Final Report

Climate Change Risk and Resilience Assessment Project for the U.S. Department of Energy Office of Legacy Management

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Table of Contents

Executive Summary

In this study, we have evaluated climate change vulnerability for each of the U.S. Department of Energy (DOE) Office of Legacy Management (LM) sites for which a detailed climate assessment survey identified some level of concern regarding the potential for future climate changes to impact LM site infrastructure, site design specifications, and/or long-term site regulatory performance. Foundational to the study was the integration of (1) institutional knowledge for the sites derived through interviews and surveys, (2) regional and climatological data and model projections, and (3) potential climate-driven outcomes that may require reassessment of existing LM environmental liabilities. The core component of the project was the development of an open-source *Python* package (pypi.org/climate-resilience) that allows the user to download, process, analyze and visualize climate datasets across the full inventory of LM sites via the Google Earth Engine. The climate projections are based on the Coupled Model Intercomparison Project (CMIP) climate models with different Representative Concentration Pathways (RCP) scenarios through the year 2099. The algorithms quantify hydroclimate variables and their forecast changes through the end of this century across the regionally distributed network of LM sites. The forecast changes include changes in the annual frequency of extreme temperature, total and extreme precipitation, and drought potential as described by the Standardized Precipitation-Evapotranspiration Index (SPEI). In addition, we have developed specific algorithms to (1) compute probable maximum-precipitation events that have been used for designing disposal cells based on multiple methods and considering regional effects, (2) calculate the future indices indicative of increased wildfire and flooding probability that account for precipitation, air temperature, wind speed, fuel aridity, and weather conditions, and (3) identify climate drivers and relevant time-scales for groundwater contaminant concentrations associated with future couplings between hydroclimate and surface water-groundwater interactions. In addition, the interviews and surveys have documented past observations of climatological impacts, such as the erosional damages of disposal cells, increased contaminant concentrations accompanying flooding, and key site infrastructure deemed vulnerable in the event of significant shifts in climate trajectories. This study represents a first-of-its-find effort linking downscaled climate-forecast data with potential future impacts to the LM inventory of field sites. Finally, we performed a comprehensive, integrated assessment of forecast climate drivers and potential impacts to the regulatory performance of two archetypal LM sites (Canonsburg, PA; Monticello, UT). These two integrated assessments serve as examples for extension to other LM sites judged to be susceptible to climate-driven impacts by rigorously evaluating site resiliency to climate change and identifying specific adaptation measures and re-assessments of environmental liabilities that may be required to assure their sustained regulatory performance.

Acronyms

AMDP: Annual Maximum Daily Precipitation
ANL: Argonne National Laboratory
AOA: Area of Attainment
CCSM: Community Climate System Model
CFWI: Canadian Fire Weather Index
CONUS: Continental United States of America
CMIP5: Coupled Model Intercomparison Project Phase 5
DOE: Department of Energy
EM: Office of Environmental Management
EL: Environmental Liabilities
EPA: Environmental Protection Agency
ET: Evapotranspiration
EU: European Union
FEMA: Federal Emergency Management Agency
FHS: Flood Hazard Study
FY: Fiscal Year
GAO: Government Accountability Office
GCM: Global Climate Model
GEMS: Geospatial Environmental Mapping System
GFDL: Geophysical Fluid Dynamics Laboratory
GWT: Groundwater Table
HadGEM: Hadley Center Global Environmental Model
IDF: Intensity-Duration-Frequency
IPCC: Intergovernmental Panel on Climate Change
IPCC AR5: Fifth Assessment Report of the Intergovernmental Panel on Climate Change
LBNL: Lawrence Berkeley National Laboratory
LM: Office of Legacy Management
LMSP: LM Strategic Partner
LTSM: Long-term Surveillance and Maintenance
MNA: Monitored Natural Attenuation
NASA: National Aeronautics and Space Administration
NASA NEX-GDDP: NASA Earth Exchange Global Daily Downscaled Projections
NLD: National Levee Database
NOAA: National Oceanic and Atmospheric Association
NPL: National Priorities List
OU: Operational Unit
PMP: Probable maximum precipitation
SPEI: Standardized Precipitation Evapotranspiration Index
Tmax: Maximum Air Temperature at 2 Meters Above Land Surface
USACE: United States Army Corps of Engineers
USGCRP: United States Global Change Research Program
USGS: U.S. Geological Survey
VARP: Vulnerability Assessments and Resilience Planning

1.0 Introduction

1.1 Background

The U.S. Department of Energy (DOE) Office of Legacy Management (LM) exists to fulfill the Department's long-term commitments to environmental stewardship and to its contractor workforce. The contaminant disposal cells/landfills could continue to pose human health and environmental risk for hundreds to thousands of years at the Category II and III sites. As such, to date, LM has addressed climate-change adaptation and organizational resilience the annual Site Sustainability Plan. In 2019, LM also conducted a pilot climate vulnerability screening based on Executive Order 13653 (since rescinded). In that screening, LM assessed site vulnerabilities at one of its sites to determine the feasibility of the process and the need for a more in-depth assessment.

In May 2020, the Government Accountability Office (GAO) completed an audit of the 75-year environmental liabilities (EL) of DOE-LM sites. As of FY2021, LM is responsible for 102 sites in 29 States and the Territory of Puerto Rico, and it is estimated that the number of LM sites will grow to 128 through FY2026 (Site Management Guide, 2020). LM's environmental liabilities (EL) are currently estimated at $7.35 billion, with the total liability growing as active remediation is completed at other sites and they are transferred to LM. One of the recommendations of the GAO audit was the need for LM to (a) assess the resiliency of its sites to climate change and (b) report and evaluate impacts that are not reflected in the current EL estimate. GAO stated that "LM has not made plans to assess the effects of climate change on its sites or to mitigate those effects," as called for in its strategic plan (GAO, 2020).

As highlighted in the US Global Change Research Program's (USGCRP) recent fifth *National Climate Assessment (USGCRP, 2017)* the impacts of climate change are broadly distributed across the United States, with regionally-specific effects having the potential to threaten sites and site infrastructure overseen by LM. The *Assessment* identifies increased incidence of frequent and extreme events, including flooding, drought, intense precipitation/wind storms, storm surge, wildfires, erosion, and vegetation mortality, among others. Such events may damage critical LM infrastructure, such as engineered disposal cells, access roads, and buildings, and fundamentally alter active and passive site remedial strategies including natural flushing and attenuation of groundwater.

Climate resilience is a particularly useful concept by which to evaluate and assess the LM site inventory and its long-term performance. In this context, climate resilience is defined as the capacity of an individual LM site to perform according to its regulatory requirements while being impacted by potential stresses imposed by climate variability, weather extremes, and related impacts projected by future climate scenarios, such as those described in the most recent United Nations Intergovernmental Panel on Climate Change (IPCC) assessment *Climate Change 2021: The Physical Science Basis*.

While climate-related impacts to LM site behavior and/or infrastructure may occur, the extent of impact depends on the inherent resilience of a given site and its natural and engineered characteristics. The climate resilience evaluation can thus be used to identify site-specific needs, as well as systemic weaknesses and risks. If important issues are identified, LM could develop strategies to transition sites to a more sustainable state consistent with predicted changes in climate and associated disturbance. Revised assessment of the environmental liabilities of individual LM sites may then be made in an informed manner wherein the full range of strategies needed to increase their resilience is more accurately accounted for. Pursuant to the GAO Recommendation to LM, actions taken at sites to increase their resilience or adapt to climate change need to be reflect in the 75 Year EL estimates.

By way of example, and of particular concern to LM, are the engineered cover systems designed to isolate contaminated materials, from the environment. LM has recently completed, or is planning, major maintenance projects on several containment due to unforeseen damage for which intense precipitation and erosion were contributing factors. The cost of such unplanned maintenance projects significantly exceeds what has historically been spent on "site maintenance" and reflects a situation where the EL of a given site needs to be adjusted. For more than one of these major maintenance projects, disturbances associated with climate change are potential contributing factors in generating a need for repair. In general, LM site remedies are aging and changes from natural processes are occurring more rapidly than projected when the remedies were implemented more than 30 years ago. As instigated by the GAO audit, this project has sought to provide a more robust understanding of the magnitude of such climate impacts, their regional and site-specific distribution, and the extent to which additional resources are needed.

1.2 Objectives and goals

LM has sought to undertake an assessment of its program's susceptibility to climate change impacts, with the objective of using findings from the assessment to better inform its long-term surveillance and maintenance (LTSM) responsibilities and revision of its environmental liabilities associated with climate resilience. To achieve this, LM partnered with Lawrence Berkeley National Laboratory (LBNL) to perform the assessment and submit a final report to the Director of DOE LM in late 2022. The findings and data deliverables, prepared as part of this final report, may then be used by the Director in formal response to the GAO recommendations.

The primary goals of the climate resiliency study were as follows:

- Provide a comprehensive and scientifically informed assessment of potential future climate drivers identified through survey-derived input from DOE LM and LM Strategic Partner (LMSP) staff that are capable of exceeding LM infrastructure and remedy design requirements and their long-term regulatory performance.
- Develop a detailed set of climate forecast data products through 2099 for both the regional classifications defined by the U.S. Global Change Research Program (USGCRP) and each of the Category II and III sites currently overseen by DOE LM.
- Utilize one or more case studies for which synthesized climate forecast data products associated with a specific DOE LM site are used to evaluate anticipated climate-related changes in site performance and which may require changes, upgrades, and modifications needed to better insulate them to predicted climate impacts. Such case studies are designed to serve as templates for DOE LM and LMSP staff to use in (re)assessing environmental

liabilities for all the sites currently under their oversight, as well as those sites entering the DOE LM portfolio in the coming years.

The climate resiliency study performed by LBNL was focused on three primary activities. First was a review of current state-of-practice climate-resilience activities pursued by other Federal and State agencies. Second was to derive "institutional knowledge" of LM and LMSP staff concerning potential future climate impacts to the 102 sites currently in the LM inventory, as well as the 26 sites expected to be transferred to LM through FY2026. Third was a critical analysis of climate trajectories predicated on future projections forecast by the IPCC, with such projections deemed the gold standard within the climate community (reference). This forward-looking climate analysis is an essential component of generating accurate predictions regarding future climate trajectories and the geographically distinct impacts to LM sites. The work focused on future trends in precipitation, temperature, risk of wildfire, drought, erosion, and flooding as these were identified as most concerning to LM

2.0 Climate Resilience Assessment and Response at the Federal and State Agency Level

As a precursor to performing the climate resilience analysis for DOE LM, we reviewed the climate resiliency assessments being undertaken by other Federal and State agencies such as the Environmental Protection Agency (EPA). The vulnerability assessment considers the vulnerability of a site remedy, including the remedy's exposure to climate or weather hazards and the remedy's sensitivity to hazards that could reduce remedy effectiveness; US EPA 2014b). EPA provides resources to help project managers and other stakeholders understand climate change implications and identify potential hazards at specific sites.

EPA's Guidance
- Climate Change Adaptation Plan (US EPA, 2014a): Guidance on climate resilience at the Superfund sites.
- Vulnerability assessment (US EPA, 2014b)
- Resilience measures (US EPA, 2014c)
- Adaptive capacity (US EPA, 2014d)

Based on the identified vulnerabilities, EPA then provides various resilience measures to achieve climate- and weather-resilient site remedies such as dikes, fire barriers, dams, and storm water ponds (US EPA 2014c). In general, these measures aim to (1) physically secure the remediation systems, (2) provide additional barriers to protect the systems, (3) safeguard access to the site and individual systems, and (4) alert project personnel of system compromises.

In addition, EPA provides methodology to assure the climate change adaptive capacity of a site remedy, which is particularly important for the sites that require long-term remediation and/or institutional controls for more than 30 years (US EPA 2014d). The methodology includes guidance on implementing new or modified measures to increase resilience of the remedy or site infrastructure, as well as establishing plans for periodically reassessing remedy and site vulnerabilities, to determine if additional capacity is needed as cleanup progresses and climate conditions change.

Following Executive Order (EO) 13653, DOE has been developing strategies to enhance climate preparedness and resilience (Moore et al., 2016). DOE released a series of DOE Climate Change Adaptation Plans (US DOE, 2014, 2017), as well as the DOE Climate Change Vulnerability Screening Guidance (US DOE, 2016) to build resilience and mitigation across the Department and include climate change adaptation as part of its operations. Moore et al. (2016) investigated three DOE sites that were impacted by wildfire, flooding, and groundwater changes. Currently, DOE has a guidance document for each site to develop a sustainability plan, including promoting the resilience to disturbances from a variety of sources (US DOE, 2018). Although this guidance is not specific to contaminated sites, it describes a general climate resilience framework that serves as a useful foundation for the work undertaken as part of the LBNL study for DOE LM.

In a report published in 2019 (GAO-20-373), the GAO reviewed various potential issues related to the impact of climate change on non-federal National Priorities List (NPL) sites. The analysis was focused on flooding, storm surge, wildfires, and sea level rise. Their report suggests that climate change may result in more frequent or intense extreme events, such as flooding, storm surge, and wildfires, which could damage remedies at non-federal NPL sites and lead to releases of contaminants About 60 percent of all nonfederal NPL sites are in areas that may be impacted by these potential climate change effects. The GAO recommends broadly incorporating climate resilience into the site-level decision making process to ensure long-term protection of human health and the environment.

