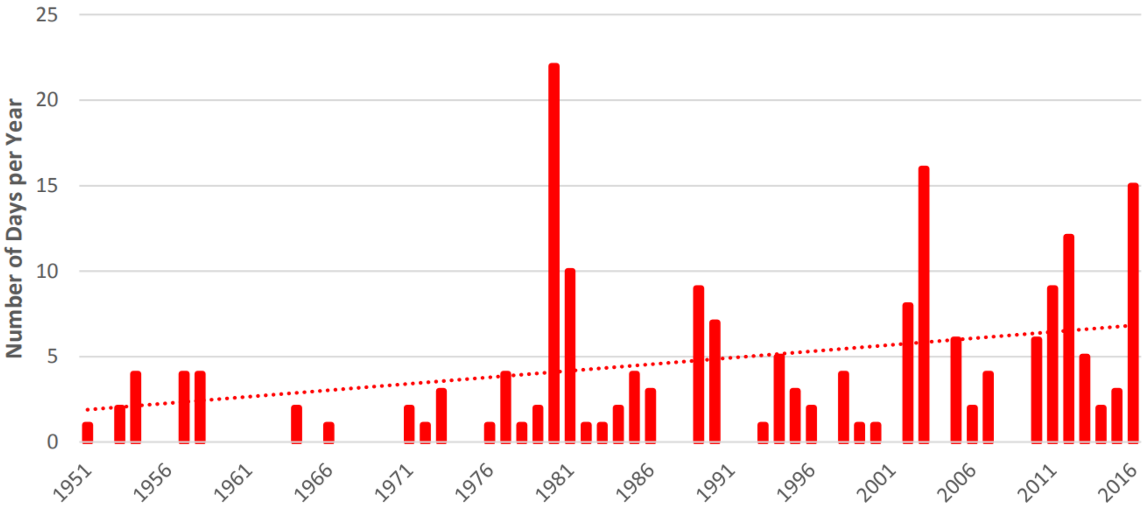
Changes in temperature and precipitation can, in turn, expose the Pueblo community to hotter temperatures, extreme heat events, droughts, wildfires, storms and flooding, and changes in snowmelt and streamflow. Below we describe these climate hazards and how they may adversely affect the Pueblo community.

3.2.1 Hotter Temperatures and Extreme Heat Events

The coldest and warmest temperatures of the year have important implications for human health and many sectoral activities, such as agricultural practices, heating, refrigeration, and air conditioning. Throughout the United States, cold extremes have become less severe while warm extremes have increased over the past century (Vose et al., 2017). In the Southwest, the coldest daily temperature of the year has increased by nearly 4°F and the warmest daily temperature of the year has increased by 0.5°F over the past century (Vose et al., 2017). Daily temperatures are projected to continue to increase substantially over the next century. In the Southwest, both the coldest and warmest daily temperatures of the year are expected to increase by approximately 6°F by mid-century. Not only will daytime temperatures increase, but nighttime temperatures and humidity are also projected to increase (Gershunov et al., 2013; Peterson et al., 2013).

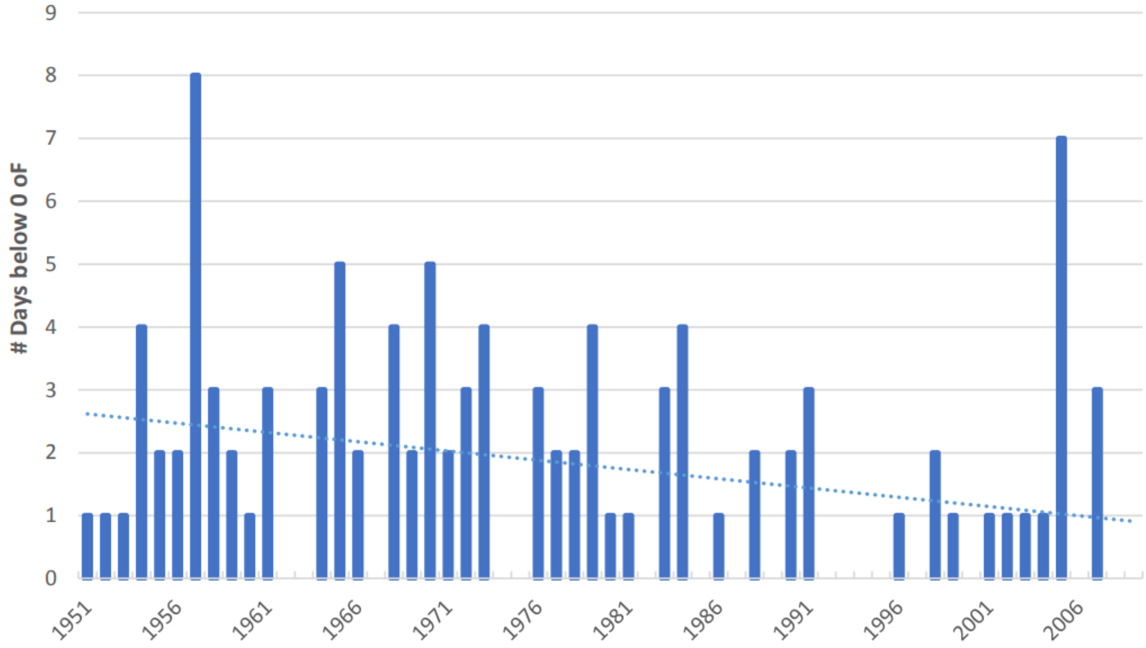
Throughout the United States, historically rare heat events have become increasingly common as global temperatures increase (Peterson et al., 2013; Wobus et al., 2017). Trends near the Pueblo (recorded at LANL) show a positive trend in the number of days with a maximum temperature greater than 90°F (Figure 10) and a negative trend in the number of days with a minimum temperature less than 0°F (Figure 11; Bruggeman, 2017). In the Southwest, projections indicate that extreme cold waves and extreme heat waves (5-day, 1-in-10-year events) will have temperature increases of at least 10°F by mid-century (Vose et al., 2017).

Figure 10. Number of days per year with maximum temperatures above 90°F for Los Alamos.



Source: Bruggeman, 2017.

Figure 11. Number of days per year with minimum temperatures less than 0°F for Los Alamos.

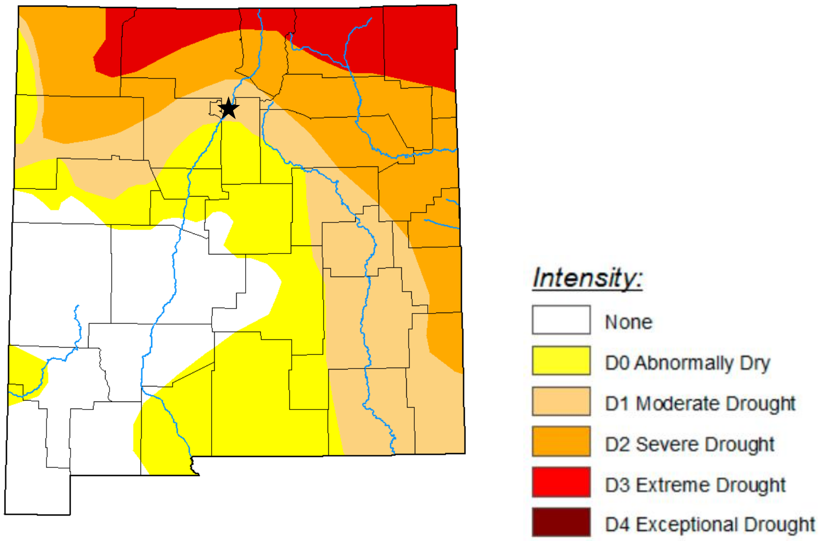


Source: Bruggeman, 2017.

3.2.2 Droughts

Much of New Mexico is currently experiencing drought conditions, with Pueblo lands in a moderate drought (Figure 12). In New Mexico, the flow of the Rio Grande is an important indicator of drought (Hoerling et al., 2013); on average, New Mexico's portion of the Rio Grande was drier every year from 2009 to 2014 (UCS, 2016).

Figure 12. New Mexico drought monitor for June 9, 2020 displaying drought intensity. The black star indicates the approximate location of the Pueblo.

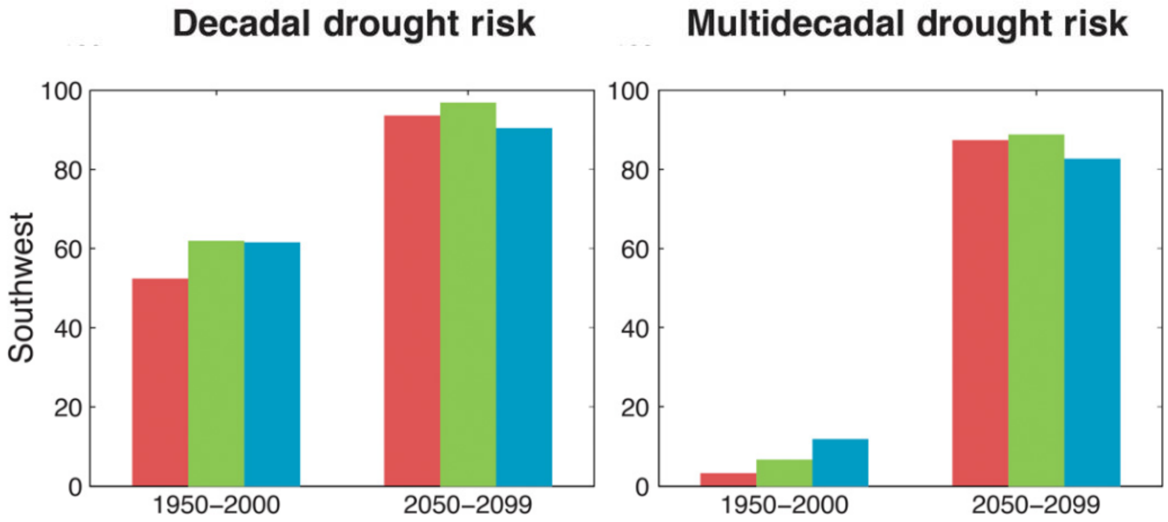


Source: National Drought Mitigation Center, 2020.

Climate change is expected to result in future droughts in the Southwest and an increased risk of mega-droughts, which are persistent droughts lasting longer than a decade, even if precipitation increases over that period (Gonzalez et al., 2018). Climate models suggest drying during the latter half of the 21st century (2050–2099) in the Southwest (Cook et al., 2015). Drying is largely the result of reduced cold season precipitation and increased evapotranspiration with reduced soil moisture (Cook et al., 2015). By mid- to late century (2050–2099), the risk of droughts will exceed historical periods (1950–2000; Figure 13), even the most severe mega-drought periods of the Medieval era (Cook et al., 2015).

More frequent, future droughts in the region will occur in a significantly warmer world with higher temperatures than recent historical events. These conditions will further stress natural ecosystems, as well as agriculture. In addition, adaptation to future droughts may be more challenging because of the widespread depletion of nonrenewable groundwater reservoirs in recent years. Historically, these groundwater resources have allowed communities to mitigate drought impacts. Increases in drought will also increase wildfire-related risks (see next section).

Figure 13. Risk (percent chance of occurrence) of decadal (11-year) and multidecadal (35-year) droughts in the Southwest, calculated from the multimodel ensemble for the Palmer Drought Severity Index (red), SM-30cm (green), and SM-2m (blue). Risk calculations are conducted for two separate model intervals: 1950–2000 (historical scenario) and 2050–2099 (Representative Concentration Pathway, RCP 8.5).