GAO also developed a disaster resilience framework for *Analyzing Federal Efforts to Facilitate and Promote Resilience to Natural Disasters* (GAO-20-100SP). Although this report is not specific to contaminated sites or areas, it provides guidance on how to address climate change liabilities. This framework is organized around three broad overlapping principles: (1) accessing information that can help decision makers to identify current and future risk and the impact of risk reduction strategies, (2) integrated analysis and planning that can help decision makers take resilience actions, and (3) incentive structures that can help prioritize risk-reduction investments. This report provides key questions to guide the assessment and planning associated with climate resilience, such as “To what extent could federal efforts enhance the validity and reliability of the disaster risk information produced?”

Interstate Technology & Regulatory Council (ITRC, 2021) published extensive guidance on state-level climate resilience assessments and activities. These assessments delivered useful examples resilience measures and adaptation strategies including *Massachusetts Climate Change and Hazardous Waste Site Screening* and the State of Washington Department of Ecology’s *Adaptation Strategies for Resilient Cleanup Remedies* (Asher et al., 2017). These state-wide analysis reports provide a useful example for LM to perform the national-wide climate resilience assessments.

These documents have guided our strategies. EPA’s Vulnerability Assessment guidance provided key climate hazards to consider, and climate metrics that we can calculate from climate data and model projections. Although many guidance documents are available, the actual implementation was not widely performed at the time of initiating this project (Although DOE has completed the vulnerability assessments and resilience planning (VARP) recently, VARP is more focused on existing operational facilities and infrastructure rather than long-term liability). In addition, we have developed or used new climate metrics such as the wildfire and flooding risks.

3.0 Survey-based Assessment of LM Site Climate Resiliency

To gather detailed information about the LM sites at greatest risk to climate change, we used the GAO's *Disaster Resilience Framework* to "access information that is authoritative and understandable" in an effort to assist decision makers in "identifying current and future risk and the impacts of risk-reduction strategies" (GAO-20-100SP). This information – referred to hereafter as institutional knowledge – was gathered by means of a questionnaire sent to LM and LMSP staff responsible for the 102 sites in the current LM inventory, as well as points of contact for the 26 sites anticipated to be transferred to LM through FY2026. The survey solicited institutional knowledge regarding the climatological resiliency of the 128 sites to be overseen by LM through 2026. Information generated though this survey was specifically focused on gaining insights into future impacts having the potential to exceed design requirements of site infrastructure. Survey respondents were asked to avoid inputs that would result in negligible change in long-term system performance.

The survey was broken into a series of questions designed to gather institutional knowledge about a wide variety of topics, impacts, and concerns including the following:

- Which site features do you feel are vulnerable to climate impacts and/or weather extremes capable of exceeding infrastructure design requirements and/or altering long-term regulatory performance?
- Which, if any, climate disturbances do you consider to have the potential to alter design requirements and/or long-term site performance as regards meeting regulatory requirements?
- Should climate disturbance be found to exceed the design specifications of site infrastructure and/or alter system performance (e.g. violate an existing groundwater compliance action plan), what do you consider the greatest risks to your site?
    - If "Intense precipitation" is deemed a key risk to your site, what is the primary consequence?
    - If "Flooding" is deemed a key risk to your site, what is the primary consequence?
    - If "Erosion" is deemed a key risk to your site, what is the primary consequence?
    - If "Wildfire" is deemed a key risk to your site, what is the primary land cover type at your site?
- Do historical weather and/or climatological data exist for your site or from a nearby weather station you have relied on for meteorological information?
- Have you observed or been made aware of climate- and/or weather-related impacts at your site that were directly found or strongly believed to have exceeded design requirements of critical infrastructure or to have altered system performance? (Note: This question reflects a desire to gather institutional knowledge that may not be readily available, so any relevant details are deemed especially useful.)
- Has any sort of resiliency assessment been made at your site that evaluates the risk of climate change, climate disturbance, and/or weather extremes? (These may include both informal and formal assessments.)

- If yes, were financial estimates (e.g. costs associated with repairs or improvements) included as part of the assessment that address impacts deemed capable of exceeding infrastructure design requirements or altering system performance?
- Can you briefly describe the findings of the resiliency assessment at your site? If financial estimates were included in your assessment, please describe briefly how those were determined.
- Are any active measures being taken at your site to improve its resilience to climate change and/or extreme weather events?
- If yes, were these measures taken in a proactive (e.g. prior to impact) or reactive manner?

A total of 141 responses were collected with input from LM, LMSP, and primary points of contact for all 128 sites being represented in the replies. A complete record of the replies is provided as auxiliary information included as a supplementary digital spreadsheet for future reference and referral.

Analysis of the survey findings identified precipitation, erosion, and flooding as potential climate-driven impacts to site infrastructure and environmental characteristics. The survey findings also identified three "administrative or records only" sites (Attleboro, MA; New Brunswick, NJ; Bayo Canyon, NM) for which climate concerns were expressed by the relevant LM and LMSP site managers. Drought, and by extension temperature extremes, were also viewed as potentially problematic across a diversity of sites and geographic regions. These impacts are problematic for the engineered disposal cells for which LM is responsible While a number of limited climate drivers/disturbances were viewed as potentially problematic (e.g. wildfire), their number and predicted on. Based on the GAO's recommendations these survey findings revealed the greatest risk of impacts to engineered disposal cells is associated with increased future incidence of intense precipitation, flooding, and erosion.

LM site categorization as a function of regional geography and site-specific location. The 5th USGCRP National Assessment Report provides the climatic region: (a) Southwest; (b) Northwest; (c) Northeast; (d) Southeast; (e) Midwest; (f) Northern Great Plains; and (g) Southern Great Plains.

4.0 Climate Analysis

In this section, we investigate historical climate data and climate projections through 2099 across the seven climate regions. We focus on precipitation and daily maximum temperatures, within each region, and at each LM site, and evaluate these metrics. Precipitation is mainly associated with flooding, erosion, and performance of groundwater remedies. The maximum temperature is mainly related to evapotranspiration, extreme heat days. Temperature and precipitation, and their forecast trajectories, help define drought severity, calculated as the Standardized Precipitation Evapotranspiration Index (SPEI).

4.1 Climate Datasets

Coupled Model Intercomparison Project (CMIP5) datasets are used for most of the climate analysis performed in this study. CMIP5 (Taylor et al.; 2012) is an ensemble of global climate model outputs that improve understanding of future climate conditions. The use of CMIP5 ensures the results of this study are consistent with National and International norms. In the following analysis and consistent with the approach presented in the USGCRP *National Climate Assessment*, we used the CMIP5 simulation data during the historical period (1950-2006), which were downscaled from coarser GCM outputs, and have been validated by measurements. The climate projections from 2006 to 2099 under four greenhouse gas emission scenarios known as Representative Concentration Pathways (RCPs; Meinshausen et al. 2011). The scenarios included RCP2.6, RCP4.5, RCP6.0 and RCP8.5, with the suffix numerals indicative of a possible range of radiative forcing values in the year 2100 (2.6, 4.5, 6, and 8.5 W/m2, respectively). Among those scenarios, RCP4.5 is described by IPCC as an intermediate scenario where greenhouse-gas emission in RCP4.5 peaks around 2040 then declines. RCP8.5 is the worst-case climate change scenario in which greenhouse-gas emissions continue to rise throughout the 21st century. These two scenarios were primarily chosen and analyzed, since they have been used in other studies such as VARP. There are exceptions for SPEI and flooding, since the results were not available in these RCPs to compute the metrics.

In additional to the historical (1950-2006) vs. projection (2007-2099) period over the CONUS, we also used four periods below to run climate change analysis across U.S. regions. The four periods allow the evaluation of trends and changes since the baseline time period, and the visualization of the trend over time in the near and far future in the projection.

Periods	Years
Baseline	1950-1989
Recent 30 years	1990-2019
Near Future	2020-2059
Far Future	2060-2099

The raw outputs of CMIP5 are developed at a resolution of 1-degree. Instead of using these data, the National Aeronautics and Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) dataset at ¼-degree (~25 x 25 km) resolution was used. The NEX-GDDP comprises the statistically downscaled historical and projection scenarios derived from the CMIP5 GCM runs (Trasher et al., 2012). The NEX-GDDP dataset includes downscaled projections for RCP4.5 and RCP8.5 from the 21 models and scenarios for which daily scenarios were produced and distributed under CMIP5. The use of such downscaled CMIP5 climate forecast data for the purposes of assessing potential climate-driven impacts to individual sites, site infrastructure, and site regulatory performance is a unique aspect of the current study and is directly responsive to GAO's recommendations to LM.

The datasets are publicly available and obtained via Google Earth Engine:

https://developers.google.com/earth-engine/datasets/catalog/NASA_NEX-GDDP. The climate datasets and the statistical analysis for the 71 Category II and III sites are archived at https://github.com/ALTEMIS-DOE/LM_climate_data. The README file for this dataset is attached in Appendix A, and it includes the details of model, datasets, statistical metrics, and the shifting index computed from the historical to projection periods.

4.2 Software and Workflow Development

A climate vulnerability assessment tool was developed as part of this study. The tool is an open-source *Python* package (https://pypi.org/project/climate-resilience/) capable of evaluating the potential for climate change impacts at a given site location. This tool automatically downloads historical climate data and climate model projections from Google Earth Engine (https://earthengine.google.com/) through the climate-resilience python package and extracts the time series of daily temperature and precipitation at the sites (Figure 1). The climate data acquisition is done through the Google Earth Engine, and the data are processed using a Jupyter Notebook (http://jupyter.org/), which is a web-based interface used to configure workflow in data science, operate datasets and run computer codes.

Various climate metrics, such as average temperature, annual total precipitation, extreme precipitation days, and extreme temperature days can be computed. The automation allows analysis of climate data at hundreds of sites simultaneously and updates the results as new datasets arrive. As an example, the automation tools developed as part of this study are readily capable of ingesting new forecast projects associated with the NASA GDDP datasets for CMIP6, which were released in December 2021 although the results are not yet available through Google Earth Engine [https://doi.org/10.7917/OFSG3345; Thrasher et al. 2022]. Additionally, these data can be combined with the site information, such as infrastructure, environmental remedies, and remediation treatments, to examine the effect of extreme precipitation on the erosion of disposal cells. In addition, visualization functions have been developed that allow for plotting the change of climate metrics over different time periods, with user specified features. The codes are available at https://pypi.org/project/climate-resilience/ with training sessions for LM and LMSP staff available on an *as-needed* basis. A schematic representation of the workflow is presented in **Figure 1**.

4.3 Air Temperature

The CMIP5 datasets indicate that air temperatures are projected to increase persistently through time but with different behaviors across the CONUS (**Figure 2**). Compared to the historical period in the RCP4.5 scenario, maximum air temperature at 2 meters above land surface (Tmax) is projected to increase approximately +1.5 to +2.0 ℃ at the LM sites in the western and eastern US, with Tmax increases generally greater than +2.2 ℃ in the central CONUS. In the RCP8.5 scenarios, increasing Tmax are generally more than 1℃ higher than the RCP4.5 scenario. In the RCP8.5 scenario, increasing Tmax values are approximately +2.6 to +2.9 ℃ in the Northwest US, +2.9 to + 3.3 ℃ in the Northeast US, and greater than +3.3 ℃ in the Southwest and Midwest regions of the U.S.

The 99th percentile Tmax (**Figure 3**) – defined as the top 1% of the daily temperature per convention – is used as a metric for evaluating future impacts associated with extreme temperature. In **Figure 3**, the 99th percentile Tmax are disaggregated into four periods (1950-1989 (baseline), 1990-2019 (recent historical), 2020-2059 (near future), 2060-2099 (far future) across the seven geographical regions. Different from the greater variability of annual average and extreme precipitation of LM sites in geographic regions, the differences across Tmax variability are relatively small. In contrast to the approximately +2.5 to +3.5 °C changes of annual average Tmax, the increase of the 99th percentile Tmax in the projection period is more significant (+6 to +8 °C). In the RCP8.5 scenario, the 99th percentile Tmax in the period at the far future of the projection (2060-2099) could increase as much as +7°C compared to the beginning of the baseline period (1950-1989). The LM sites in the Southern Great Plains region had the highest 99th percentile Tmax in the projection period.

4.4 Annual Total Precipitation

CMIP5 climate projections of average annual total precipitation over the simulated historical period (1950-2006), and RCP4.5 and RCP8.5 projection scenarios (**Figure 4**), show an increase in total precipitation over the projection period for most of CONUS. The few exceptions of precipitation decrease of 0 ~ -2.5% are for a few LM sites in the southwestern U.S. (e.g., Gnome-Coach, NM). In the RCP4.5 scenario, 0 ~ +2.5% precipitation increases are projected for the LM sites in California, Nevada, and Utah, with +2.5 ~ + 7.5% precipitation increases forecast in the Southwest region through 2099. Precipitation increases of +2.5 ~ +5.0% are projected for the LM sites in the Midwest region with forecast increases exceeding +5.0% in the Northeast. In RCP8.5, the spatial patterns of precipitation changes are like RCP4.5 but with greater magnitude. For example, precipitation at the majority of LM sites in the western U.S. increase +2.5 ~ 7.5%, and can exceed +10% at a few sites in the Southwest. The LM sites in the Midwest and Northeast regions also show a greater magnitude of increase in precipitation, as compared to the RCP4.5 scenario projection.

Among the seven geographic regions within CONUS, the Southwest region has the largest number of LM sites but the least precipitation, while the Southeast region has the highest precipitation (**Figure 5**). Greater variabilities of precipitation are found at LM sites in the Northwest and Northeast regions. Increasing precipitation is observed at the LM sites in all seven geographic regions. Similar to **Figure 3**, four periods are disaggregated to evaluate the trend of changing precipitation. Compared to the baseline period (1950-1989), an average of +7.3% precipitation increase over all LM sites is observed in the period of 2060-2099. The projected increases in total precipitation are tied to the greater moisture-holding capacity of warmer air masses associated with future increases in maximum air temperature (Section 4.3).

4.5 Extreme Precipitation

While the increase in total precipitation is a useful metric, the impacts to LM site regulatory performance may be more profoundly impacted by extreme precipitation events of short duration. Toward this end, we have evaluated forecast changes in so-called extreme precipitation days, which are defined by EPA as the number of days with total precipitation intensities in the top 1% of all days having recordable precipitation over the historical period. The threshold values of daily precipitation computed from the historical period are used to calculate the number of extreme precipitation days in the projection periods. Over the projection period. Since the extreme precipitation is not normally distributed, we used Kolmogorov–Smirnov test, which has been used for a nonparametric change point analysis (Padilla et al., 2021) to evaluate whether the changes are significant between the historical and projected values.

Except for two sites in New Mexico, all LM site locations are forecast to experience a significant increase in the number of extreme precipitation days per year under the RCP8.5 projection scenario (**Figure 6**). Overall, the change in the number of extreme precipitation days exceeds the climatological average total precipitation, indicating higher possibilities of severe flooding or erosion on site infrastructure. The approximate 0 to 75% chance of increasing precipitation in the Southwestern U.S. represents nearly average 5-6 extreme precipitation days per year throughout the projection period. In the Midwest and Northeast U.S., the percentage increase in extreme precipitation days can exceed 150%, resulting in more than 8 extreme precipitation days in the late century period.

In the RCP4.5 scenario, more than 90% of LM sites have approximately 4 to 7 extreme precipitation days, a nearly 100% increase over the historical period (**Figure 7**). In the RCP8.5 scenario, the number of increasing extreme precipitation days ranged from approximately 3 to 10 days.

Based on the definition of extreme precipitation (99th percentile daily precipitation during the period of 1950~1989), CMIP5 historical and RCP8.5 projections show an increasing number of extreme precipitation days at the LM sites over all seven geographical regions (**Figure 8**). The spatial variability of extreme precipitation within each geographic region increases with time, especially later (2060-2099) in the climate analysis. And, this is particularly so in the Southwest, Northeast, and Southeast regions, where the chances of extreme precipitation increase to 10 days per year, or three times higher compared to the baseline case.

4.6 Drought Severity

The intensity and duration of drought is another important consideration for site management. The Standardized Precipitation-Evapotranspiration Index (SPEI) considers both precipitation and potential evapotranspiration, which is strongly correlated with temperature although the computation includes humidity, precipitation and other metrics from the CMIP5 data. The SPEI values are dimensionless and computed based on long-term (>30 years) climatological information. Instead of computing SPEI with the CMIP5 datasets, an existing global 1-degree resolution SPEI dataset (Araujo and Nikolopoulos, 2021) for the historical period (1981-2014) and projection scenarios (RCP2.6 and RCP8.5) were used in this study. Due to data availability, the RCP2.6 scenario is analyzed for SPEI instead of RCP4.5 in the CMIP5 datasets, with RCP2.6 considered a “best case” scenario given the decreased magnitude of forecast climatological changes relative to RCP4.5.

In the RCP2.6 scenario, divergent spatial patterns of SPEI values are shown over the CONUS (**Figure 9**), as all sites in the Eastern U.S. are shifting wetter in the future, with most sites in the Western U.S. shifting drier with increased drought severity forecast. In the RCP8.5 scenario, the sites in the eastern U.S. show a similar pattern as the RCP2.6 scenario (**Figure 9**). SPEI projections for the Southwestern U.S. states (New Mexico, Colorado, and Utah) hosting the greatest number of LM sites have significantly elevated chances (SPEI values approximately -1.5 to -1.0 in the RCP8.5 scenarios) of experiencing sustained drought, relative to current conditions into the future. Such increases in drought persistence and severity stand in contrast to forecast projections in this region of modest increases in precipitation, highlighting the added value of considering temperature and precipitation as part of the SPEI analysis.

5.0 Climate Change Outcomes

In addition to the generation of downscaled regional and site-specific forecast data for Tmax, total precipitation, and extreme precipitation days through 2099, such data were also used to evaluate several potential climate-associated outcomes that could impact site infrastructure and site regulatory performance. These outcomes include wildfire, flooding, probable maximum precipitation, and groundwater behavior.

5.1 Wildfire

The Canadian Fire Weather Index (CFWI) has been identified by Brown et al. (2021) and Yu et al., (2022) as one of the measures that have better performance to quantify wildfire potential. In performing an analysis of future changes in wildfire likelihood, we utilized CFWI to develop relevant datasets and to perform risk analysis. The CFWI is computed using the Climate/Hydrologic Risk Analysis Tool (Brown et al., 2021), which includes methods and future climate projection datasets for a wide range of climate drivers. The specific focus of this activity was to provide and evaluate datasets to assess wildfire risks and to assess future climate-related changes in wildfire potential at the LM sites. The activity utilized the dynamical downscaled WRF simulations forced by the climate projections of relevant climate variables from three GCM models (GFDL CCSM, and HadGEM models representing a range of climate model sensitivity with the lowest, mean and highest future temperature change) for scenarios RCP4.5 and RCP8.5 and utilized methods for uncertainty evaluation.

Based on CFWI daily values, we computed the annual maximum value for each year, and computed the return frequency by fitting the generalized extreme value distribution. As a result, we calculated the fire severity (i.e., CFWI) at 2- and 50-year return periods for each grid cell over CONUS. CFWI at 2-yr return period represents 50% chance of wildfire potential likely occurring at this level at any given year. The extreme CFWI data for RCP8.5 was extracted from our existing national dataset and the extreme CFWI for RCP4.5 calculated using available projections of relevant climate variables from the downscaled climate dataset.

Figure 10 shows that most LM sites are projected with medium to high shifts of CFWI 2-yr and 50-yr return period, indicating that wildfire risk is projected to increase in the near and far future of the 21st century. The wildfire risks are particularly high in the southwestern U.S. with CFWI values greater than 100 in both CFWI 2-yr and 50-yr return period. The CFWI is used to assess fire danger in a harmonized way across Europe, uses information about fuel moisture and weather conditions to determine fire behavior. The CFWI can be categorized into 6 EU classes of danger as follows: Very low danger: CFWI is less than 5.2. Low danger: CFWI is between 5.2 and 11.2. Moderate danger: CFWI is between 11.2 and 21.3. High danger: CFWI is between 21.3 and 38.0. Very high danger: CFWI is between 38.0 and 50. Extreme danger: CFWI is greater than 50."

5.2 Flooding

The flooding risk has traditionally been evaluated by flooding zones classified by the Federal Emergency Management Agency (FEMA). The creation of flooding zones was mandated under the National Flooding Insurance Program originating from the National Flood Insurance Program Act of 1968 (Brown, 2016). The first sets of maps were created through the Flood Hazard Study (FHS), which consists of compiling geophysical and environmental data, conducting land and aerial surveys, and interviewing local citizens. The flooding zone map was then improved and digitized under the Map Modernization program between 2003 and 2008 for approximately $1B in federal funds (Morrissey, 2006; Maidment, 2009). The FEMA flooding zone, however, is based on historical flooding and meteorological records so that it does not account for future flooding risk associated with changes in climatological parameters of direct relevance to flooding including total and extreme precipitation.

In addition, there is extensive literature on flooding risk assessments or flood inundation models (e.g., Teng et al., 2017; Mignot and Dewals, 2019). In general, there are two groups of methods: empirical data-driven models and physically-based hydrodynamic models. The empirical methods are based on historical records of flooding extents and river stage measurements and remote sensing-based inundation areas (Smith et al., 1997), as well as various statistical/machine learning methods models (e.g., Darabi et al., 2019). The physically-based models are based on either one-dimensional river-routing/channel-flow models or two-dimensional shallow-water equations (depth-averaged Navier-Stokes equations) for representing the water depth at a given location (Teng et al., 2017). These models require a digital elevation model and meteorological inputs, and they are solved by numerical methods.

The First Street Foundation Flood Model is a nationwide, probabilistic flood model that shows any location's risk of flooding from rain, rivers, tides, and storm surge. The model is built on a recently developed hydraulic model, which has been validated by the past flooding events (e.g., Sampson et al., 2015; Wing et al., 2017). Traditionally, the flooding risk analysis was local-scale and/or based on historical occurrences. This model employs a coupled data-driven and physical-based model to simulate flooding at the continental scale, by taking advantage of recent advances in computing capabilities as well as variability of topography and other spatial data layers. The model incorporates the U.S. Geological Survey (USGS) National Elevation Dataset, and the U.S. Army Corps of Engineers (USACE) National Levee Database (NLD) to represent known flood defenses.

The model first estimates extreme discharge based on the regionalized flood frequency analysis of Smith et al. (2015) as well as clustering approaches to classify catchments based on climate zone, catchment area, and upstream annual rainfall so that the datasets so that flood frequencies are transferred from gauged catchments to ungauged ones. The mode also includes a physically-based hydraulic model, which solves the shallow water equations (i.e., kinematic wave equations) in two dimensions (Neal et al., 2012). To improve the accuracy, it incorporates the sub grid representation of river channels, the width of which can be smaller than the grid size. In addition to fluvial flooding, the model incorporates pluvial flooding for simulating flood hazard in small headwater channels. Since flooding is typically flashy and driven by intense local rainfall events, the pluvial model uses rainfall scenarios derived from the Intensity-Duration-Frequency (IDF) relationships from the National Oceanic and Atmospheric Administration (NOAA).

For the future prediction, the model incorporates the output of an ensemble of 21 Global Climate Models (GCM) under the RCP4.5 scenario to account for the future precipitation as well as their uncertainty (the PCP8.5 scenario is not available). The resulting high, median, and low environmental scenarios are then used as inputs for the flooding model. The model outputs are the extent and depth of flooding given selected probabilities (0.2%, 1%, 10%, 20%, 50%) 15 or 30 years into the future (the results are not available beyond 30 years).

Using the nation-wide First Street Foundation Flood Model results from floodfactor.com, we mapped the flooding extent having a likelihood of 1% in the next 30 years. We performed this analysis at 21 sites at which flooding was identified as a concern in the site manager survey (Section 3). Since the website (floodfactor.com) does not provide the shape file delineating the flood zone, we evaluated the flooding extent by comparing two images: (1) the site boundary from the DOE LM Geospatial Environmental Mapping System (GEMS) database and (2) the flooding extent. Note that the results are available for the lower 48 states; we did not have the data for the Amchitka, AK and Bonus, Puerto Rico sites.

Among the 19 sites identified by LM/LMSP managers as a potential risk (**Table 1**), none of the sites are fully inundated by the 1%-probability flooding extent. At four sites (Bluewater, NM; Canonsburg, PA; Old Rifle, CO; Sherwood, WA), there is some area impacted by the flooding zone (**Figure 11** for the Old Rifle site serves as an example). At eight sites (L-Bar, NM; Burrell, PA; Mound, OH; Monticello, UT; Monument Valley, AZ; Rocky Flats, CO; Slick Rock, CO), the flooding zone is limited to the drainage features (**Figure 12** for the Rocky Flats site serves as an example).

Of note, we have noticed that the same flooding analysis applied to the Riverton, WY site (**Figure 13**) does not overlap with the flooding zone even at the 0.2% likelihood or 500-year flood, despite the fact that flooding has been observed at the site on multiple occasions since 2010. Multiple reasons may exist for this predicted outcome: (1) the snowmelt-induced flooding is not well captured, (2) high resolution lidar data is needed, as the digital elevation model is not sufficiently accurate to represent the small elevation difference typically found in the extensively meandering, low gradient floodplain regions, (3) the site is located near the confluence of two rivers where the model has to account the impact both, and (4) the model is not extensively validated in rural regions of the Western US, as opposed to the Southeastern US where extensive flooding studies have been conducted.

5.3 Probable Maximum Precipitation

Probable maximum precipitation (PMP) is defined as the greatest depth of precipitation for a given storm duration that is meteorologically possible at a particular location. PMP has been used to design the slope of the disposal cells, and also the grain size and thickness of the protection layer. Although this design basis PMP is conservatively set, there is a concern that the future climatic conditions would increase the intensity of precipitation thereby altering calculated PMP values. This is a particularly important metric for LM given environmental remedies, such as engineered disposal cells, are the assets having the greatest environmental liabilities within the LM site network.

Historically, the most prominent historical calculations of PMP were published as a series of reports published between the 1960s to 1990s, describing the methodologies of calculating PMP in climatically similar regions. These reports varied in their approach to the calculation, but generally focused on using historical storm data as well as physical methods to maximize the precipitation at a given temperature and humidity. One example is the Hydrometeorological Report No. 49 (HMR 49), which was completed in 1977 by the United States Weather Bureau. It outlined PMP calculations for Nevada, Utah, Arizona, and parts of California, Colorado, Idaho, New Mexico and Wyoming. The report calculates PMP by splitting it into two primary components, convergence (non-orographic) PMP and orographic PMP, which are calculated for both general and local storms, using the NOAA Atlas 2 precipitation data. However, the HMR method only provided interpolated and regional (10 to 10,000 mi^2) PMP calculation, and the HMR method is difficult to extrapolate into the future. Recently, the Hershfield method (Hershfield, 1965) has been commonly used for calculating PMP based on empirical data (Chavan et al., 2017; Sarkar et al., 2020). In our work, we are using an upgradation of the Hershfield method documented in Sarkar and Maity (2022), which is able to compute both site specific and regional PMP, using multiple sources of precipitation data.