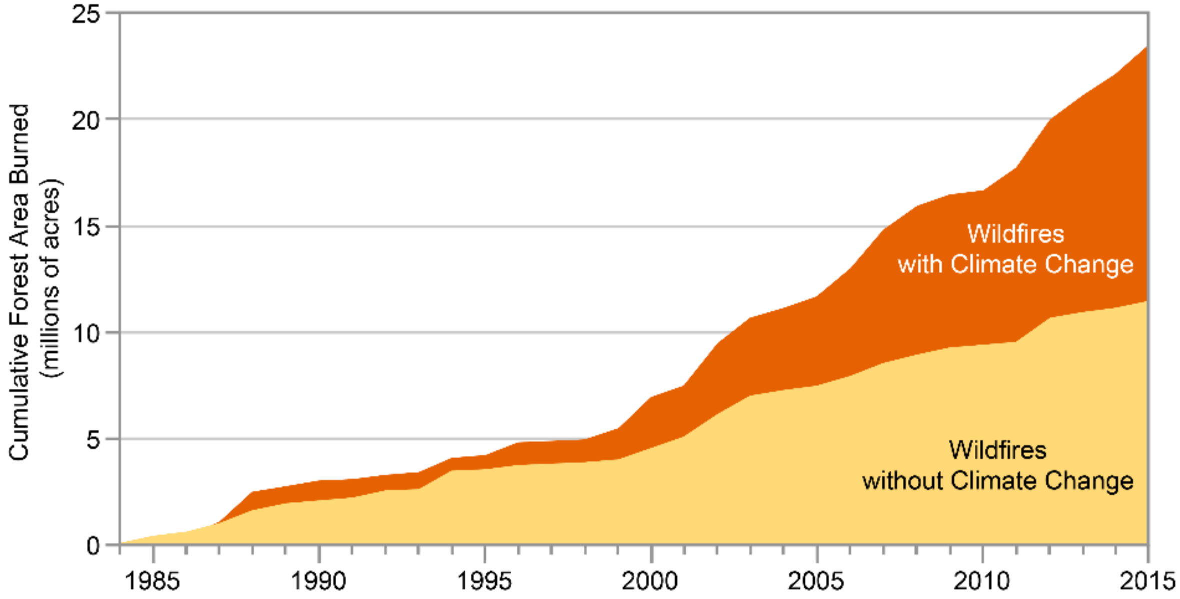
Source: Cook et al., 2015.

3.2.3 Wildfires

As a natural part of Southwest ecosystems, wildfires facilitate the germination of new seedlings and kill pests; however, excessive wildfires can also permanently alter an ecosystem’s integrity (Gonzalez et al., 2018). The frequency and intensity of large wildfires are influenced by natural and human factors such as temperatures, soil moisture, humidity, winds, and vegetation density. More intense and frequent wildfires are also associated with other climate hazards, such as droughts and drier forest conditions, reduced snowpack and earlier snowmelt, and high winds.

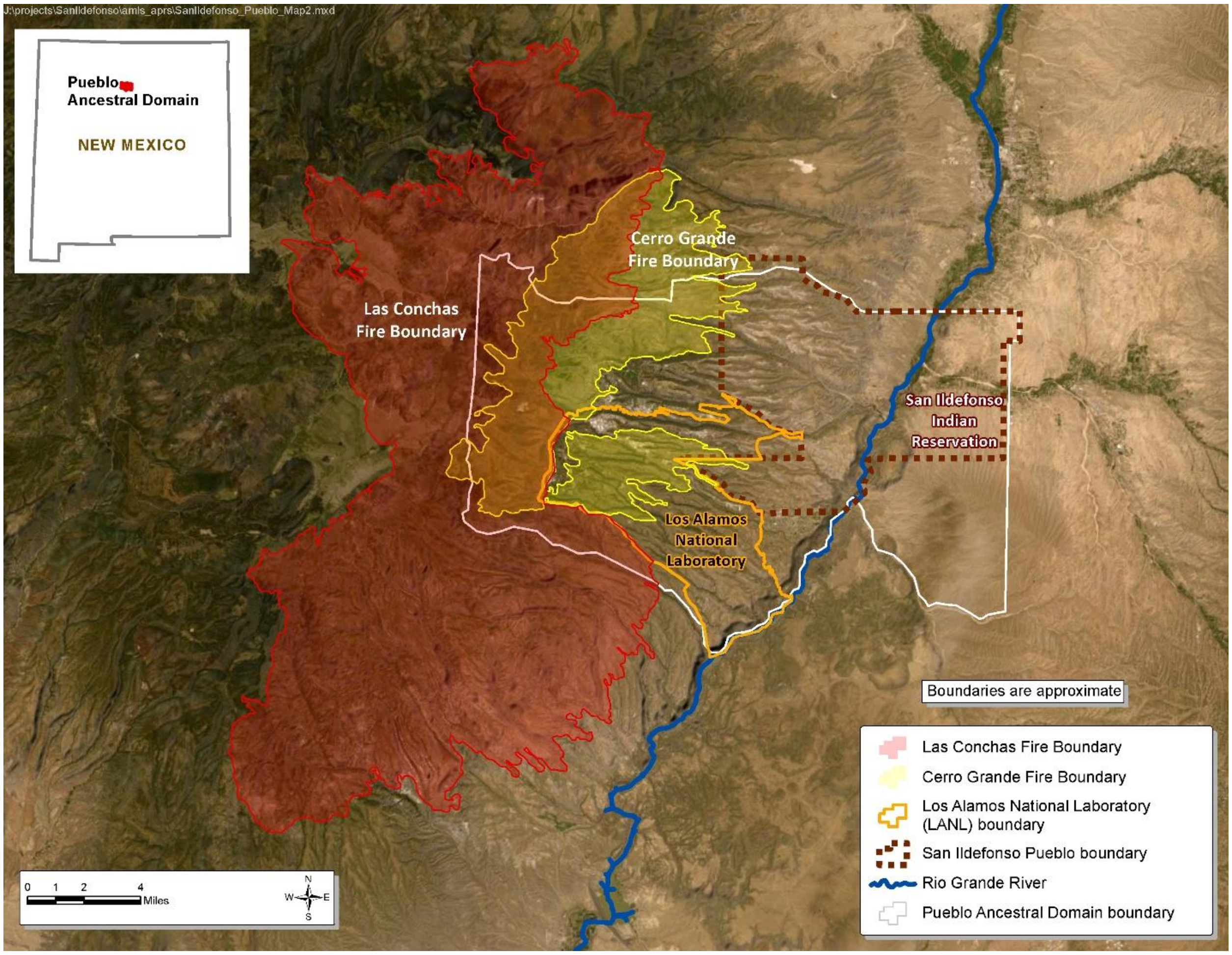
The cumulative forest area burned by wildfires in the western United States has greatly increased between 1984 and 2015, with analyses estimating that the area burned over that period was twice what would have burned had climate change not occurred (Figure 14; Gonzalez et al., 2018). For wildfires around the Pueblo, acres burned per fire have also increased dramatically over time, with the 2000 Cerro Grande fire burning 43,000–48,000 acres and the 2011 Las Conchas fire burning 154,000 acres (Fowler et al., 2015; Figure 15). Climate change models project more wildfires across the western United States (Stavros et al., 2014) and the Southwest region (Gonzalez et al., 2018). Fire frequency could increase by 25% and the frequency of very large fires (greater than 5,000 hectares) could triple (Gonzalez et al., 2018).

Figure 14. Wildfires with climate change compared to wildfires without climate change in the western United States.



Source: Gonzalez et al., 2018.

Figure 15. Boundary of the 2000 Cerro Grande fire that burned 43,000–48,000 acres and the 2011 Las Conchas fire that burned 154,000 acres near the Pueblo.



3.2.4 Storms and Flooding

Extreme precipitation events have increased throughout the United States since 1901 (Easterling et al., 2017). In New Mexico, monsoon rains – defined as sudden, intense downpours that last less than one hour – generally occur in July and August and can incite flash floods. Drought and wildfires can also exacerbate flash flooding because very dry and scorched soils have a limited capacity to absorb water *(or Poe)* (Chief et al., 2008). Although monsoon precipitation and heavy rainfall data near the Pueblo (recorded at LANL) do not demonstrate a significant trend from 1951 to 2015 (Bruggeman, 2017), significant flooding has been associated with the large wildfire events described above.

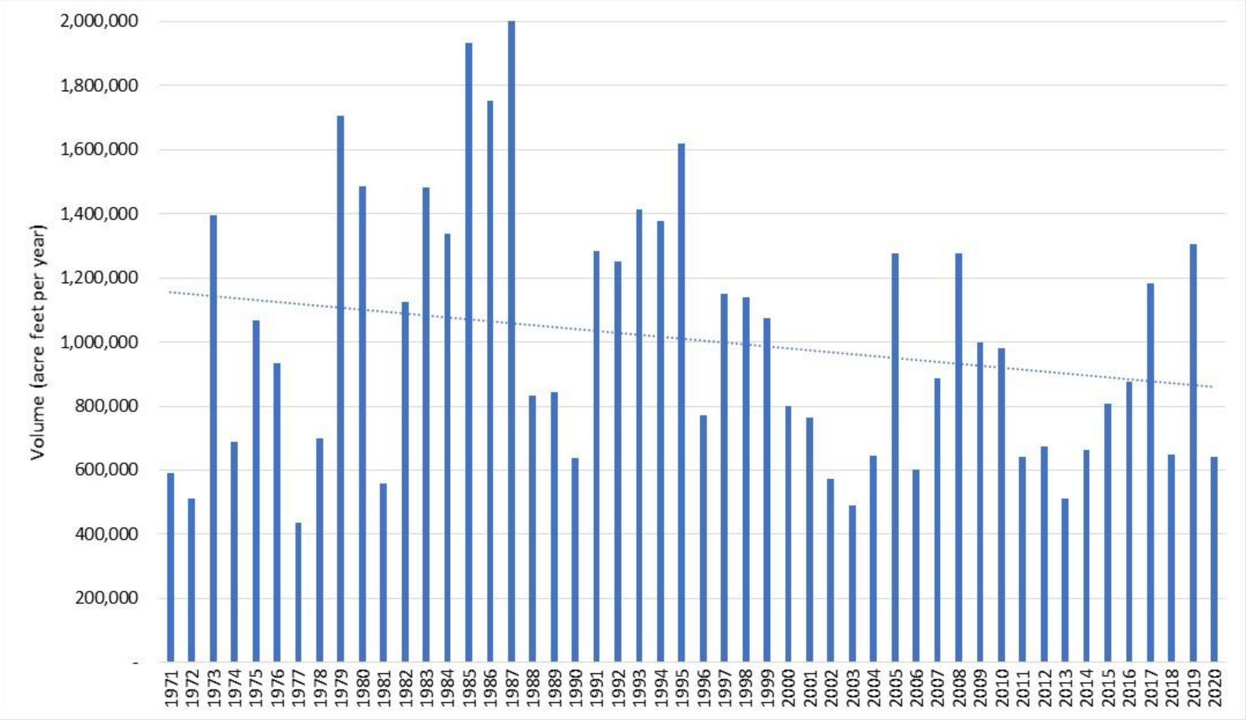
In the Southwest, climate models project an increase in the frequency of heavy downpours and an increase in daily extreme summer precipitation, based on projected increases in water vapor resulting from higher temperatures (Gonzalez et al., 2018). An increase in extreme precipitation may also lead to more frequent and intense flooding events.

3.2.5 Changes in Snowmelt and Streamflow

Increasing temperatures have altered the Southwest’s water cycle. Specifically, warm temperatures are occurring earlier in the spring and precipitation has declined (Gonzalez et al., 2018). These changes, which have decreased the region’s snowpack and its water content, have resulted in earlier peaks for snow-fed streamflows and increased the proportion of snow *(or Pho’)* to rain *(or Kwan)* (Gonzalez et al., 2018). Warmer temperatures have also been associated with increases in snowline elevation (Knowles et al., 2007). Hotter temperatures and reduced snowpack attributed to climate change have already amplified recent droughts and reduced river flow in the Rio Grande (Lehner et al., 2017; Gonzalez et al., 2018). Water flows in the Rio Grande at the Otowi Bridge gage (U.S. Geological Survey [USGS] 08313000) have trended lower over the last five decades: after rising to an average of 1.4 million acre-feet/year in the 1980s and early 1990s, the volume decreased to approximately 830,000 acre-feet/year during drought years in the 2000s and 2010s (Figure 16; USBR, 2018). The highest-recorded volume was 2,592,837 acre-feet/year in 1941 and the lowest was 359,480 acre-feet/year in 1956 (USBR, 2018). In the Upper Rio Grande River Basin, researchers (Lehner et al., 2017) found that reduced snowpack reduces river runoff efficiency. They estimate that in years with below-median precipitation and above-median temperatures, low runoff ratios (i.e., the portion of the precipitation that ends up in the river each year, rather than evaporating) are 2.5 to 3 times more likely (Lehner et al., 2017).