Both site specific and regional PMP are calculating using different datasets. Our PMP calculations account for both temporal and spatial data characteristics. Temporally, a 24-hr time interval was utilized for consistency across calculations in various datasets. Site-specific calculations only made use of annual maximum daily precipitation at the site location from the climate datasets. On the other hand, regional calculations that supplement site-specific calculations utilize “regional” data referring in this case to data collected from nearby sites having the requisite measurements or climatologically similar sites. Since the data used is slightly different in each case, the method of calculation also varies slightly. For site-specific calculations, the calculation follows the traditional Hershfield Method outlined by Equations 1 and 2 below, which shouldn’t be comparable with the HMR methods. As only site-specific data are used for this calculation, it is less likely that an extreme event has been observed and therefore that the site will have a small frequency factor (k_m) leading to a decreased PMP estimation. Hence, PMP calculations derived via the site-specific Hershfield method are typically much smaller than those determined using the regional calculation.

Therefore, the Hershfield method is used to compute the final PMP step outlined by Equation 1, however, the frequency factor is calculated via Equation 3. Equation 3 is fit to the data maxima, such that all data falls near or below the line. This line then represents the corresponding frequency factor for each site dependent only upon the observed average of annual maximum precipitation events for the site of interest. As this approach requires substantially more data from many additional locations, the likelihood of observing an extreme event is more likely and therefore the PMP calculation for all sites included will increase. However, it is important that the sites included in this calculation are deemed to reasonably experience similar extreme events as any of the others included in the calculation. In our calculations, this limitation was approached from two angles: geographically and climatically. A ‘geographic’ calculation was made by only including site data within a reasonable radius from the site of interest. Whereas a 'climatic' calculation was made using only those sites that are similar according to the Koeppen Geiger classification system, one of the most commonly used climate classifications (Peel et al., 2007).

Reference Equations and Variables.

Equation 1: $PMP = X_n + k_m S_n$

Equation 2: $k_m = \frac{X_m - X_{n-1}}{S_{n-1}}$

Equation 3: $k_m = k_A e^{-a X_n}$

X_n: The mean of the annual maximum daily precipitation (AMDP) series for 'n' years.

S_n: The standard deviation of the AMDP series for n events.

k_m: The maximum frequency factor for estimating PMP at that location.

X_m: The maximum value in the AMDP series.

X_{n-1}: The mean of the AMDP series after removing X_m.

S_{n-1}: The standard deviation of the AMDP series after removing X_m.

k_A: The intercept frequency factor. It's a function of the study area and duration of rainfall.

a: The slope factor. It's a function of the study area and duration of rainfall.

The CMIP5 climate projections (Section 3) were used to quantify daily maximum precipitation and standard deviations for each year, for each site. Then the maximum value of annual PMP are reported for each period and/or RCP scenario (e.g., near future and far future).

Table 2 and **Figure 14** shows the comparison between the design-basis PMP, with the historical PMP and projected PMPs computed in Equation 2. Although separate near-term (i.e., not historical) and far future calculations were not made as part of this analysis, such work could be done at a later time. For the purposes of the current work, the comparative PMP analysis performed (historical vs. projected) was deemed to be adequate. For the historical and projected PMPs, we only have 24-hour durations. The conversions to shorter durations are regionally dependent, typically 60-80% for the 6-hr PMP, and even smaller for the 1-hr PMP. Critically, our analysis indicates that future PMP values do not exceed the design-basis PMP values without duration conversion. The only exceptions are for the Gunnison, CO and Weldon Spring, MO sites. At the Fall City, TX site, the RCP8.5 value is slightly higher than the design basis, but conversion from 24-hr to 1-hr estimates would reduce the future projected PMP value significantly. For the remaining two sites, the duration conversion and more detailed analysis will be necessary to evaluate whether the design PMP is sufficiently higher than the future PMP values for the same time duration. In general, our analysis has determined that the currently assumed PMP values for designing disposal cells (i.e., those not specifically accounting for climate change) are largely overestimated thereby providing some level of assurance via our analysis that future changes are not expected to exceed the PMP values used as part of the cell construction process. We would note, however, that accurately predicting extreme weather events is still very much a developing science. Any effort to improve upon our long-term assessments would require direct measurement of climate/meteorological parameters to improve the observed time series, particularly for precipitation duration and extreme values (e.g. those that exceed by an established percentage values measured over the historical period).

5.4 Groundwater Behavior

Climate change impacts to the groundwater system have been studied extensively from the water resource perspective (e.g., Crosbie et al., 2013; Meixner et al., 2016; Smerdon, 2017). There are ground-based and remote sensing-based observations (e.g., Borsa et al., 2014; Frappart and Ramillien, 2018) documenting decreases in water table elevations and hence declining groundwater storage. There are a few studies, however, that document future projections of groundwater resources based upon climate models (Crosbie et al., 2013; Wu et al., 2020). Although there have been many studies focused on water resource predictions under a changing climate, their impacts on contaminant behaviors have not been fully explored. Precipitation changes, as well as evapotranspiration, snowmelt reduction, and snow-to-rain transitions that can strongly impact groundwater recharge (Smerdon et al., 2017). Wu et al. (2020), for example, reported that the current groundwater depletion in the Central Valley of California was attributed to groundwater pumping, predicting that groundwater storage would have been otherwise flat over the next 100 years without anthropogenic impacts.

Across multiple LM sites, studies have focused on documenting and quantifying the impact of groundwater changes or groundwater fluctuation on subsurface residual contaminants; particularly in the Western U.S. Zachara et al. (2013) and Looney et al. (2017) documented the importance of residual uranium in the vadose zone, which was accumulated during the waste water discharge (i.e., the groundwater table was high), and is currently being released when the groundwater table rises. In addition, Noel et al (2019) reported that the annual water table fluctuations – accompanied by strong evapotranspiration in low-permeability sediments – promote the conversion of non-crystalline U(IV) to relatively immobile U(VI), which increases the persistence of the uranium at these sites.

In parallel, Libera et al. (2019) and Xu et al. (2022) used model simulations to evaluate the trade-off between dilution, remobilization, and changes in geochemical conditions and contaminant mobility under variable groundwater recharge behavior. Xu et al. (2022) coupled high-performance, computing-based reactive transport simulations with the climate-model prediction results from CMIP5, with the key findings being (1) after extreme precipitation, local dilution could reduce contaminant concentrations until remobilized contaminants arrive and increase concentrations a few years later, and (2) the increase in contaminant concentrations may not impact downstream concentrations and export significantly, given that changes are most heavily concentrated in the upper portion of the aquifer. They also reported that the impacts and the timing of the impacts are strongly dependent upon well locations (for concentrations) as well as the decision metrics.

In evaluating the published literature, we determined that any subsequent groundwater analysis needs to be done on a site-by-site basis, given that the groundwater impact is dependent not only upon climate conditions but also depends highly upon local and regional geologic composition (e.g., aquifer hydrogeological properties) as well as geographic conditions (e.g., closeness to surface water; mountain block recharge, etc.). Additionally, climate-driven impacts to groundwater behavior need to be evaluated within a regulatory context, considering the spatial-temporal variability of contaminant concentrations and export. For example, many sites report increased concentration of well contaminants after the groundwater rises at monitoring wells, which may or may not impact surface water concentrations or well concentrations at the boundary given the increased volume of dilutionary water that accompanies increases in groundwater storage/elevation.

6.0 Site Specific Assessments

It was beyond the scope of this study to evaluate and reassess environmental liabilities for *each* LM site potentially at additional risk due to climate change. As a result, a detailed assessment of impacts to site infrastructure and regulatory performance in response to future climate change scenarios was performed, in conjunction with LM and LMSP staff, for two archetypal sites in the LM inventory to develop a framework for evaluating additional sites. The Canonsburg, PA and Monticello, UT sites were selected, based on LM input, for site specific impact analysis. LBNL, LM and LMSP staff collaborated to assess climate forecast data downscaled to the location of the two sites with respect to remedy impacts. LBNL recommendations for modifying site infrastructure, with a focus on measurements and monitoring, or reassessing current site behavior (e.g. for natural flushing or attenuation) are presented herein. However, the implementation cost estimates are out of scope for this study. The site assessment process for the two sites *serves as an example for future such assessments by LM and LMSP staff for the remaining inventory of LM sites.*

6.1 Canonsburg, PA

The Canonsburg disposal site is a 37-acre former uranium ore processing site located in southwestern Pennsylvania, approximately 20 miles southwest of Pittsburgh. The site is adjacent to Chartiers Creek and hosts an engineered disposal cell of ca. 2.4 hectares (**Figure 15**). LM manages the disposal site in accordance with a Long-Term Surveillance Plan to ensure that the remedy functions as designed to prevent release of contaminants, primarily uranium, to the environment. Site inspections are performed annually with long-term sampling of surface water and groundwater to evaluate contaminant levels and trends. Site-relevant climatological and hydrological information are sourced from local weather stations, groundwater monitoring wells, and a stream gaging station on Chartiers Creek operated by USGS (USGS03085250; approximately 2km downstream of the Canonsburg site).

6.1.1. Climate data

Present/future climate statistics at the Canonsburg site are presented in **Table 3**. The annual precipitation is expected to increase from the historical average of 2.84 mm/day to 3.02 mm/day, while the average temperature is forecast to increase from 16.7C in the historical period (1950-2006) to 18.9C and 19.9 C in the projection period (2007-2099) in the RCP4.5 and RCP8.5, respectively. The number of extreme precipitation days is expected to increase from 2.6 days per year on average to 3.4 days in RCP4.5 and 4.1 days in RCP8.5, while the maximum daily precipitation is expected to increase from 46.1 mm/day in the historical period to 50.0 mm/day in

RCP4.5 and 54.8 mm/day in RCP8.5, to a 20% increase. The fire and drought risks were low or negligible.

6.1.2. Flooding

FEMA's current estimates of 100, 500 and 1000-year floods are 950 feet (above mean sea level), 954 feet and 955 feet, respectively. As presented in Section 5.2, the future flooding risk is significant for the Canonsburg site (**Figure 16**), particularly in the northern portion of the site including some portions of the disposal cell having larger than 1 meter of inundation. Such flooding potential is exacerbated given the site's location along a meandering reach of Chartiers Creek; three sides of the boundary are surrounded by the river. The site managers also reported the observation of surface inundation at the site after several hurricanes and storm events in the past.

6.1.3. Surface Erosion

According to the site document (US DOE, 1983), the disposal cell was designed in terms of the riprap cover thickness, the slope of the cell edge and median grain size in the riprap layer based upon an estimated PMP value. The design basis PMP is 31.8 inches (in one hour), which is much higher than the record maximum of 3.4 inches (in 24 hours) in the historical period (1950-2006) of climate data, and 4.4 inches in the RCP8.5 projection data. As presented in Section 5.3, we computed the future PMP based on the climate model projections. The maximum among multiple models is 13.46 inches, which is still significantly smaller than the original design-based PMP value suggesting no reassessment of the utilized PMP value is required as a result of climate change.

6.1.4 Groundwater Behavior

The groundwater and streamflow behavior were evaluated using climate forecast data, in the vicinity of the site. We used the publicly available the groundwater level and concentration data from the LM GEMS to this end (**Figure 17**).

We first compared the groundwater table (GWT) elevation and uranium concentrations (**Figure 18**). Uranium concentrations have been increasing in recent years, particularly in monitoring well 412, north of the disposal cell. Although Well 412 maximum uranium concentrations sometimes correspond to the higher GWT, the overall correlation between GWT and uranium concentration was not statistically significant (p-value larger than 0.1). The recent increase in uranium concentration since 2013 in Well 412 is a concern, since the trend is opposed to the groundwater modeling results done in the 1990s (DOE, 2000), which predicted that the uranium concentrations would decrease over time. In addition, the increasing groundwater table could be a concern, since it might reach the bottom of the disposal cell (950ft).

In addition, we compared GWT with the adjacent streamflow data (i.e., gauge height) as well as the annual precipitation data (**Figure 19**). The correlation between GWT and gauge height was 0.95 (p-value <0.001), while the one between GWT and the annual precipitation was 0.87 (p-value <0.001). In the past several years, the regulatorily required sampling frequency has decreased, but this has diminished the ability to compare the dynamics between surface water and groundwater behavior are. Given that both total precipitation and extreme precipitation days are forecast to increase in the future, the groundwater table elevation is expected to increase with potentially problematic issues for site infrastructure and long-term behavior. Specifically, any future increases in GWT that have the ability to permanently, or for a sustained period of time, saturate the base of the disposal cell are of concern in terms of enhanced contaminant leaching to Chartiers Creek.