Projected annual flow of the Rio Grande at the Otowi Bridge gage is generally expected to decrease by 2050 and 2080 under various climate scenarios, compared to current conditions (USBR, 2018). Climate models project hotter temperatures, which can shift precipitation from snow *(or Pho’)* to rain *(or Kwan)* in the mountains. By 2050, colder and higher areas in the Intermountain West are projected to receive more rain *(or Kwan)* in the fall and spring but would likely continue to receive snow in the winter at the highest elevations (Gonzalez et al., 2018). Reduced snowpack and earlier snowmelt in the headwaters of New Mexico’s major rivers *(or P’ok’ay)* can reduce water availability throughout the year (Garfin et al., 2014) and can also increase wildfire risk by extending the fire season and increasing drought (Vose et al., 2018).

Figure 16. Historical Rio Grande at Otowi Bridge flows.

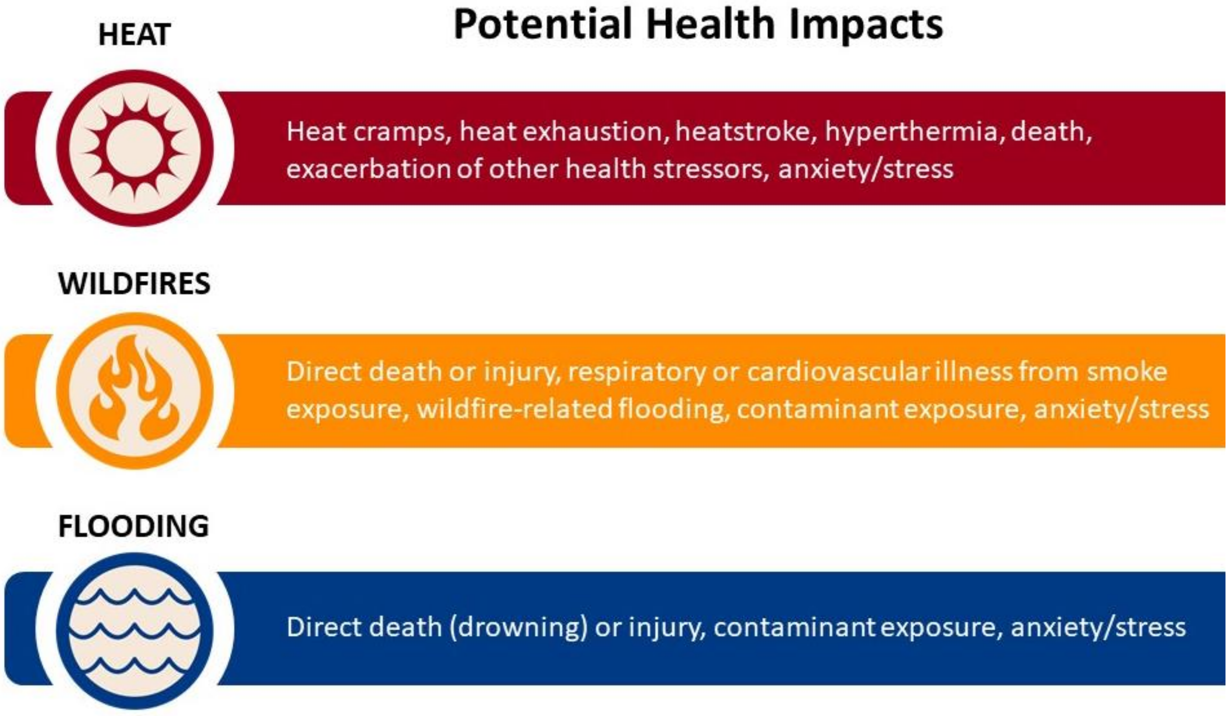


Source: USGS surface water data for Rio Grande at Otowi Bridge (USGS 08313000), New Mexico.

3.3 Climate-Related Health Risks

The climate hazards described above, particularly extreme heat, wildfire, and flooding, can lead to direct and indirect effects on the health of members of the Pueblo (Figure 17). Below we describe the potential health implications of each of these climate hazards for the Pueblo in more detail. In addition to the impacts of climate change on physical health, there are also implications for cultural health and community well-being. As encapsulated in the community vision, the Pueblo is particularly concerned with the impacts of climate change on family and community relationships, in essence, on the mental and spiritual health of the community.

Figure 17. Physical health impacts that may be caused by climate hazards experienced by members of the Pueblo.



3.3.1 Extreme Heat Events and Hotter Temperatures

Extreme heat is a known hazard that can pose a significant threat to the health of human beings. Extreme temperatures most directly affect health by interfering with the body’s ability to regulate its internal temperature (Lay et al., 2021). This can lead to a cascade of illnesses, including heat cramps, heat exhaustion, heatstroke, and hyperthermia (i.e., condition of having a body temperature greatly above normal). Prolonged exposure to high temperatures can increase hospital admissions for cardiovascular, kidney, and respiratory disorders; and can result in death (Sarofim et al., 2016). Extreme heat can be particularly threatening to vulnerable populations, as it can worsen chronic conditions such as cardiovascular disease, respiratory disease, cerebrovascular disease, and diabetes-related conditions (Anderson and Bell, 2011; Mills et al., 2015; Lay et al., 2021).

As climate change increases the intensity, duration, and frequency of extreme heat events, adverse effects on human health are likely to result. Mills et al. (2015) examined this issue for 33 metropolitan areas in the United States, and developed temperature-related mortality projections for historical and potential future climates. These projections covered 100 million of the 310 million U.S. residents in 2010. The authors found that projected mortality from extremely hot and cold days combined increased significantly over the 21st century because of the overwhelming increase in extremely hot days (i.e., heat-related mortality increased by approximately 3,000–5,000 people per year in 2100). Mills et al. (2015) also found that greenhouse gas mitigation, which would reduce climate change, could substantially reduce this mortality risk. Lay et al. (2021) expanded these analyses to account for the ability of populations to adapt to extreme heat over time, which could reduce mortality risk. They found that while historically people have been able to adapt to higher temperatures and reduce mortality risk, their ability to do so in the future will be more limited as temperatures become hotter and few additional adaptation options are available.

In addition to direct effects of heat on health, extreme heat can also interact with other health-related stressors, making their impacts worse. For example, multiple studies have shown that the effects of ozone and particulate matter (PM) become significantly worse as temperatures rise (Ren and Tong, 2006; Staffogia et al., 2008; Noyes et al., 2009). These findings suggest that the physical stress caused by heat could also make members of the Pueblo more vulnerable to other diseases (e.g., respiratory, cardiovascular, or cardiopulmonary disease). See Section 6 for a more detailed discussion about the potential for heat to interact with other health-related stressors.

3.3.2 Wildfire

Increases in wildfire can directly affect the health of members of the Pueblo through a few different mechanisms (Reid et al., 2016). First, wildfires can cause death or injury to people trapped within or very close to a fire. While there is typically sufficient warning to evacuate prior to such impacts occurring, rapidly moving fires can sometimes preclude timely evacuations, particularly in areas with limited evacuation routes.

Second, wildfire can degrade air quality in nearby areas and at broad geographic scales (Mallia et al., 2015; Reid et al., 2016; Koman et al., 2019). For example, David et al. (2021) found a significant increase in the number of state applications for “exceptional events” since 2007 – exceptional event waivers allow states to avoid liability when wildfires or other events cause pollution levels to exceed National Ambient Air Quality Standards. They found that most of the exceptional events in the western United States were due to wildfires. In addition, multiple studies have shown that wildfire-associated increases in PM can cause or exacerbate respiratory or cardiac illnesses (Cascio, 2018). For example, during the 2011 Wallow Fire in New Mexico, Resnick et al. (2013) found an increased risk of respiratory emergency room visits for conditions such as asthma (8%) and other diseases of the respiratory system (23%) during the peak of the wildfire exposure period. Similarly, during a particularly intense wildfire season in 2012 in Colorado, Alman et al. (2016) found positive relationships between emergency visits for respiratory issues (e.g., asthma, chronic obstructive pulmonary disease) and concentrations of $PM_{2.5}$ during the wildfire period. Gan et al. (2020) found a similar result during the 2013 wildfire season in Oregon, with a strong link between wildfire smoke-related $PM_{2.5}$ and asthma diagnoses at emergency departments.

Third, in areas near contaminated sites (such as the Pueblo), wildfires result in increases in exposure to contaminants. For example, wildfires can burn vegetation and soils that are sequestering hazardous contaminants, which can lead to their mobilization and transport offsite via ash or PM (i.e., “dust”; Whicker et al., 2006a, 2006b). Severe wildfires that damage forest vegetation can also reduce the ability of soils to absorb water and plants to remove water through transpiration, making them more prone to flooding and erosion. When these post-fire conditions are combined with intense rainfall or rapid snowmelt, localized flooding and erosion can transport contaminated soil and water to areas beneath the burned area. See the next section for more information on flooding-related health risks.

3.3.3 Flooding

Similar to wildfire, increases in flooding can threaten the health of members of the Pueblo through various mechanisms. A flood can directly threaten human health through drowning and injuries, and, depending on its location and scale, can limit access to health-related infrastructure, services, and materials (e.g., hospitals, clinics, medicine; Paterson et al., 2018). However, a more central concern for the Pueblo is the potential for floods to facilitate the transport of contaminants from LANL to the Pueblo via sediment transport. While in typical years the rates of sediment transport from LANL to the Pueblo is quite low, large floods could lead to increases in contaminant exposure for Tribe members.

For example, two years after the 2011 Las Conchas fire (which burned 154,000 acres in the vicinity of the Pueblo; see Figure 15 above), a 1,000-year rain event occurred in September 2013, during which 8.72 inches of precipitation fell (LANL, 2014). The fire-damaged forests, unable to retain this massive influx of water, incurred flooding in areas beneath the burned areas, damaging roads, bridges, and other infrastructure (Walterscheid, 2015). Sampling conducted on Pueblo lands after this flood event showed elevated concentrations of plutonium and other contaminants in the newly deposited surface sediments/soils, compared to concentrations at greater depths, suggesting that the event resulted in the transport of contaminants from LANL onto Pueblo lands (see Section 5.2).

Similarly, after the earlier Cerro Grande fire (which occurred in 2000 and burned 43,000–48,000 acres; see Figure 15 above), Englert and Ford-Schmid (2011) showed that the movement of plutonium from LANL increased during storm events, and that most of this plutonium (about 80%) was deposited on Pueblo lands, with the remainder discharging to the Rio Grande.

3.3.4 Impacts on Cultural/Spiritual Health and Family/Community Relationships

The impacts of climate change can also have deleterious effects on an individual’s spiritual and mental health, and more holistically on the broader community’s health overall (Donatuto et al., 2011, 2016). Individuals whose physical health is impaired due to climate effects may be less able to engage in cultural practices, which may in turn adversely affect their spiritual and mental health. Changing climate conditions can also directly affect members’ abilities to engage in cultural practices, which in turn may impact the cultural/spiritual health of individuals and the community as a whole:

- The increased uncertainty of the effects of climate change on the future availability or health of culturally significant resources can negatively impact community health (Donatuto et al., 2016).
- When an individual’s physical health is deteriorated due to the climate impacts described above, they may be less able to engage in cultural practices that require physical exertion, such as hunting, gathering plants, farming, etc. The inability to engage in these cultural practices may then result in a deterioration of spiritual/mental health.
- Increased requirements to shelter in place to avoid extreme heat, low air quality, or extreme events (e.g., flooding); or in the extreme case of needing to evacuate the Pueblo (e.g., due to wildfires) not only limit the ability to engage in cultural practices but can be very isolating experiences and cause negative disruptions to family and community relationships. Many

cultural/traditional practices, such as ceremony, prayer, pilgrimages, hunting, and celebrating feast days, are family or larger group activities. Loss of the ability to interact with others in many cases means cultural practices where multiple individuals fulfill distinct roles cannot be executed, which can negatively affect the cultural health of the community and the mental/spiritual health of individuals.

- During the development of the community vision, youth participants described the disruptive nature of climate change on family interactions, noting that people were more irritable when temperatures are higher and less willing to engage in family interactions.

These impacts to the spiritual and mental health of individuals, to family and community relationships, and to the overall cultural health of the community are challenging to characterize in a quantitative index such as we describe below for climate impacts on physical health (Donatuto et al., 2011, 2016). However, these are nevertheless very real repercussions of a changing climate that should not be ignored, and it is important to include consideration of cultural/spiritual health and sustaining family and community relationships when developing climate adaptation and resiliency strategies.

4. Estimation of Current and Future “Climate Load” Facing Members of the Pueblo and Development of a “Climate Load Health Index”

As described in Section 3.2, key climate change hazards facing the Pueblo such as extreme heat and wildfires can pose important health risks to Tribe members. We describe below how we quantified the future, integrated climate-related stress facing members of the Pueblo, borrowing from an analogous approach used in the health risk assessment literature. In the health risk field, it is widely recognized that what is referred to as an individual’s “allostatic load” can influence how likely they are to suffer adverse health outcomes. An allostatic load is essentially the wear and tear on the body that can result from exposure to chronic stress (Guidi et al., 2021). Individuals with high allostatic loads are more likely to experience negative health outcomes (e.g., chronic conditions, disabilities, mortality) than individuals with low allostatic loads (Guidi et al., 2021). Below, we develop an analogous index related to projected climate change-related stress – the “climate load,” which will help members of the Pueblo understand the climate-related stress that they may face in the future. The Pueblo-specific climate load, as described in Section 4.2 below, may influence how sensitive members of the Pueblo are to future exposures to non-contaminant and contaminant health stressors. The climate load can be used an indicator of the severity of climate-related health impacts.

4.1 Approach to Estimating the Climate Load

To develop a quantitative estimate of the Pueblo’s climate load, we leveraged climate change impacts research that we have conducted for a range of clients over the past five years, which has been published in the peer-reviewed literature (Mills et al., 2018; Lay et al., 2021). Although these studies were completed for other purposes, we were able to tailor them, as much as possible, for the Pueblo. We developed quantitative projections for extreme heat and wildfire. Because we leveraged climate change projections from other studies, with more substantial time and resources, these projections could be refined. Below we describe the methods we used to repurpose data from our previous efforts to provide Pueblo-specific projections for extreme heat and wildfire impacts. In the next section, we also describe how we integrated these projections to develop an overall index of climate load for the Pueblo. As is typical in the climate change literature, we provide estimates of each climate change impact for the present (between 2010 and 2020, depending on the analysis), mid-century (2050), and end of century (2090) to provide a sense of how the magnitude of these impacts will change over time.

4.1.1 Extreme Heat

Lay et al. (2021) estimated the projected impacts of extreme temperatures on human mortality in the United States. While the methodology used to develop these projections are described in detail in the paper, here we provide a brief overview of the methodological approach. The authors used historical mortality and temperature data from 208 U.S. cities to develop projections of temperature-related mortality under various climate scenarios, and to assess the degree to which populations exposed to extreme heat over time became less sensitive to these higher temperatures. They used geographically structured meta-regression to characterize the relationship between temperature and mortality from 1973 to 1982 and from 2003 to 2013, and compared how sensitive the populations were to extreme heat during the different time periods.

Lay et al. (2021) projected future temperature-related mortality using downscaled and bias-corrected[1] Localized Constructed Analog datasets for RCP 8.5 – a high emissions scenario – for six global climate models (GCMs) chosen for concordance with previous studies. For each model, they selected time periods with projections averaging a 1–6°C change from the 1986 to 2005 baseline period.

We used these data to develop estimates of heat-related mortality for two cities that were included in the study – Albuquerque and Aztec, New Mexico – as these two cities are most proximal to the Pueblo. We used extreme heat-related mortality as an indicator of heat-related stress that would be faced by the Pueblo. Because Lay et al (2021) were most interested in projections of temperature-related mortality at a given global temperature change rather than at a specific time period (e.g., 2050), we only had access to data that expressed temperature-related mortality at different levels of global temperature change. To use these data to develop projections for specific time periods (i.e., the present, 2050, and 2090), which is how the wildfire and flooding data discussed below were analyzed, we selected global temperature changes that most closely aligned with each of these time periods (i.e., 1, 3, and 6 degrees of global temperature increases, respectively).

For each of the chosen time periods, we then extracted the data for Albuquerque and Aztec, and averaged the temperature-related deaths. Temperature-related deaths are currently very rare (they are essentially non-existent), but they are projected to increase to an average of 5 per year in 2050 and about 15 per year in 2090, driven by increased exposure to extreme heat (Table 1).

4.1.2 Wildfire

Mills et al. (2018) estimated future populations within the contiguous United States exposed to projected changes in wildfire smoke and inland flooding (see the next section for a discussion of inland flooding). To do this, they developed spatially explicit projections of exposure to wildfire smoke and inland floods by integrating data from multiple GCMs under two climate scenarios in the mid- (2040–2059) and late (2080–2099) 21st century. To isolate the impact of projected

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[1] Bias correction is a common step in climate projection and climate impact modeling (Cannon et al., 2020).

climate changes on wildfire- and flooding-affected populations, their analyses assumed a static 2010 population level and distribution across U.S. counties.

Mills et al. (2018) used downscaled and bias-corrected[2] Localized Constructed Analog datasets for RCP 8.5 – a high emissions scenario – for five GCMs that capture much of the variability observed across the full suite of models that provided publicly available projections (i.e., projections include models that run relatively hot, cool, wet, or dry relative to other climate models). Mills et al. (2018) also developed projections for a more "moderate" emissions scenario (i.e., RCP 4.5), but we did not include those results here because projections for RCP 4.5 were not available for extreme heat.

Mills et al. (2018) projected the acreage burned by wildfires using the MC2 Dynamic Global Vegetation Model (DGVM) developed for the U.S. Environmental Protection Agency's (EPA's) Climate Impacts and Risk Assessment project (U.S. EPA, 2017). MC2 DGVM is a spatially explicit model with three integrated modules that address biogeography, biogeochemistry, and fire (OSU, 2011). This model accounts for the potential impacts of a future climate, primarily through temperature and precipitation data provided by GCMs. The MC2 DGVM simulates changes in future terrestrial ecosystem vegetative cover, including shifts in vegetative type, growth, decay, and transition over time. The model's fire module incorporates algorithms that account for vegetation characteristics (e.g., type, volume, moisture content) to determine when fire occurs in a grid cell. Mills et al. (2018) used results for each of the five GCMs for each year in mid-century (2040–2059) and late-century (2080–2099) 20-year time periods. MC2 DGVM reports the impacts of fire as the percent of area within a grid cell that has burned, among other metrics, where grid cells are 1/16º in resolution. Because MC2 DGVM does not model wildfire smoke dispersion, Mills et al. (2018) assumed that only residents in the burning grid cell and in the eight surrounding cells would be exposed to wildfire smoke and associated health risks.

In this analysis we are interested in documenting not only the potential impacts of wildfire smoke but also the physical and mental stresses associated with wildfires more generally. Thus, we utilized data addressing the frequency of wildfire occurrence, not just exposure to smoke. We focused our analysis on the Sandoval, Santa Fe, Los Alamos, and Rio Arriba counties – the counties most proximal to the Pueblo. Modeled wildfire frequency (i.e., the number of years out of 20 that a grid cell falling within those counties burns) for areas near the Pueblo was estimated at 2.9% for 2015 (the present; Table 6). Fire frequency is projected to increase slightly to 3.1% in 2050, and almost doubles the 2015 frequencies to 5.3% in 2090 (Table 1). Unlike our analysis of extreme heat where we directly correlated the climate stressor with a health endpoint (i.e., mortality), our wildfire analysis does not correlate the increased rate of wildfires directly with a health endpoint. However, as noted above in Section 3.3.2, several studies have shown a direct correlation between increased asthma and other respiratory issues (e.g., chronic obstructive pulmonary disease) and exposure to wildfire smoke and associated PM. Thus, it stands to reason that an increase in respiratory health issues would be expected with this increase in wildfire frequencies.

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[2] Bias correction is a common step in climate projection and climate impact modeling (Cannon et al., 2020).

Table 1. Projected changes in extreme heat-related mortality and wildfire frequency near the Pueblo under RCP 8.5 (a high emissions climate change scenario)

	Impact projections		
Climate hazard	**Present (2015)**	**2050**	**2090**
Extreme heat-related mortality (deaths/year)[a]	-0.03[c]	4.9	14.7
Wildfire frequency[b]	2.9%	3.1%	5.3%

a. Average total annual deaths projected that can be attributed to temperature increases for Albuquerque and Aztec.

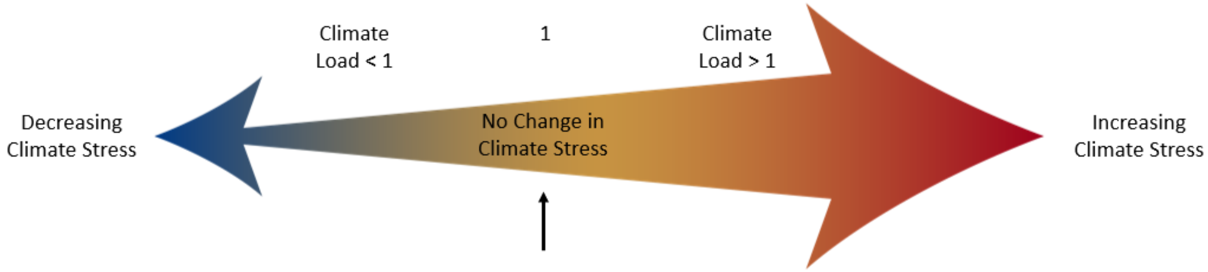
b. Average percentage of years within a 20-year timeframe in which a fire occurred within Sandoval, Santa Fe, Los Alamos, and Rio Arriba counties.

c. Since the model estimates a slight increase in cold-related deaths compared to heat-related deaths, this value is negative.

4.2 Climate Load Health Indices for the Pueblo

Given the projections for key climate change impacts for the Pueblo presented above, we developed a quantitative index of the climate-related stress that could be associated with such impacts (Figure 18). Below we describe how we estimated this climate-related "load" separately for extreme heat and wildfire. We then describe how we integrated each of those individual indices into an overall climate load health index for the Pueblo.

Figure 18. Depiction of climate load health index. As climate load health indices increase, climate stress increases. The climate load is calculated separately for extreme heat and wildfire (climate load = future conditions ÷ present conditions).



Extreme Temperatures

To calculate the change in climate load related to extreme temperatures, we simply divided the number of future deaths by the absolute value of current heat-related deaths listed in Table 1. This provides a ratio that shows how much worse 2050 and 2090 will be compared to current conditions. For example, if the 2050 heat-related climate load is 1.5, this means that future heat-related stress is estimated to be 50% greater in 2050 than current conditions; if the heat-related climate load is 100, this means it is estimated to be 100 times greater in 2050 than current conditions. Because current heat-related deaths are rare, the increases in projected heat-related deaths, though small in absolute amounts, represent substantial changes in heat-related climate load (Table 2); in 2050, this heat-related climate load is estimated at about 180, and in 2090 at about 540, meaning that the temperature-related stress that the Pueblo could face may be 180 and 540 times worse than present conditions.