6.1.5 Site Recommendations

The detailed synthesis of forecast climate metrics and potential climate-driven outcomes afford the opportunity to evaluate increased future risks to the performance of site infrastructure and expected site behavior. This synthesis enables a set of recommendations to be made in terms of identifying current knowledge gaps that should be remedied in order to rapidly detect and changes in environmental conditions over the coming decades that may require action on the part of LM to reevaluate key climate related design assumptions and potential impacts to regulatory performance. The climate synthesis has identified several areas of potential risk associate with projected climate change:

- Potential changes in coupled surface water-groundwater behavior leading to flooding, inundation, and increases in groundwater that permeate the base of the disposal cell.
- Insufficient spatiotemporal coverage of groundwater elevations and meteorological data
- Knowledge or assessment of future flood control activities by local stakeholders

A variety of relatively easy and cost-effective corrective measurements can be considered by LM in response to the site-specific climate projections. Based upon the analysis of future precipitation trends (total and extreme), we argue strongly in favor of the need to install the meteorological and groundwater sensors as well as associated data telemetry to standards established at other LM sites where real-time meteorological data is deemed critical (e.g. Mexican Hat, UT). Observations of events that exceed a designated threshold (e.g. rainfall rates and amount, increases in GWT, etc.) represents triggers for site visitation and assessment that are informed by site conditions, and thus move beyond the traditional model wherein site visits and inspections are performed on an annual to semi-annual basis. While such regularly scheduled visits will continue to be important, enabling the ability to rapidly respond to real time environmental conditions (also referred to as "Even Driven Monitoring") is deemed to be of highest priority.

Critically, our analysis does not indicate any immediate need for modification of the disposal cell as regards forecast projections of increased extreme precipitation, given the design basis PMP is sufficiently high. Given the climate analysis, an important future objective for the site is to quantify the impact of forecast changes in precipitation behavior on uranium dynamics. While multiple approaches can be envisioned to achieve this objective, our systematic evaluation suggests the following recommendations to be viable. Based upon the groundwater analyses, we would recommend (1) more frequent groundwater sampling and (2) in situ GWT monitoring with pressure transducers particularly for understanding the impact of extreme precipitation events at Canonsburg. To the extent that (2) requires the installation and instrumentation of new wells that are more proximal to the predicted areas of enhanced flooding, we encourage such measures.

Analysis of coupled surface water-groundwater behavior heavily emphasizes the importance of the existing USGS stream gauge on Chartiers Creek. Given the current USGS model wherein the costs of maintaining and overseeing the operation of local stream gauges is overwhelmingly borne by local stakeholders, LM and LMSP staff overseeing the Canonsburg site are strongly encouraged to ensure future funding is made available to sustain operations of this critical monitoring location.

6.1.6 Assessment of Climate Change Risks

Based upon our analysis, we feel that the current environmental liabilities associated with the Canonsburg site require only a modest reassessment. Specifically, we recommend installation of a standardized meteorological and data telemetry network, an expanded network of higher temporal resolution GWT measurements – and where warranted, installation of new groundwater monitoring wells that better constrain groundwater elevations in the vicinity of the disposal cell – and sustained, guaranteed operation of the existing USGS gauge on Chartiers Creek. A precise assessment of the financial increase in site expenses associated with these recommendations is left to LM and LMSP staff given their direct knowledge of the site and site expenses, but the increase is expected to be modest over the lifetime of the LTSM effort at the Canonsburg site.

6.2 Monticello, UT

The Monticello, Utah, Disposal and Processing Sites are located near the city of Monticello in southeastern Utah and encompasses a 110-acre tract of land formerly owned by DOE. The mill site is situated in an east-trending alluvial valley formed by Montezuma Creek, an intermittent stream that flows from the Abajo Mountains immediately to the west. The site is broken into three operational units (OU), which segregate the mill site and its environs into areas associated with the former militia and associated mill buildings including the engineered disposal cell (OU I), peripheral properties where mill tailings were used for construction purposes (OU II), and surface water and groundwater primarily along the reach of Montezuma Creek that flows past and downstream of the mill site (OU III). More specifically, OU III involves a plume of contaminated groundwater in the shallow alluvial aquifer that exists beneath a portion of the former mill site and extends approximately 1 mile to the east (downstream).

The Monticello site assessment and synthesis of forecast climate metrics for the site was guided by a series of specific questions:

- What is the impact of climate change on evapotranspiration (ET)? The disposal cell at Monticello has an ET barrier with a sagebrush steppe community that includes a synthetic, multiple-layer liner system at its base.
- What is the likelihood and severity of wildfires that may have an impact on the ET barrier?
- What is the likelihood and severity of episodic precipitation? What is its impact on hydroclimatic coupling between precipitation, groundwater, interactions with the vadose zone, and stream flow?
- What, if any, impact will change in site groundwater recharge behavior have on MNA as a desired long-term remedy at the site?

6.2.1. Climate data

The climate statistics are shown in **Table 4**. The annual average daily-maximum temperature is likely to increase from the historical average of 26.5C to 28.9C in RCP4.5 and 29.2C in RCP8.5. The annual precipitation is expected to increase by 20%, while the number of extreme precipitation days is forecast to increase from 0.94 days on average to 1.26 days in RCP4.5 and 1.33 days in RCP8.5. Maximum precipitation is forecast to increase from 26.5 mm/day to 28.9 mm/day in RCP4.5 and 29.2 mm/day in RCP8.5. We note that there is a large annual variability in the likelihood and severity of extreme precipitation. Drought likelihood and severity is forecast to increase with SPEI values decreasing significantly from -0.01 to -0.34 in RCP4.5 and -0.58 in RCP8.5. The drought risk is increasing, even though the precipitation is increasing, which is driven largely by forecast increases in air temperature (Tmax) and ET.

6.2.2. Evapotranspiration

In addition to the datasets above, we downloaded the ET projection from the climate models (**Figure 20**). The ET projections are available in a subset of climate models and indicate that annual ET is projected to increase from 398 mm/year to 407 mm/year in RCP4.5 and 410 mm/year in RCP8.5. It is expected that the increase of ET would enhance, or at a minimum maintain, the performance of the ET barrier atop the disposal cell in minimizing infiltration. We would note that typically the climate models do not include the changes in plant type or plant succession associated with climate change, which is an active area of research. Although ET is nearly balanced with precipitation at annual scale, increased extreme events and plant succession could alter these dynamics. Regardless, the forecast increase in drought likelihood – or in the case of many locations within the desert Southwestern US – drought persistence would indicate plant succession is likely, with a shift towards more xeric plant species, such as deep-rooting shrubs, and decreases in certain grasses and forbs. Early investigations of future climate states at the Monticello site by U.S. DOE (2006) identified nearby, potential future climate analog locations, which could provide insight into probable ecological succession pathways under different climate scenarios. Such shifts in plant functional type may indeed alter the design behavior of the ET cover; however, such shifts will be accounted for as part of LTSM at the site and physical inspections of the disposal cell and its vegetated cover composition.

6.2.3. Wildfire impact

As described by Section 4.8, the wildfire risk was quantified based on CFWI and European Union (EU) classes. We compared the historical values with mid-century (2045 – 2054) and late-century (2085 – 2094) projections. CFWI (along with the EU classes) is 11.3 (moderate) for the historical range. The mid-century CFWIs are 11.2 (moderate) for RCP4.5, and 12.3 (moderate) for RCP8.5, while the late-century CFWIs are 14.6 (moderate) for RCP4.5 and 14.3 (moderate) for RCP8.5. We see nonlinear increases for different scenarios, and also for different periods, which would be attributed to the trade-offs between increasing precipitation and increasing temperature, both of which affect ET and vapor pressure deficit. The wildfire risk is significant, and higher than other LM sites, although it does not increase significantly in the future according to our climate model projections.

6.2.4. Groundwater behavior

Long-term groundwater datasets are relatively limited at this site. Aside from two wells (88-85, IW-1), all other wells were installed after 2014. Both Well 88-85 and IW-1 have long periods of missing time series data. For example, IW-1 has a particularly long missing time period from 2012-2017. We compared the Well 88-85 data (water table and uranium concentration) with the climate data (precipitation) in a manner consistent with the Canonsburg analysis (**Figure 21**).

We found that the annual average water table data is moderately correlated with January-June precipitation amounts ($R = 0.3$), with the highest water table elevations observed in 2010. Given peak evaporative demand and transpiration losses during the growing season, summer rains are predicted to contribute negligibly to groundwater recharge and dynamics. Not surprisingly, this emphasizes the expected impact of winter snowpack on infiltration and groundwater recharge at the site, although it's not possible to directly identify the specific geographic location where recharge predominates (e.g. proximal to the site or more distal in the Abajo Mountains). Again, drawing strong correlations between precipitation, recharge, and uranium dynamics is challenging given the paucity of data; however, there is a statistically significant increase in the uranium concentration in 2015 that may have a relationship to coupled hydroclimate behavior notwithstanding the fact that the water table elevation data is missing over that period. It is difficult to extrapolate more broadly given data emanating from only a single, long-term monitoring well prior to 2014.

Through the LM and LMSP staff survey, institutional knowledge revealed that during the winter of 2018-2019, Monticello had more than twice its annual average snowfall, with the results corroborated by local meteorological station data, which led to the decrease in groundwater extraction due to the evaporation pond limitation (personal communication, site responsible LM/LMSP staff, 2021). As a result and per communication with site operators, the increased water table resulted in the release of vadose zone contaminants. The combination of increased loading of contaminants and reduced extraction rates caused uranium concentrations to increase in the Area of Attainment (AOA). Two years later, uranium concentrations in the AOA still had decreased to their previous levels. It suggested that the groundwater impact needs to be evaluated in conjunction with the record of the groundwater treatment.

Because groundwater behavior is a critical component of the MNA remedy, it is worth considering the impacts of the forecast climate metrics on the groundwater system more broadly. Specifically, MNA at the site is largely predicated upon the availability of metal oxyhydroxides as sorbents for upgradient advecting uranium. Increases in drought duration and intensity are expected to have consequences on groundwater levels and the baseflow elevation – here defined as the groundwater elevation associated with minimum surface water flows in Montezuma Creek and other local streams – with decreasing elevations expected with climate change due to marginal increases in precipitation totals more than compensated for by increases in ET thereby limiting recharge. Such decreases in baseflow groundwater elevations expand the oxic interface between land surface and groundwater. This promotes the formation and/or regeneration of iron and manganese oxyhydroxides within the alluvial aquifer that can in turn, following inundation associated with seasonal increases in groundwater elevation during snowmelt or singular extreme precipitation events, promoting enhanced rates of uranium sorption and thus enhanced efficacy of MNA.

Counterbalancing this process, however, are potential changes in groundwater chemistry associated with drought and increased ET, which can lead to increases in vadose zone pore water solute concentration and total dissolved solids. In the arid Southwestern U.S., carbonate mineral concentrations can be elevated in soils and sediments, with carbonate salts being concentrated in pore spaces exposed to sustained elevated temperatures and rates of ET. Such elevated concentrations of carbonate minerals and salts can have a negative impact on sorption-predicated MNA such that they find their way into the groundwater system tied to groundwater recharge and/or episodic increases in groundwater elevation that temporarily access shallow inventories of carbonate. Dissolution of solid phase carbonates leads to increases in groundwater and pore water alkalinity and aqueous carbonate – primarily as bicarbonate – concentrations, which can promote uranium desorption from metal oxyhydroxide sorbents thereby increasing, at least temporarily, groundwater concentrations of uranium. Such effects are expected to be largely ephemeral and transient; however, future groundwater or surface water observations wherein punctuated increases in uranium concentrations are observed should be evaluated against the aforementioned climate-induced behavior. Such changes are thus not expected to significantly impact MNA as a long-term and viable remedy for the site.

6.2.5 Site Recommendations

The detailed synthesis of forecast climate metrics and potential climate-driven outcomes enabled us to evaluate increased future risks to the performance of site infrastructure and expected site behavior. This synthesis revealed current knowledge gaps that should be remedied to detect and assess environmental conditions over the coming decades that may require LM to address changes in design requirements and site regulatory performance. The climate synthesis has identified several key areas of concern:

- Persistent drought and increased potential ET will cause plant communities to evolve toward deep-rooting, xeric shrubs, with potential consequences for disposal cell cover performance.
- Insufficient monitoring stations of groundwater elevations along the inferred hydrologic flow paths developed as part of the Monticello site conceptual model.
- Potentially insufficient site-specific meteorological data
- Although the wildfire risk is significant, forecast projects do not indicate a substantial increase in future risk, and the ongoing/planned site wildfire mitigation activities are deemed sufficient.

A variety of relatively easy and cost-effective corrective measurements can be recommended as part of the synthesis activity. Based on the analysis of future extreme precipitation trends, we suggest that LM ensure meteorological measurements continue to be made according to standards established at other LM sites where real-time meteorological data is deemed critical. Observations of events that exceed a designated threshold should trigger site visitations and assessments and thus move beyond the traditional model wherein site visits and inspections are performed on an annual to semi-annual basis. While regularly scheduled visits will continue to be important, the ability to rapidly respond to real time environmental conditions should be prioritized.

A critical objective for the site is the continued performance of MNA as a long-lasting, viable, and climate resilient approach for minimizing the release of uranium to offsite locations. While a number of approaches could be envisioned to achieve this objective, our evaluation suggests the following to be the most optimal. Specifically, we recommend a temporally extensive network of groundwater monitoring wells for evaluating seasonal and annual changes in groundwater elevation particularly for understanding the impact of extreme precipitation events. Where possible, we would recommend installing new (or replacing existing) pressure transducers for monitoring changes in groundwater elevation with those that also measure changes in fluid conductivity. Such tandem sensors will enable LM to directly assess the coupling between groundwater behavior and solute (e.g. bicarbonate) generation. Additionally, some level of sustained monitoring and active management of vegetation growing atop the disposal cell may be required over time to remove transitionary species with rooting behavior capable of altering cover cell performance.

6.2.6 Assessment of Climate Change Risks

Based on our analysis, we feel that the climate change risks associated with the Monticello site require only a modest reassessment. Specifically, we recommend installation of a standardized meteorological and data telemetry network, an expanded network of higher temporal resolution GWT measurements and fluid conductivity. A precise assessment of the financial increase in site expenses associated with these recommendations is left to LM and LMSP staff given their direct knowledge of the site and site expenses, but the increase is expected to be modest over the lifetime of the LTSM effort at the Monticello site.

7.0 Conclusions

In this study, we have (1) compiled all the federal level climate resilience guidance documents and reviewed assessments, (2) surveyed the institutional knowledge about potential impacts of climate change across 102 LM sites, and (3) analyzed the historical climate data and climate model projections at 102 LM sites. In addition, we analyzed climate-driven outcomes capable of impacting LM’s site inventory including wildfire, flooding, probable maximum precipitation for evaluating erosion damage potential, and groundwater dynamics and contaminant concentrations.

The following is a list of our findings:

- The synthesis of the historical data and climate projections confirmed that the LM sites are forecast to experience increases in maximum air temperature along with increasing extreme rain frequency and severity through 2099, particularly.
- Temperature increases are found to be particularly large at Site A/Plot M Decommissioned Reactor Site, IL; Green River, UT Disposal Site; Salt Lake City, UT Disposal Site; and Monticello, UT Disposal and Processing Sites. Increases in extreme rain frequency are

particularly noteworthy at Amchitka, AK; Colonie, NY; Parkersburg, WVS; and Canonsburg, PA.

- Although the extreme precipitation is increasing and the erosion damage of disposal cells is a concern, our analysis suggests that the disposal cell design specifications have a significant engineering safety margin that accounts for projected increases in PMP except for two possible sites: Gunnison, CO and Weldon Spring, MO. These disposal cells are designed based on lower than potentially forecast PMP values and additional assessments are recommended.
- For sites where it was identified as part of the survey of LM and LMSP site leads, flooding is a concern for those located within the floodplain or close to the inland waterways (Bluewater, NM; Canonsburg, PA; Old Rifle, CO; Sherwood, WA). There have been some observations of surface inundation including the Canonsburg, PA and Riverton, WY sites. In addition, there are eight sites that have drainage features that could be inundated (L-Bar, NM; Burrell, PA; Mound, OH; Monticello, UT; Monument Valley, AZ; Rocky Flats, CO; Slick Rock, CO). The presence of identified, proximal contaminant source zones and/or infrastructure at these sites may require additional attention/assessment.
- Wildfire risk is particularly high for the North Great Plains and Southwest US regions by CFWI calculation. The three sites with the highest potential for wildfire shifting from historical to future projection are: Central Nevada Test Area, NV; Salt Lake City, UT; and Durango, CO.
- Impacts to groundwater behavior were analyzed using the long-term groundwater datasets at the Canonsburg, PA and Monticello, UT sites. The groundwater table responds to seasonal or annual precipitation variability, such as annual or snow precipitation and/or streamflow dynamics. Uranium concentration trends appear to be variable, increasing at some sites while others decreasing at other sites. , although the cause remains unclear as to its attribution to climate-driven trajectories. In general, many LM sites have a residual contamination mass above the water table, creating a vulnerability to climate change. The Monticello, UT study suggests that more detailed assessment and/or monitoring is warranted to consider potential changes in MNA efficiency tied to future climate change.

We would note that our analysis relies overwhelmingly on publicly available datasets. There could be site-specific features or details that were not captured in our analysis. It is our contention through survey results and detailed, site-specific discussions that LM has already implemented many measures that address and preemptively respond to future climate-driven impacts to its network of sites Supplementing such work, we offer the following overarching recommendations:

- Continuous groundwater monitoring (in situ sensors for groundwater table dynamics and fluid conductivity) and new or sustained stream gaging for all LM sites adjoining inland waterways
- Climate sensors at more vulnerable sites particularly at the Gunnison, CO and Weldon Spring, MO sites as concerns exceedance of potential Probable Maximum Precipitation events
- Detailed groundwater modeling and prediction (informed by historical data) to evaluate the groundwater change and its impact on contaminant concentrations

LM recognizes that maintaining a long-term record of climate and groundwater datasets are critical for assessing the impact of extreme climate events, as well as the consequence of those events on disposal cell integrity and performance and associated surface water and groundwater systems. Maintaining, expanding, and standardizing these monitoring assets is critical for ensuring climate resilience across the growing inventory of LM sites.

Tables

Table 1. Flooding extents at the 19 LM sites. "Some area" means that the flooding extent overlaps with the site boundary, "Drainage" means that the flooding area is limited to the drainage area, and "None" means that there is no overlap between the flooding extent and the site boundary.

Name	Code	Flooding
L-Bar, NM, Disposal Site	BAR	Drainage
Bluewater, NM, Disposal Site	BLU	Some area
Burrell, PA, Disposal Site	BUR	Drainage
Canonsburg, PA, Disposal Site	CAN	Some area
Green River, UT, Disposal Site	GRN	None
Laboratory for Energy-Related Health Research, CA, Site	LEH	None
Lowman, ID, Disposal Site	LOW	None
Mound, OH, Site	MND	Drainage
Monticello, UT, Disposal and Processing Sites	MNT	Drainage
Monument Valley, AZ, Processing Site	MON	Drainage
Pinellas County, FL, Site	PIN	None
Parkersburg, WV, Disposal Site	PKB	None
Rifle, CO, Disposal/Processing Site	RFL	Some area
Rocky Flats, CO, Site	RFS	Drainage
Shirley Basin South, WY, Disposal Site	SBS	Drainage
Sherwood, WA, Disposal Site	SHE	Some area
Shiprock, NM, Disposal Site	SHP	None
Salt Lake City, UT, Disposal/Processing Site	SLP	None
Slick Rock, CO, Disposal/Processing Site	SRD	Drainage

Table 2. Design basis PMP and PMP calculated from climate data

	Design basis		24-hr PMP from Climate data (in)		
Site	PMP (In)	Duration	Historical	RCP4.5 Projection	RCP8.5 Projection
Ambrosia Lake, NM, Disposal Site	11.6	1	4.77	8.88	4.69
Burrell, PA, Disposal Site	31.4	1	6.31	6.15	24.99
Canonsburg, PA, Disposal Site	31.8	1	5.08	4.93	13.46
Durango, CO, Disposal/Processing Site	8.3	1	5.36	6.99	5.57
Falls City, TX, Disposal Site	19	1	11.06	10.75	19.6
Grand Junction, CO, Disposal Site	7.9	1	3.82	3.7	7.26
Green River, UT, Disposal Site	8.5	1	8.31	6.95	4.76
Gunnison, CO, Disposal Site	7.7	1	6.15	5.53	15.06*
Lakeview, OR, Disposal Site	7.2	1	8.75	3.86	7.08
Lowman, ID, Disposal Site	8.6	1	4.11	6.44	5.83
Maybell, CO, Disposal Site	7.3	1	4.37	4.33	3.6
Mexican Hat, UT, Disposal Site	8.1	1	3.15	2.96	3.07
Naturita, CO, Disposal Site	8.2	1	4.67	5.41	7.83
Rifle, CO, Disposal Site	7.4	1	4.24	3.59	5.15
Salt Lake City, UT, Disposal Site	9.7	1	2.96	3.41	3.3
Shiprock, NM, Disposal Site	8	1	3.71	2.98	3.49
Slick Rock, CO, Disposal Site	8.1	1	5.32	5.57	6.96
Tuba City, AZ, Disposal Site	8	1	3.93	5.68	4.98
Bluewater, NM, Disposal Site	10.5	1	4.77	8.88	4.69
Edgemont, SD, Disposal Site	11.25	6	3.96	4.05	5.96
L-Bar, NM, Disposal Site	10.96	1	4.51	5.19	5.04

Maybell West, CO, Disposal Site	7.3	1	4.33	2.96	3.79
Sherwood, WA, Disposal Site	18.3	1	2.73	3.34	6.32
Shirley Basin South, WY, Disposal Site	11.57	1	3.27	5.7	5.32
Monticello, UT, Disposal Sites	7.2	1	5.37	5.89	4.8
Weldon Spring, MO, Site	38.4	6	6.42	7.91	44.55*

Table 3. The climate statistics for the Canonsburg site: historical mean (hist_mean), historical standard deviation (hist_std), historical maximum (hist_max), RCP4.5 mean (rcp45_mean), RCP4.5 maximum (rcp45_max), RCP8.5 mean (rcp85_mean), and RCP8.5 maximum (rcp85_max). * represents a significant change or beyond one STD, and ** beyond two STD.

	hist_mean	hist_std	hist_max	rcp45_mean	rcp45_max	rcp85_mean	rcp85_max
Annual precipitation (mm/day)	2.84	0.08	3.08	3.02 **	3.29	3.12 **	3.41
Extreme precipitation day	2.5	0.83	6.76	3.29 *	9.05	3.83 *	10.86
Annual avg Tmax (C)	16.72	0.37	17.93	18.93 **	20.71	19.9 **	22.82
Maximum Daily Precipitation (mm/day)	43.72	7.48	85.11	47.24 *	97.15	52.19 *	112.44
SPEI	0	0.21	-0.48	0.29	-0.59	0.24	-0.64
Wildfire	3.88			5.08		4.07	

Table 4. The climate statistics for the Monticello site: historical mean (hist_mean), historical standard deviation (hist_std), historical maximum (hist_max), RCP4.5 mean (rcp45_mean), RCP4.5 maximum (rcp45_max), RCP8.5 mean (rcp85_mean), and RCP8.5 maximum (rcp85_max). * represents a significant change or beyond one STD, and ** beyond two STD.

	hist _mean	hist _std	hist _max	rcp45 _mean	rcp45 _max	rcp85 _mean	rcp85 _max
Annual avg precipitation (mm/day)	0.8	0.04	0.9	0.86 *	1.03	0.85 *	1.03
Extreme precipitation day	0.57	0.72	4.29	1.02 *	5.1	1.19 *	5.33
Annual avg Tmax (C)	16.43	0.37	17.26	18.95 **	20.13	20.05 **	23.52
Maximum Daily Precipitation (mm/day)	23.57	6.29	69.01	26.5	77.23	26.56	72.52
SPEI	-0.01	0.28	-0.55	-0.34 *	-1.16	-0.58 **	-1.57
Wildfire	11.3			12.9 *		13.33 *	

Figures

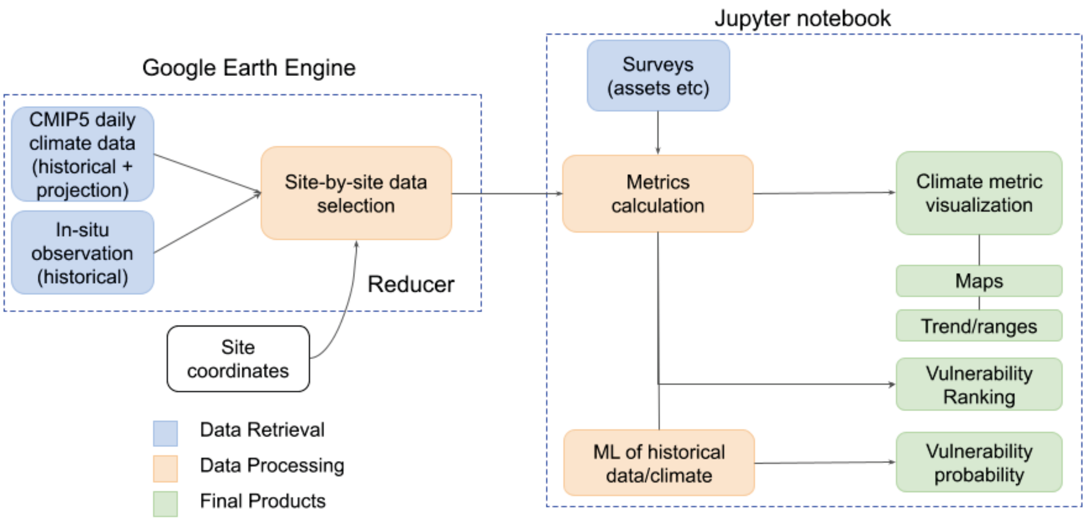


Figure 1. Workflow chart of the climate data pipeline and vulnerability assessment tool.