Wildfires

As with extreme heat, we calculated the wildfire-related climate load by dividing the future wildfire frequency by the present wildfire frequency listed in Table 1. The Pueblo's wildfire load is thus estimated at 1.06 in 2050, or only 6% worse than current conditions; and 1.81 in 2090, or nearly twice as bad as current conditions (Table 2).

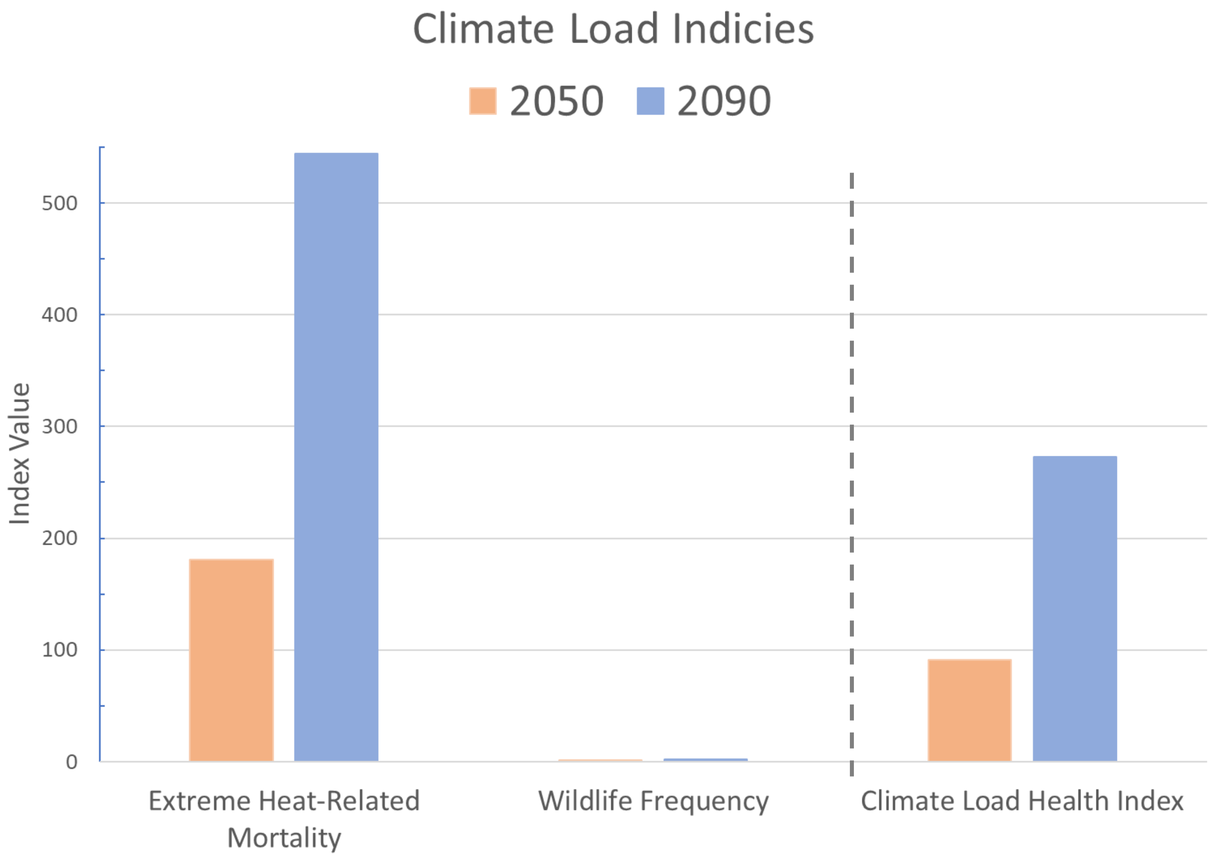
Table 2. Climate load health index for the Pueblo

Climate hazard	2050	2090
Extreme heat-related mortality	181.1	544.1
Wildfire frequency	1.06	1.81
Climate load health index (average across hazards)	**91.1**	**273.0**

Integrated Climate Load Health Index

To develop an integrated climate load health index for the Pueblo, we averaged the heat and wildfire climate load indices. This overall climate load index is approximately 90 in 2050 and 270 in 2090, suggesting that climate change-related stress could be 90 times worse for the Pueblo in 2050 and nearly 300 times worse in 2090 (Table 2; Figure 19). The main driver of this increase in climate load is extreme heat, which is projected to change the most over the next century; wildfire impacts are expected to change, but not as much as extreme heat.

Figure 19. Projected climate load indices for the Pueblo. The climate load health index was estimated by taking the average climate load index across hazards for each year.



5. Approach for Quantification of Increased Exposure to Contaminants due to Climate Change – 2013 Storm Event Case Study

As noted above, the Pueblo is directly adjacent to LANL, and members of the Pueblo have long-standing concerns about potential health impacts associated with exposure to contamination originating from the facility. Additionally, wildfires and flooding, which are predicted to increase in frequency and intensity because of climate change (see Sections 3 and 4), can result in the mobilization and transport of LANL contaminants onto Pueblo lands. As described above in Section 3, environmental sampling during storm events that followed recent large wildfires (e.g., Las Conchas and Cerro Grande fires) has confirmed that elevated concentrations of LANL contaminants can be mobilized and transported downstream to the Pueblo during such storms. Empirical environmental data may confirm that such individual events have resulted in the transport of contaminants. However, it is difficult to predict how burn-flood events will contribute to contaminant transport from LANL toward the Pueblo on broader spatial and temporal scales. This is due in part because these events are highly localized and contaminant concentrations vary across the canyons, and are therefore challenging to project with the resolution available in current climate models.

Therefore, rather than attempting to predict how contaminant concentrations may vary in the future in general due to climate change, and how those varying concentrations may impact health, we instead present a case study of a single large storm event. In this case study analysis, we compare pre- and post-storm conditions as an illustrative example of how climate impacts may affect contaminant exposure levels and health risks. This case study should not be construed as a comprehensive projection of future health impacts; rather, it is illustrative of the potential health impact of individual extreme events.

Specifically, we use the September 2013 storm event described in Section 3 as a case study and employ a Tribal Risk Assessment (TRA) approach to characterizing potential human health impacts resulting from increased contaminant exposure due to this extreme event. Below we provide a brief overview of the TRA approach, and then describe our case study analysis and the results of the analysis.

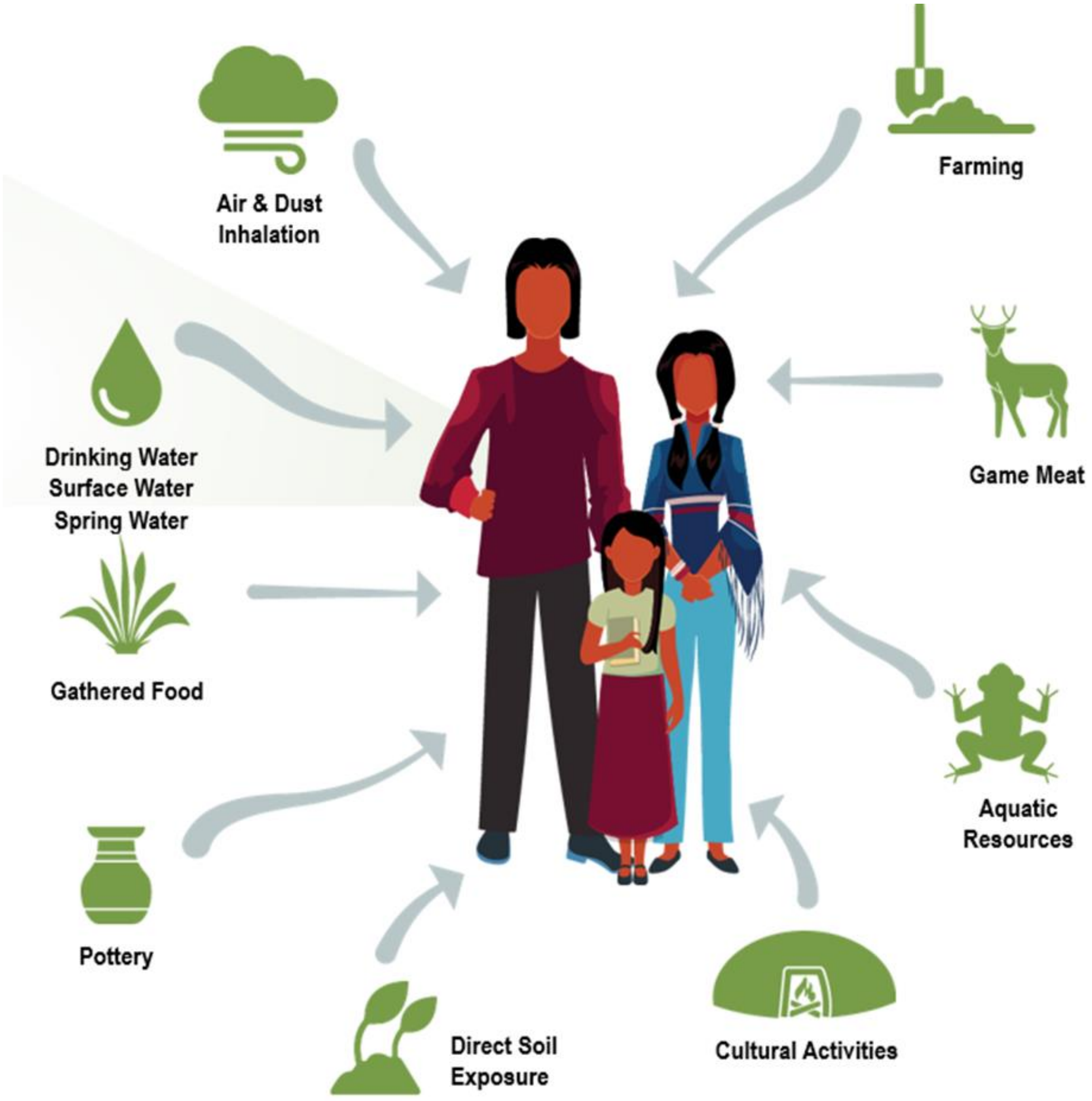
5.1 Contaminant-Based TRA

Human health risk assessment (HHRA) is a process that agencies, such as EPA, use to examine the extent and probability of adverse effects in human populations that may be exposed to contaminated natural resources. A typical HHRA focused on the general public may underestimate the health risks to members of the Pueblo who use natural resources differently than the general public. By contrast, a TRA is a HHRA that is tailored to specifically assess health risks associated with Tribal lifeways, including contemporary and traditional uses of natural resources.

The Pueblo is currently developing a comprehensive TRA that examines the human health risks of members of the community that live on the Pueblo and rely on natural resources located within the Pueblo's current boundaries, as well as the Ancestral Domain, which encapsulates the LANL facility (see Figure 2 map above). The TRA takes into consideration contaminant exposure pathways for a member of the Pueblo that would be included in a "standard" HHRA analysis (e.g., exposure to contaminated terrestrial soil, biota, air, sediment, and surface water).

In addition, the TRA also characterizes the level of risk to Tribal members based on an extended suite of exposure activities, including those that are of cultural significance to the Pueblo (e.g., ceremonial practices, gathering pottery materials and making pottery; Figure 20). Exposure frequencies and durations are also based on Pueblo-specific information, rather than solely relying on EPA default values for the general public, which may underestimate exposures resulting from practicing Tribal lifeways.

Figure 20. Tribal lifeways considered for the TRA that is currently being conducted to assess health risks to members of the Pueblo.



The Pueblo's TRA is being conducted according to EPA general guidelines (U.S. EPA, 1989), but input parameters have been adjusted so that they are inclusive of a broader suite of Tribal lifeway practices. Briefly, for the TRA we are estimating the exposure to contaminants for members of the Pueblo and comparing that exposure to either non-cancer effect levels (for non-radionuclides) or excess cancer risk levels (for radionuclides). Below we describe the input parameters for the comprehensive Pueblo TRA.

Exposure Pathways, Media, and Exposure Routes

For the Tribal lifeway exposure pathways shown in in Figure 20, we considered the following exposure media and exposure routes in our analysis:

- Air – inhalation
- Surface water/drinking water – ingestion and dermal contact
- Soil/sediment – ingestion, dermal contact, and external radiation
- Plants – ingestion, dermal contact, and inhalation
- Food – ingestion and dermal contact.

Contaminants

In Table 3 we present the contaminants that we are including in the TRA.

Table 3. List of contaminants being assessed in the TRA

Non-radionuclides	Radionuclides
Barium	Cesium (Cs)-137
Beryllium	Strontium (Sr)-90
Chromium	Uranium (U)-238
Mercury	Radium-226
Uranium	Plutonium (Pu)-239/240

In general, the comprehensive Pueblo TRA has shown that the risk associated with metal exposure is less than the risk associated with radionuclide exposure. The risk associated with Pu-239/240, Cs-137, Sr-90, and U-238 exceeded the Pueblo excess cancer risk threshold of 10^{-5}. The TRA examines health risks due to contaminant exposure but does not consider health impacts from climate change-related contaminant transport or health impacts from non-contaminant stressors. The analysis we present below shows that the incorporation of climate hazards, such as large storm events, could increase contaminant exposure and risk.

5.2 2013 Storm Event Case Study

To assess the potential effects of climate change on exposure to contaminants and associated human health risk, we ran “before/after” calculations for the September 2013 storm event. We focused this illustrative example on one particular Tribal lifeway exposure pathway, specifically, the ceremony and prayer exposure pathway. During ceremony and prayer activities, members of the Pueblo are exposed to both surface water and sediment, and so we included contaminant concentration data for these two media in our analysis. We further focused our analysis on Pu-239/240, Cs-137, and Sr-90, three legacy contaminants that are found across LANL in sediments, soils, surface water, and other natural resources. The geographical focus of the analysis was Los Alamos Canyon, located within the Pueblo boundaries, because we have pre- and post-flood contaminant data for this area. The exposure parameters for the ceremony and prayer exposure pathway used in this analysis were obtained from the comprehensive Pueblo

TRA (Table 4), and we relied on surface water and sediment contaminant data that represent pre- and post-flooding conditions (see the surface water and sediment discussion below).

Table 4. Pueblo-specific ceremony and prayer exposure parameters used during this TRA

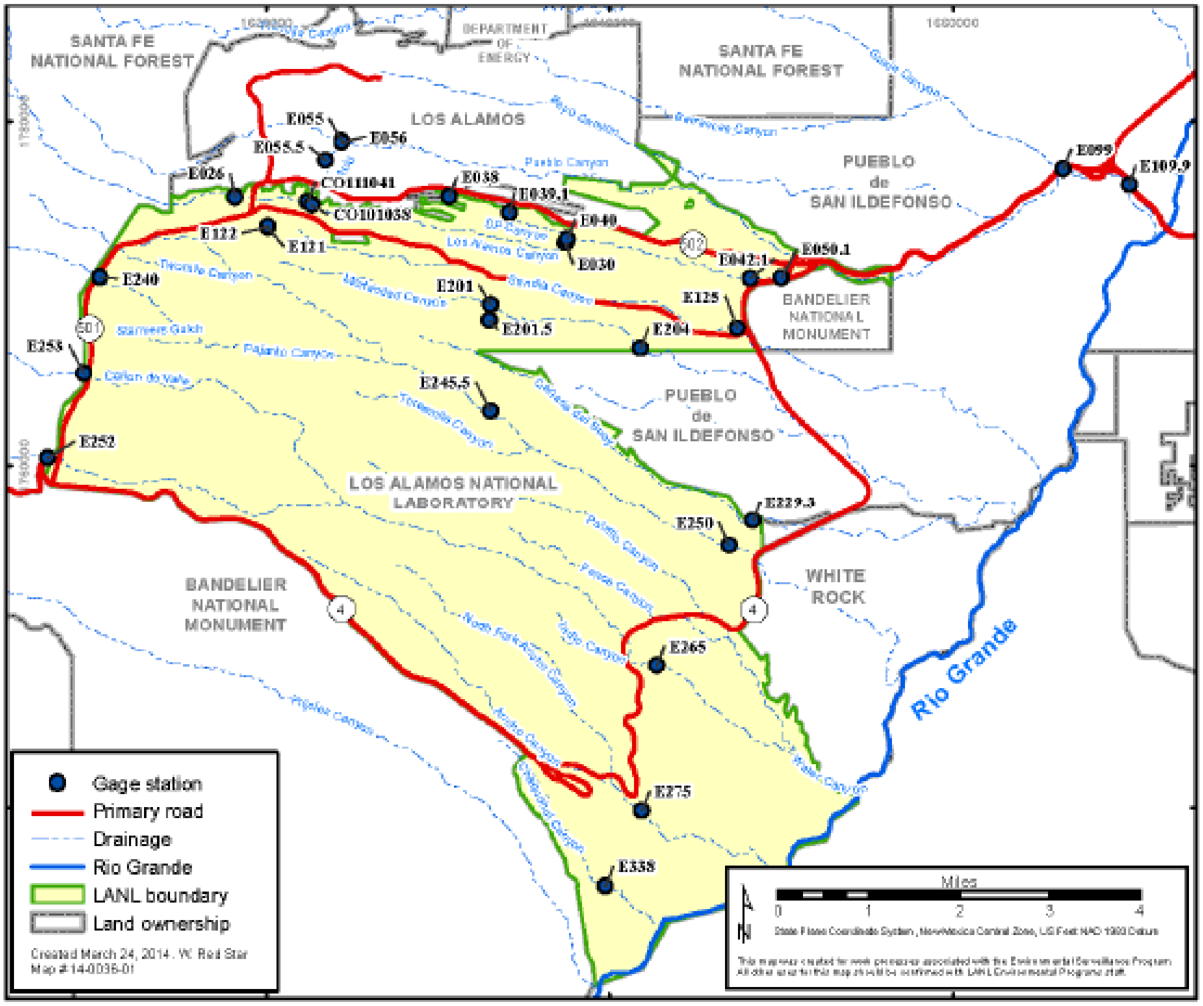
Parameter definition	Value	Units	Citation
Soil ingestion pathway			
Ingestion rate	400	mg/day	Harper, 2008
Event time	1	Hour/day	Pueblo TRA
Exposure frequency	30	Days/year	Pueblo TRA
Exposure duration	70	Years	Harper, 2008
CSF Pu-249/250	2.76E-10	Risk/pCi	U.S. EPA, 2001
CSF Cs-137	4.33E-11	Risk/pCi	U.S. EPA, 2001
CSF Sr-90	1.44E-10	Risk/pCi	U.S. EPA, 2001
External radiation pathway			
Shielding factor	1	Unitless	U.S. EPA, 2000
Event time	1	Hour/day	Pueblo TRA
Exposure frequency	30	Days/year	Pueblo TRA
Exposure duration	70	Years	Harper, 2008
CSF Pu 249/250	2E-10	Risk/pCi	U.S. EPA, 2001
CSF Cs-137	2.55E-06	Risk/pCi	U.S. EPA, 2001
CSF Sr-90	1.96E-08	Risk/pCi	U.S. EPA, 2001
Water ingestion pathway			
Ingestion rate	0.24	L/day	Pueblo TRA
Exposure frequency	30	Days/year	Pueblo TRA
Exposure duration	70	Years	Harper, 2008
CSF Pu-239/240	1.35E-10	Risk/pCi	U.S. EPA, 2001
CSF Cs-137	3.04E-11	Risk/pCi	U.S. EPA, 2001
CSF Sr-90	7.4E-11	Risk/pCi	U.S. EPA, 2001

CSF = cancer slope factor.

Surface Water Data

To represent concentrations of contaminants in surface water in the Pueblo, we gathered surface water data obtained from *Intellus New Mexico* (Intellus, 2021). We focused our analysis on surface water sampling on the Pueblo at or near gage E109.9, which is sampled as part of the Environmental Surveillance program in Los Alamos Canyon (Figure 21). To represent pre-flood conditions, we used 2012 base flow contaminant data (Intellus, 2021) in our analysis (Table 5). To represent post-flood conditions, we used the maximum storm runoff concentration recorded in September 2013 (Table 5). Concentrations of Pu-239/240, Cs-137, and Sr-90 were greatly elevated after the September 2013 storm compared to base flow, indicating contaminant transport onto the Pueblo after this flooding event.

Figure 21. Surface water stations sampled as part of the Environmental Surveillance program in the Los Alamos and Pueblo canyons monitoring plan. We included data from gage 109.9 in our analyses.



Source: LANL, 2014, Figure 6-7.

Table 5. Radionuclide surface water concentrations measured on the Pueblo in Los Alamos Canyon at the confluence of the Rio Grande at monitoring location E109.9

Contaminant	2012 base flow (pCi/L)	Storm runoff maximum value – September 2013 (pCi/L)
Pu-239/240	0.00199	312
Cs-137	0.0953	146
Sr-90	0.0632	10.1

Sediment Data

To represent concentrations of contaminants in sediments on the Pueblo, we gathered sediment data obtained from *Intellus New Mexico* (Intellus New Mexico, 2021). We focused our analysis on sediment samples collected on the Pueblo in 2014 (Figure 22). These samples were collected by LANL staff after the 2013 flood, with permission of the Pueblo, and with Pueblo staff present as observers during the sampling. During this sampling effort, LANL staff targeted new deposits of sediment from layers overlying previous deposits. From each of the six Los Alamos Canyon locations on the Pueblo, LANL staff also collected a sediment sample at a depth that was representative of the previous deposits (Figure 22). Thus, the subsurface and surface samples collected in Los Alamos Canyon on Pueblo lands represent pre- and post-flood contaminant concentrations, respectively. Location 36179 was the closest to the LANL and Location 45267 was the farthest from the facility (Figure 22). Figures 23–25 show the subsurface (i.e., pre-flood) and surface (i.e., post-flood) sediment Pu-239/240, Cs-137, and Sr-90 concentrations. For all three contaminants, Location 36179 (i.e., the one located closest to LANL) samples collected from surface were elevated compared to samples collected at the subsurface (Figures 23–25). In fact, all of the surface samples contained elevated Pu-239/240 concentrations compared to the subsurface samples, although the magnitude of the exceedance lessened with distance from LANL (Figure 23). This indicates the additional transport of contaminants onto Pueblo lands due to the extreme event of 2013. The relationship between the subsurface and surface samples for Cs-137 and Sr-90 are more difficult to interpret. In some sampling locations the surficial samples had a greater contaminant concentration than the subsurface samples, and in other locations we saw the opposite pattern. The differences among Pu-239/240, Cs-137, and Sr-90 are likely due to differential transport mechanisms. For example, Pu-239/240 strongly adsorbs to sediment/soil, and its transport processes are controlled by sediment/soil movement (LANL, 2004). In contrast, transport by water in the dissolved form is a more important mechanism for Sr-90 (LANL, 2004). Hence, sediment concentration profiles may be more informative of Pu-239/240 transport mechanisms than Sr-90.

Because we observed the greatest difference between pre- and post-flood sediment contaminant concentrations in Location 36179, we used data from that location in our health assessment. To represent pre-flood conditions, we used contaminant data from the subsurface sample (Intellus New Mexico, 2021) in our analysis (Table 6). To represent post-flood conditions, we used contaminant data from the surface sample (Intellus, 2021) in our analysis (Table 6).

Figure 22. Map of sediment sample locations in Los Alamos Canyon. The locations circled in blue are locations where LANL collected samples at the surface and subsurface after the September 2013 flood. This map displays the maximum Pu-239/240 concentrations at each location.