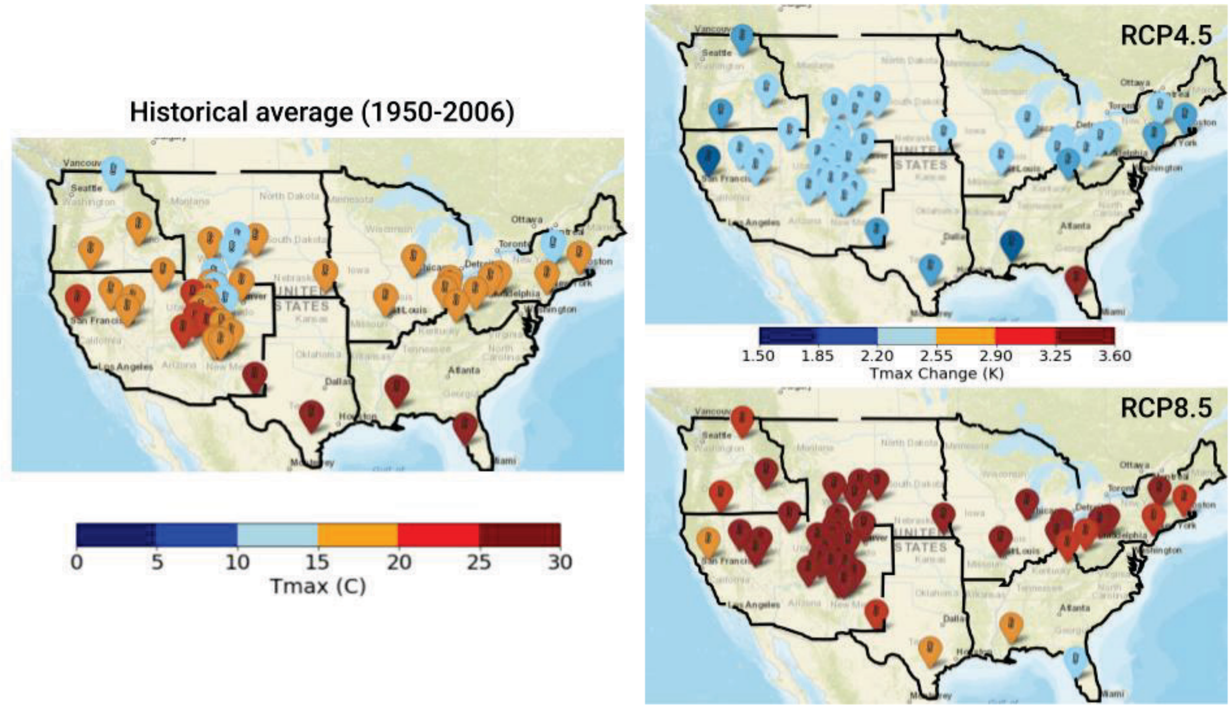


Figure 2. Annual average Tmax in the historical period (left), and the changes between RCP8.5 and RCP4.5 climate scenarios (2007-2100) and historical period (1950-2006) at LM sites over the CONUS (right). The change values are computed as Tmax_sce - Tmax_hist, which Tmax_sce and Tmax_hist are annual average Tmax of scenarios (RCP4.5 or RCP8.5) and historical periods, respectively.

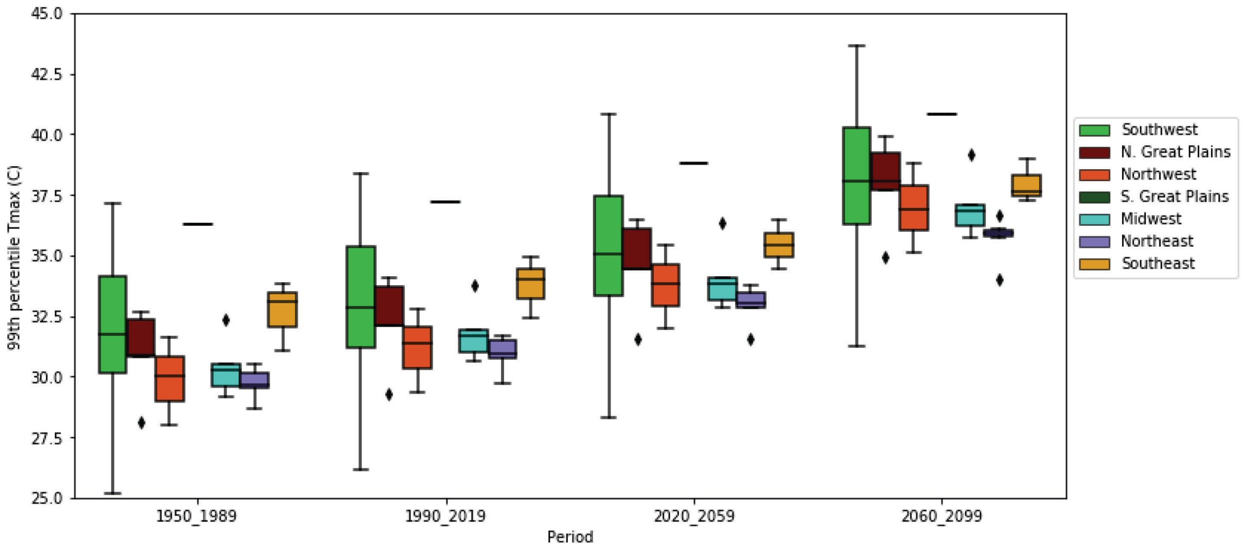


Figure 3. Box and whisker plot of 99th percentile Tmax changes at LM sites divided by seven geographical regions. The changes of 99th percentile Tmax over the four periods from 1950-2099 are computed. Each box shows the statistics of climatological average precipitation/temperature at multiple LM sites within each geography area. Climate projection data is RCP8.5 scenario.

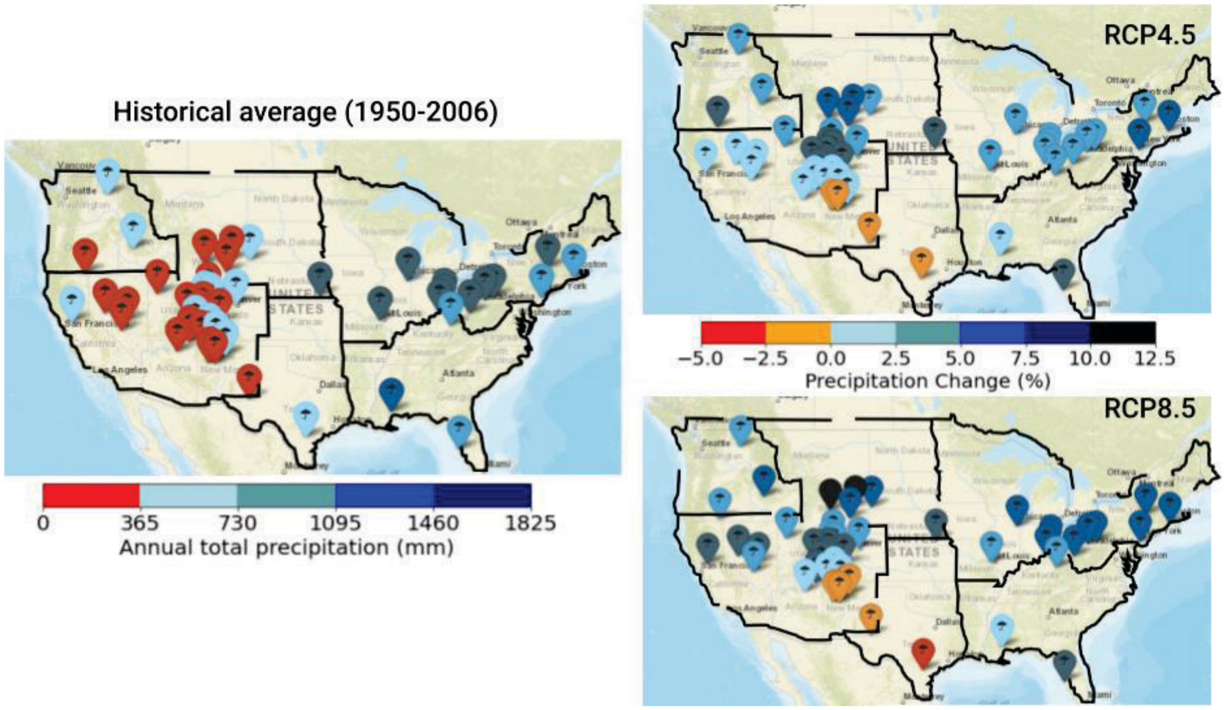


Figure 4: Annual total precipitation in the historical period (left), and the changes between RCP8.5 and RCP4.5 climate scenarios (2007-2100) and historical period (1950-2006) at LM sites over the CONUS (right). The values are computed as (Pr_sce – Pr_hist)/Pr_hist, where Pr_sce and Pr_hist

are annual average precipitation of scenarios (RCP4.5 or RCP8.5) and historical periods, respectively.

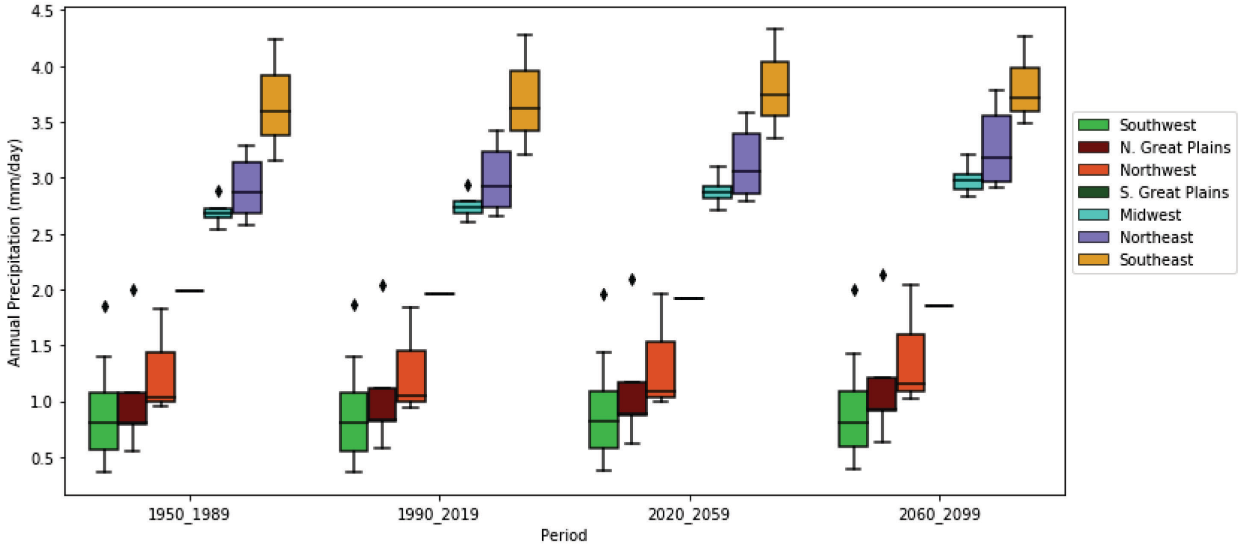


Figure 5. Box and whisker plots of precipitation changes at LM sites divided by seven geographical regions. The changes of average annual precipitation over the four periods from 1950-2099 are computed. Each box shows the statistics of climatological average precipitation at all LM sites within the geographic region. Climate projection data is the RCP8.5 scenario.

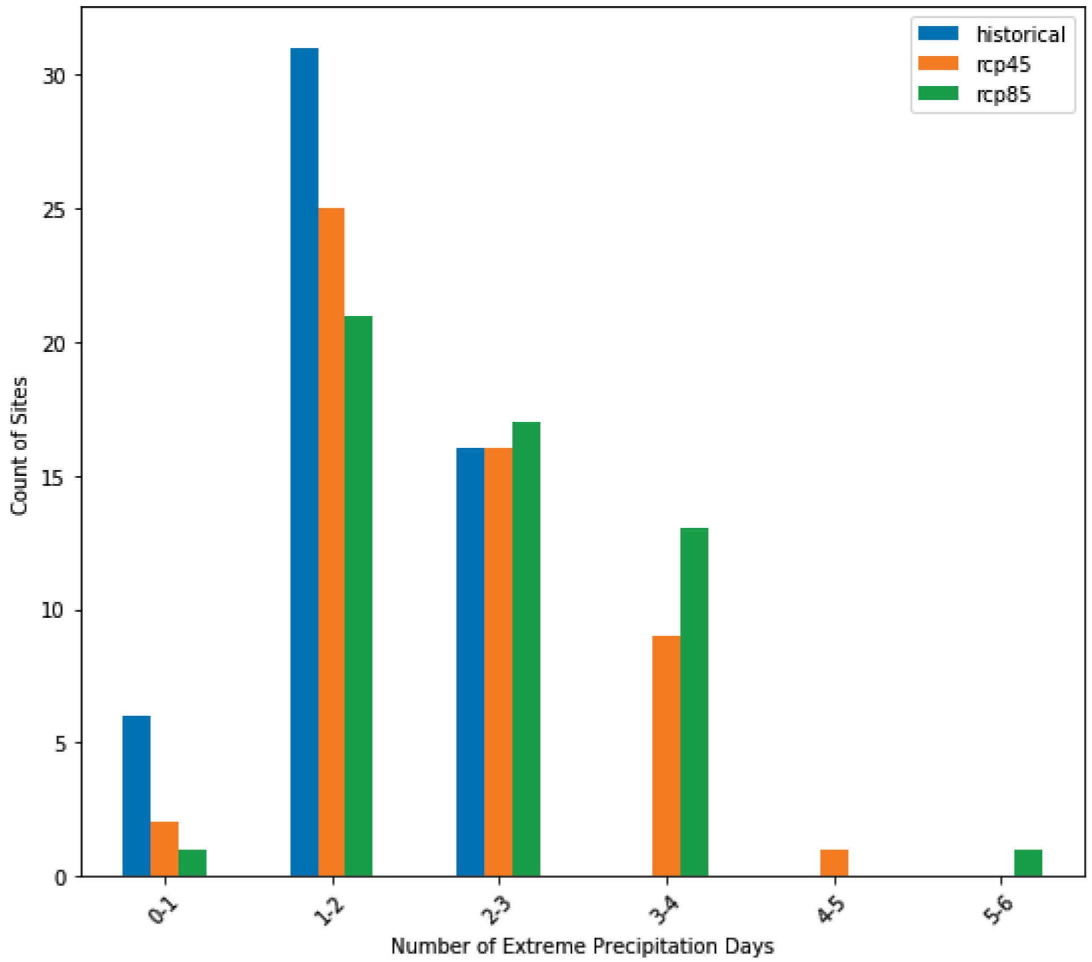


Figure 6. The counts of the LM sites with their number of extreme precipitation days, which is defined the days with precipitation in the top 1% of all days having recordable precipitation during the historical (1950-2006). Most LM sites have 1-2 extreme precipitation days, but more sites have more extreme precipitation days in the projection. The counts in the RCP4.5 (orange) and RCP8.5 (green) climate scenarios indicate that the number of extreme precipitation days increases 50%-120% in many LM sites, as compared to the historical period (blue).