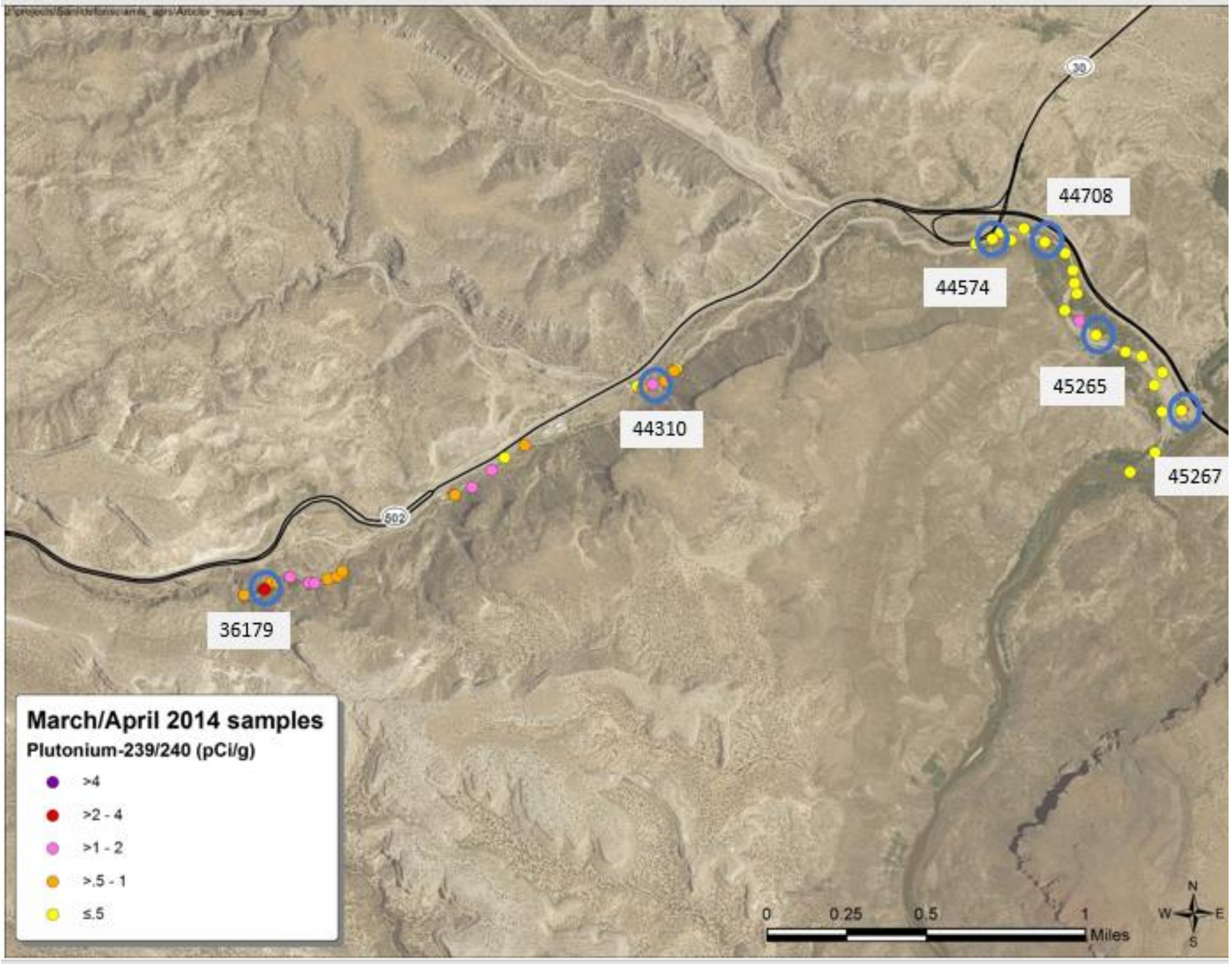


Figure 23. Pu-239/240 concentrations in sediment samples collected on the Pueblo in 2014. Sampling locations are in order spatially with Location 36179 being closest to LANL and Location 45267 being the farthest from the facility,

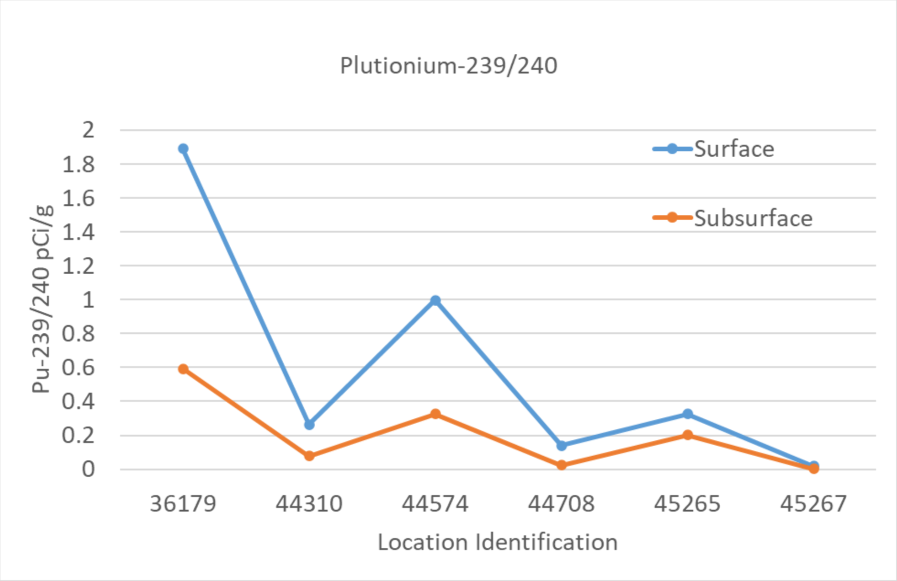


Figure 24. Cs-137 concentrations in sediment samples collected on the Pueblo in 2014. Sampling locations are in order spatially with Location 36179 being closest to LANL and Location 45267 being the farthest from the facility.

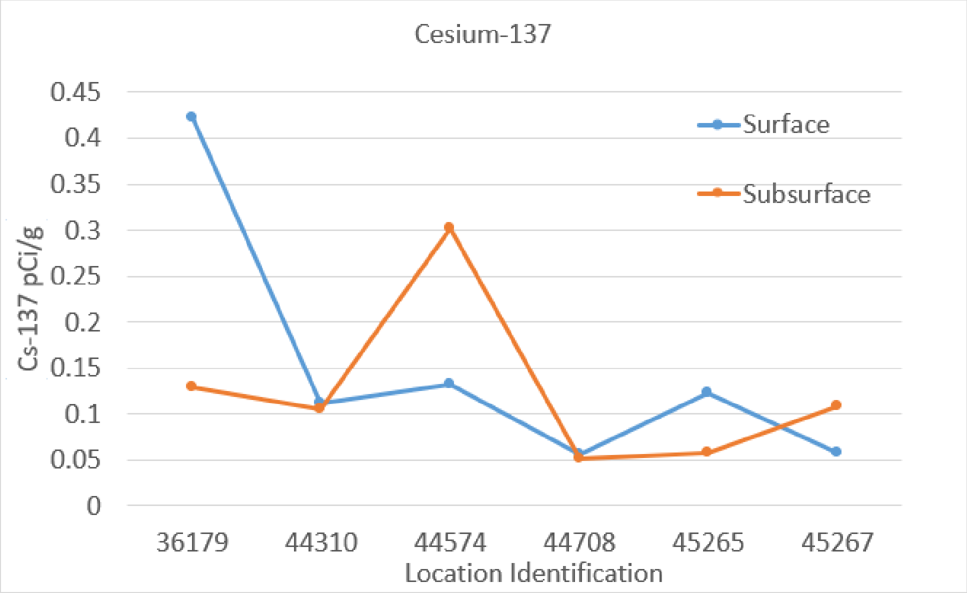


Figure 25. Sr-90 concentrations in sediment samples collected on the Pueblo in 2014. Sampling locations are in order spatially with Location 36179 being closest to LANL and Location 45267 being the farthest from the facility.

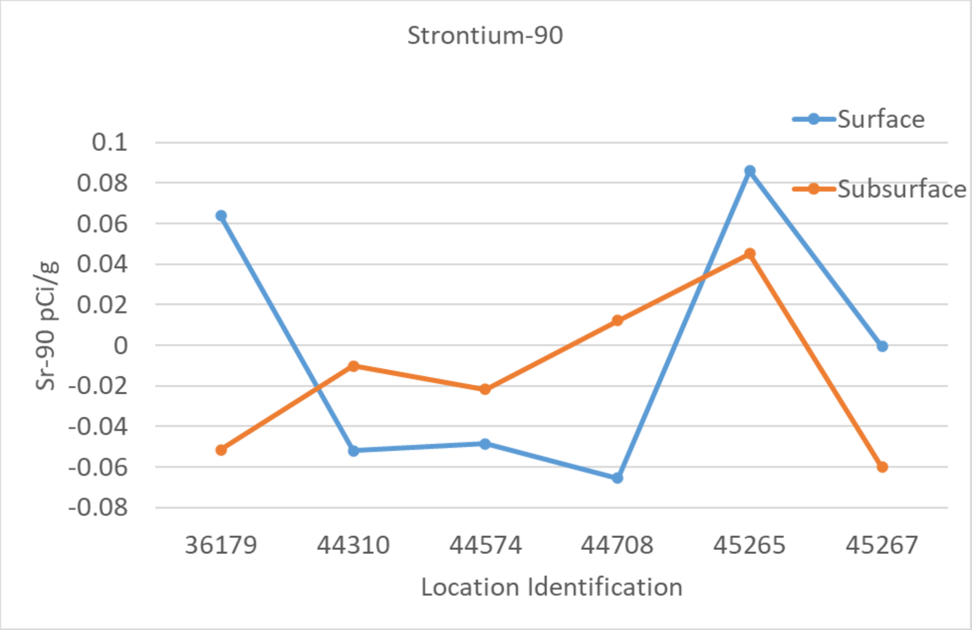


Table 6. Sediment concentrations used in our risk assessment

Contaminant	Pre-flood (subsurface, Pci/g)	Post-flood (surface, pCi/g)
Pu-239/240	0.592	1.89
Cs-137	0.129	0.422
Sr-90	0	0.064

5.2.1 Results

For all three contaminants, excess cancer risk was greater with post-flood surface water and sediment exposures compared to pre-flood surface water and sediment exposures (Table 7). The cumulative risk for post-flood conditions is three orders magnitude greater than for pre-flood conditions (2.14E-05 and 8.88E-08, respectively; Table 7). Excess cancer risk can be presented in several formats. In this report we express cancer risk in scientific notation where 1E-06 is equivalent to 1 in 1,000,000 and 1E-05 is equivalent to 1 in 100,000 cancer occurrences. The Pueblo considers a risk of 10^{-5} to be unacceptable. Post-flooding cumulative excess cancer risk is greater than 10^{-5} (Table 7). These results are largely driven by the ingestion of surface water, with Pu-239/240 exposure contributing the most to excess cancer risk. In fact, in this analysis exposure to Pu-239/240 alone resulted in excess cancer risk greater than 10^{-5}.

As noted above, it is important to keep in mind that we assessed the health risks associated with Pueblo-specific exposure to contaminants using the 2013 flood as an example. We did not predict future contaminant transport resulting from climate change. Contaminant transport from LANL to the Pueblo is highly localized and we expect that some, but not all, burn-flood events may increase contaminant transport to the Pueblo. Additionally, we did not conduct a full TRA, but rather, examined pre- and post-flood health risks associated with a single exposure pathway – ceremony and prayer activities. Therefore, while our analysis serves to demonstrate that risk may increase after large storm events due to the increased transport of contaminants, it does not characterize the total health risk subsequent to the storm event. If all exposure pathways shown in Figure 20 were incorporated into the analysis, the total exposure and calculated risk would likely be higher.

Other key assumptions include:

- We assumed that 2014 sediment samples collected on the Pueblo at the surface were representative of post-flood conditions and samples collected at the subsurface were representative of pre-flood conditions.
- Our risk assessment assumes a lifetime exposure (i.e., 70 years) for the pre- and post-flood surface water and sediment concentrations. Concentrations of these contaminants will vary across a lifetime and post-flood concentrations (especially for surface water) may be elevated for a time period and then return to base flow conditions. Therefore, our post-flood risk estimates may be elevated compared to lifetime surface water concentrations.

Table 7. Assessment of cancer risk using pre- and post-flood surface water and sediment concentrations

Exposure media	Exposure pathway	Pre-flood cancer risk	Post-flood cancer risk
Pu-239/240			
Sediment/soil	Incidental ingestion	5.72E-09	1.83E-08
Sediment/soil	External radiation	2.84E-11	9.06E-11
Water	Ingestion	1.35E-10	2.12E-05
Total risk		5.88E-09	2.12E-05
Cs-137			
Sediment/soil	Incidental ingestion	1.95E-10	6.40E-10
Sediment/soil	External radiation	7.89E-08	2.58E-07
Water	Ingestion	1.46E-09	2.24E-06
Total risk		8.05E-08	2.50E-06
Sr-90			
Sediment/soil	Incidental ingestion	0.00E+00	3.22E-10
Sediment/soil	External radiation	0.00E+00	3.00E-10
Water	Ingestion	2.36E-09	3.77E-07
Total risk		2.36E-09	3.77E-07
Cumulative risk			
		8.88E-08	2.41E-05

6. Interactions between Multiple Health Stressors

For populations that experience negative health effects from multiple stressors, the total health impacts from these multiple stressors may be greater than predicted than for a single stressor because the health impacts of these stressors may be additive or, in some cases, synergistic (i.e., greater than the sum of the individual health impacts). The combined effects of health stressors are sometimes referred to as “cumulative effects” (U.S. EPA, 2003). Climate load may exacerbate the impacts of contaminant exposure on human health (e.g., cumulative health effects from contaminant exposure can be greater than predicted in combination with climate load impacts; Figure 26). With limited site-specific data available on some of these health stressors, it is difficult to entirely understand how the climate load will interact with contaminant-related health stressors for members of the Pueblo. However, our review of the literature has found that in analogous exposure scenarios, the combined health effects from contaminant exposure and climate-related impacts may be additive or, in some cases, synergistic (Figure 26). Below, we provide examples where specific aspects of climate change that have been integrated into our estimate of climate load (e.g., PM and heat, radionuclide exposure and smoking, coronavirus disease 2019 [COVID-19] and wildfire smoke) have been documented to interact with other heath stressors.

Figure 26. Health risks related to contaminant exposure in combination with climate-related health risks may be additive (i.e., sum of health risks) or synergistic (i.e., greater than the sum of health impacts). The combined effects of multiple health stressors are referred to as cumulative health effects.

6.1.1 PM and Heat

Multiple studies have shown that wildfire-associated increases in PM can cause or exacerbate respiratory or cardiac illnesses (Cascio, 2018). The health impacts from exposure to PM are well-documented and include increased hospitalizations and deaths related to cardiovascular, metabolic, and respiratory diseases (Hamanaka and Mutlu, 2018). Similar impacts are associated with exposures to extreme heat events that are projected to increase in the future due to climate change (Section 3.3.1). While exposure to PM and heat can cause adverse health impacts by themselves, evidence indicates that both stressors may interact synergistically and cause more harm together than on their own.

In a review of synergistic effects of air pollution and temperature, Anenberg et al. (2020) concluded that there are potential synergistic effects between PM and heat. Ren and Tong (2006) assessed synergistic effects of PM and temperature exposure for a variety of cardio-respiratory outcomes. They found that interactive effects between hotter temperatures and PM led to increased respiratory hospital admissions, respiratory and cardiovascular emergency visits, non-external cause mortality, and cardiovascular mortality. Other studies have found that PM exposure effect estimates were higher at hotter temperatures, indicating a potentially synergistic effect between PM and heat (Tian et al., 2018; Zhang et al., 2018).

Most studies reporting on PM and heat interactions focused on cardiovascular and respiratory outcomes, but these are not the only impacts resulting from combined exposure to these stressors. Researchers in California examined preterm birth and joint exposures to air pollution, heat waves, and green space (i.e., more vegetation cover can act as a buffer to extreme temperatures; Sun et al., 2020). They observed synergistic effects between heatwaves and air pollution on preterm births, suggesting that extreme heat may be more harmful for pregnant women who are exposed to higher levels of air pollution before birth.

6.1.2 Radionuclide Exposure and Smoking

There is evidence that smoking cigarettes may lead to elevated cancer risk after exposure to radiation. The strongest evidence available demonstrating the joint effects of radiation exposure and smoking on cancer risk originates from the literature on radon exposure. Radon is a radioactive gas that forms from the breakdown of other elements, such as uranium, in soil, rock, and water. It is present in people's homes and exposure to radon by itself can increase the risk of lung cancer. However, in combination with cigarette smoke, lung cancer risk drastically increases. The relationship has been characterized as "submultiplicative," meaning that the interaction is above additive (e.g., the sum of the two risks; NRC, 1999). In other words, if exposed to normal levels of radon in the home, about 2 out of 1,000 nonsmokers would develop lung cancer, whereas about 20 out of 1,000 smokers would develop lung cancer (U.S. EPA, 2016).

Atomic bomb survivors provide another source of information on the interactions between radiation and smoking. Two studies from 2010 and 2012 on a cohort from Hiroshima and Nagasaki found that the joint effects from radiation and smoking were multiplicative for light-to-moderate smokers, and additive or less-than-additive for heavy smokers (Furukawa et al., 2010; Egawa et al., 2012). Although the additive or less-than-additive results for heavy smokers is not straightforward, this result aligns with other literature regarding heavy smokers. Specifically, long-term moderate smokers experience higher cancer rates than short-term heavy smokers (Lubin et al., 2008). Still, interactions were observed between radiation exposure and smoking, providing more evidence for the synergistic relationship.

While we acknowledge that smoking cigarettes is different than inhaling wildfire smoke, researchers have made comparisons between air pollution from wildfires and cigarette smoke. Using models based on EPA air pollution data and Centers for Disease Control and Prevention mortality data, scientists at UC Berkeley approximated that health effects from smoking one cigarette per day are relatively comparable to experiencing a daily $PM_{2.5}$ level of 22 ug/m^3 (Muller and Muller, 2015). During the Cerro Grade fire, $PM_{2.5}$ levels averaged 78 ug/m^3 and reached almost 300 ug/m^3 at the peak of the fire (Whicker et al., 2012). Although wildfire smoke and cigarette smoke are different mixtures of chemicals with different cancer risks, the comparison is helpful for understanding the potential negative health effects. Wildfires or cigarette smoke may expose the Pueblo to harmful chemicals that can modify members' cancer risk in the presence of radionuclide contaminants.

6.1.3 Wildfire Smoke and COVID-19

The COVID-19 pandemic has elucidated existing health disparities and exacerbated negative health outcomes experienced by vulnerable populations. Recent studies and those focusing on other airborne diseases demonstrate that communities exposed to high levels of wildfire smoke may be at an increased risk of contracting COVID-19 or experiencing worse side effects from the disease (Navarro et al., 2021). As negative respiratory outcomes are heavily associated with exposure to wildfire smoke, and COVID-19 is a respiratory infection transmitted through aerosols, joint exposure to wildfire smoke and COVID-19 may be associated with worse health outcomes.

A review article assessing smoke exposure and risk of COVID-19 for firefighters supports associations between exposure to PM in smoke with increased susceptibility to COVID-19 and risk of more severe disease (Navarro et al., 2021). Further work supports these associations not just for occupational firefighters, but communities affected by fires (Henderson, 2020). Recent modeling efforts have also predicted an increased risk of COVID-19 morbidity and mortality for communities exposed to wildfire smoke (Henderson, 2020). These models are based on work performed with a previous coronavirus, SARS-CoV-1, which was responsible for the severe acute respiratory syndrome (SARS) pandemic in 2003 (Kan et al., 2005). These authors quantified an increased risk of SARS transmission in accordance with increases in PM_{10} within Beijing in 2005. Henderson (2020) applied these concepts to the COVID-19 pandemic and estimated that a wildfire smoke episode of moderate magnitude and intensity could increase the impact of COVID-19 (in terms of cases and deaths) by approximately 10%. Henderson (2020) also detailed a recent study that found an increase in hospital admissions related to asthma associated with $PM_{2.5}$ from wildfires that was more extreme than that expected for typical $PM_{2.5}$; this complements the findings of Navarro et al. (2021) in terms of acute hospitalizations for respiratory side effects during wildfires.

Researchers recently quantified a relationship between air quality measurements and the magnitude of COVID-19 (Meo et al., 2020). In San Francisco, $PM_{2.5}$ was positively correlated with COVID-19 daily cases, cumulative cases, and cumulative deaths (though not with daily deaths). Carbon monoxide was positively correlated with cumulative cases and deaths. Further work showed significant increases in COVID-19 cases (56.9%) and deaths (148.2%) during wildfires, compared to rates before the wildfires for 10 counties in northern California (Meo et al., 2021). Air quality measurements during the wildfires also saw increases in $PM_{2.5}$, carbon monoxide, and ozone concentrations (220.71%, 151.05%, and 19.57%, respectively).

Mounting evidence supports associations between exposure to wildfire smoke and increased susceptibility to COVID-19. As wildfires are increasing in frequency and size, concomitant hazards likely pose respiratory health risks for the Pueblo, which are exacerbated by the warming climate.

7. Summary

The Pueblo is facing changing climate conditions, including increasing average temperatures as well as more frequent and/or intense incidences of extreme heat, drought, and wildfires. Climate change can adversely affect the health of Pueblo members directly (e.g., heat stress, adverse respiratory effects due to low air quality) or indirectly (e.g., increased release/transport and exposure to contaminants during wildfires or extreme storm events), and negatively impacting cultural and spiritual health.

In this report, we developed Pueblo-specific quantitative projections for extreme heat and wildfire, and integrated these projections to develop an overall climate load health index for the Pueblo. This climate load health index can be used as a proxy for understating the severity of climate-related health impacts in the future. A higher climate load health impact value indicates a higher likelihood of negative climate-related health effects for members of the Pueblo in the future. We projected that the overall climate load health index could be 90 times worse for the Pueblo by 2050 and nearly 300 times worse by 2090, compared to current conditions.

Wildfires and flooding, which are predicted to increase in frequency and intensity because of climate change, can result in the mobilization and transport of LANL contaminants onto the Pueblo and, therefore, can indirectly impact the health of members of the Pueblo. In this report, we compared pre- and post-storm conditions from 2013 as an illustrative example of how climate impacts may affect contaminant exposure levels and health risks. We found that excess cancer risk was greater with post-flood surface water and sediment exposures compared to pre-flood surface water and sediment exposures. However, we do note that it is difficult to predict how burn-flood events will contribute to contaminant transport from LANL toward the Pueblo on broader spatial and temporal scales.

Climate change may exacerbate the impacts of contaminant exposure on human health. For example, cumulative health effects from contaminant exposure can be greater than predicted when climate load impacts are also taken into consideration. With limited site-specific data available on some of these health stressors, it is difficult to entirely understand how the climate load will interact with contaminant-related health stressors for members of the Pueblo. However, our review of the literature demonstrates that climate-related impacts health impacts to members of the Pueblo may be additive or, in some cases, synergistic. To build resiliency against these climate-related impacts, members of the Pueblo can target mitigation strategies in areas that may result in increased contaminant transport resulting from burn-flood events. Members of the Pueblo can also prepare for climate change-related health impacts by understanding that climate hazards, such as extreme heat, can negatively impact human health and try to mitigate heat exposure accordingly.

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