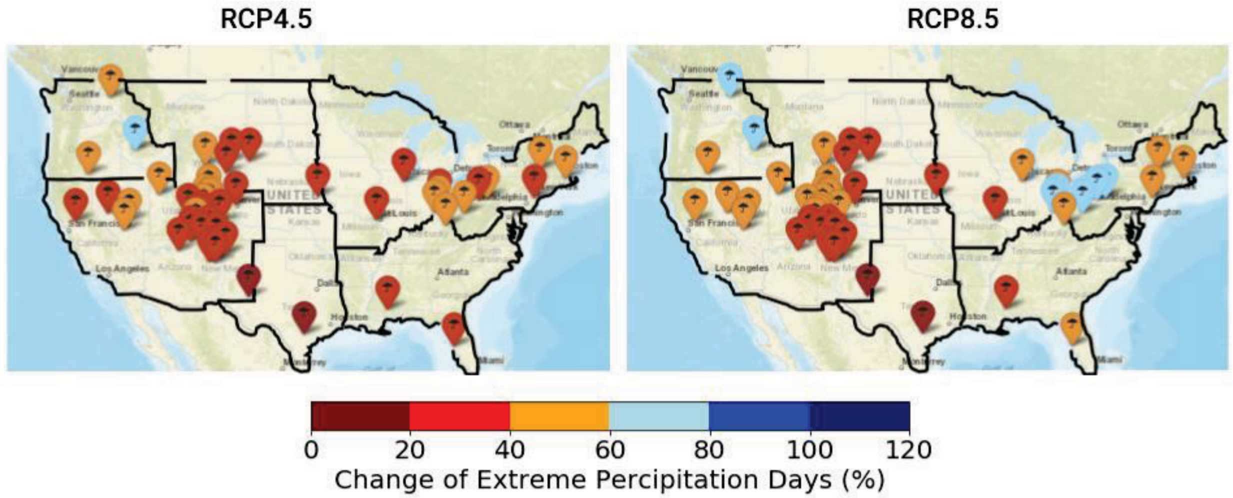


Figure 7. The change of extreme precipitation days at LM sites compared to the historical record in percentage in RCP4.5 (left) and RCP8.5 (right) scenarios.

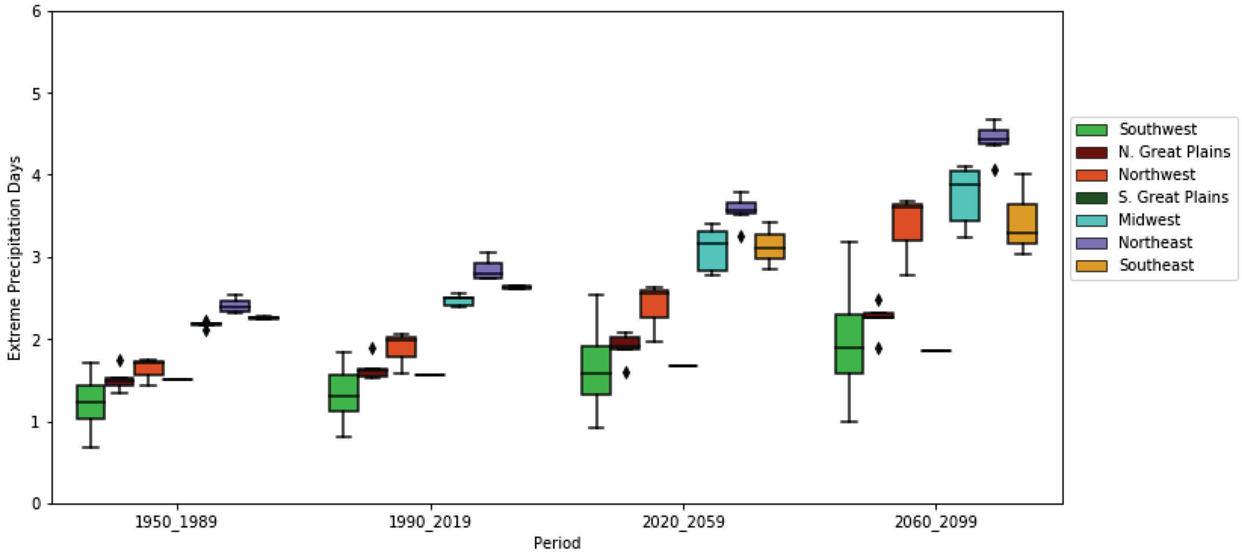


Figure 8. Box and whisker plot of extreme precipitation changes at LM sites divided by seven geographical regions. The changes of average annual precipitation over the four periods from 1950-2099 are computed. Each box shows the statistics of extreme precipitation days at multiple LM sites within each geography area. Climate projection data is the RCP8.5 scenario.

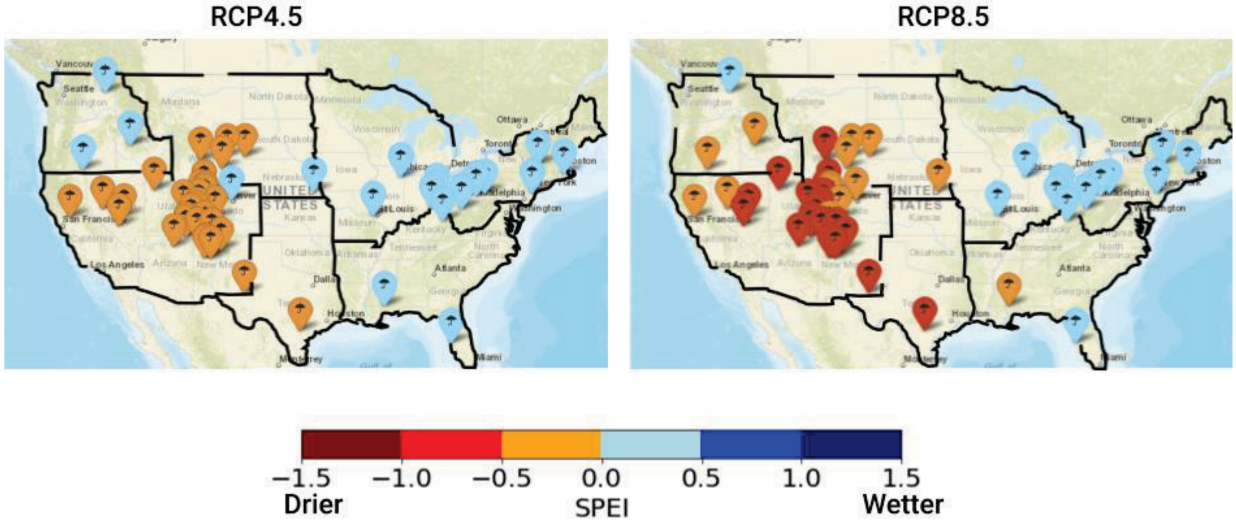


Figure 9. The SPEI projection at LM sites in RCP4.5 (left) and RCP8.5 (right) scenarios. The SPEI projections (2007-2099) are computed using the historical period (1950-2006) as the baseline. The negative (red colors) indicates the drier pattern, and the positive (blue colors) indicates the wetter pattern.

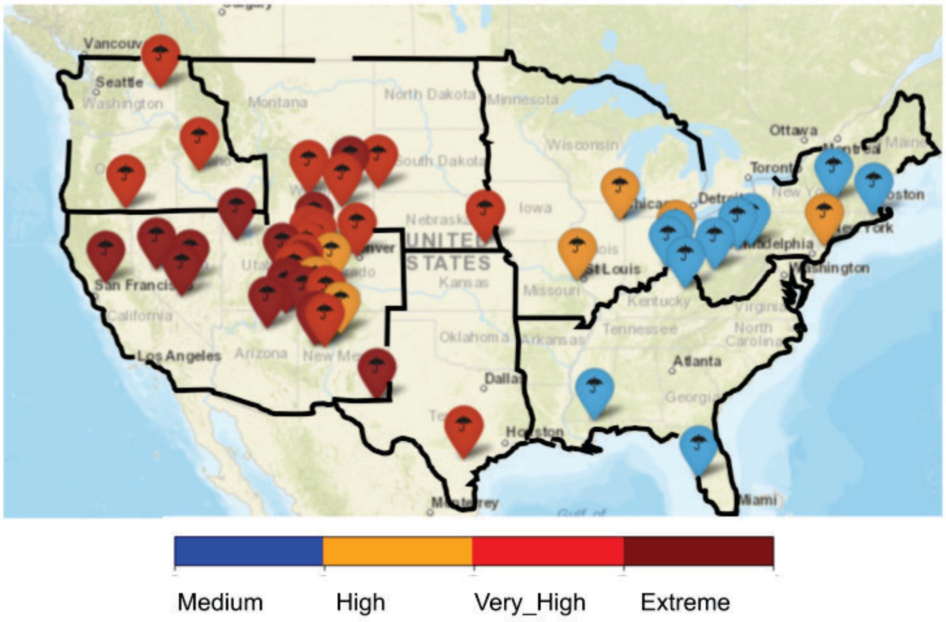
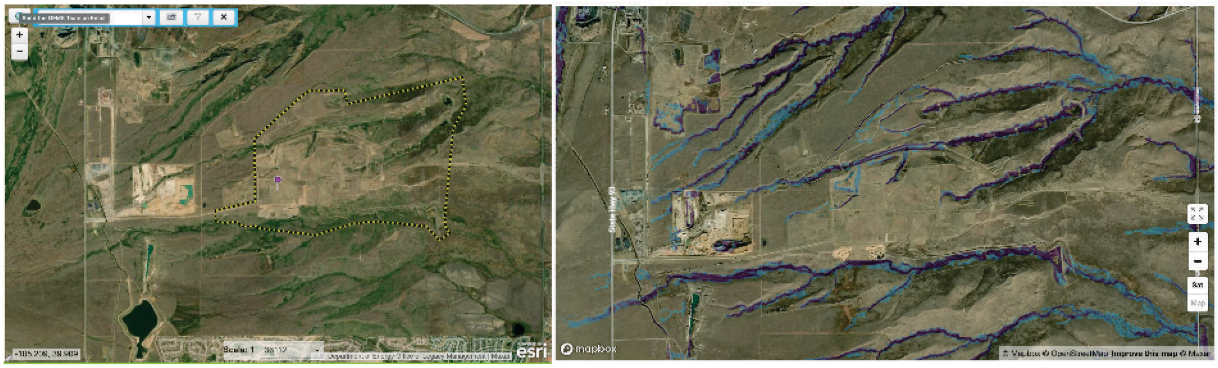


Figure 10. Upper: The EU classes of CFWI 95th percentile in the mid-late period (combination of 2045-2054 and 2085-2094) at LM sites.

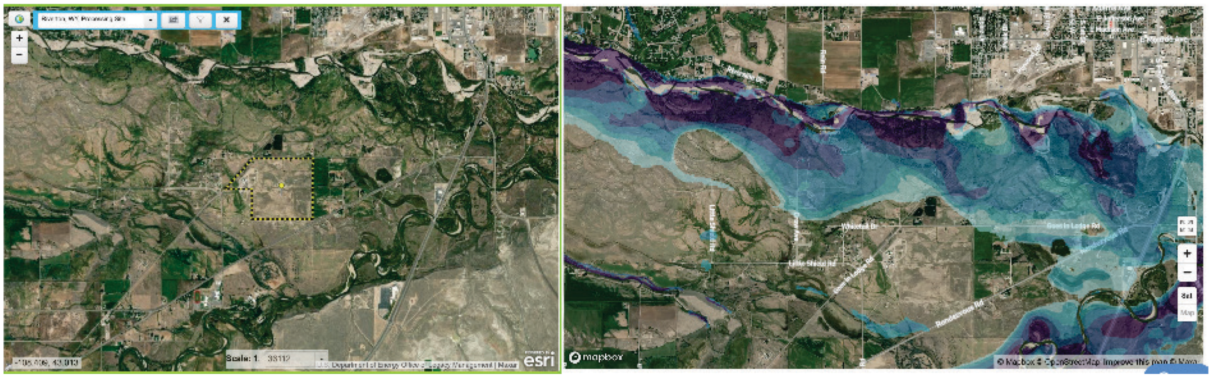
(a) (b)

Figure 11. Old Rifle (CO): (a) the site boundary from the GEMS database and (b) the flooding extent from the First Street Foundation Flood Model.



(a) (b)

Figure 12. Rocky Flats (CO): (a) the site boundary from the GEMS database and (b) the flooding extent from the First Street Foundation Flood Model.



(a) (b)

Figure 13. Riverton (WY): (a) the site boundary from the GEMS database and (b) the flooding extent from the First Street Foundation Flood Model.

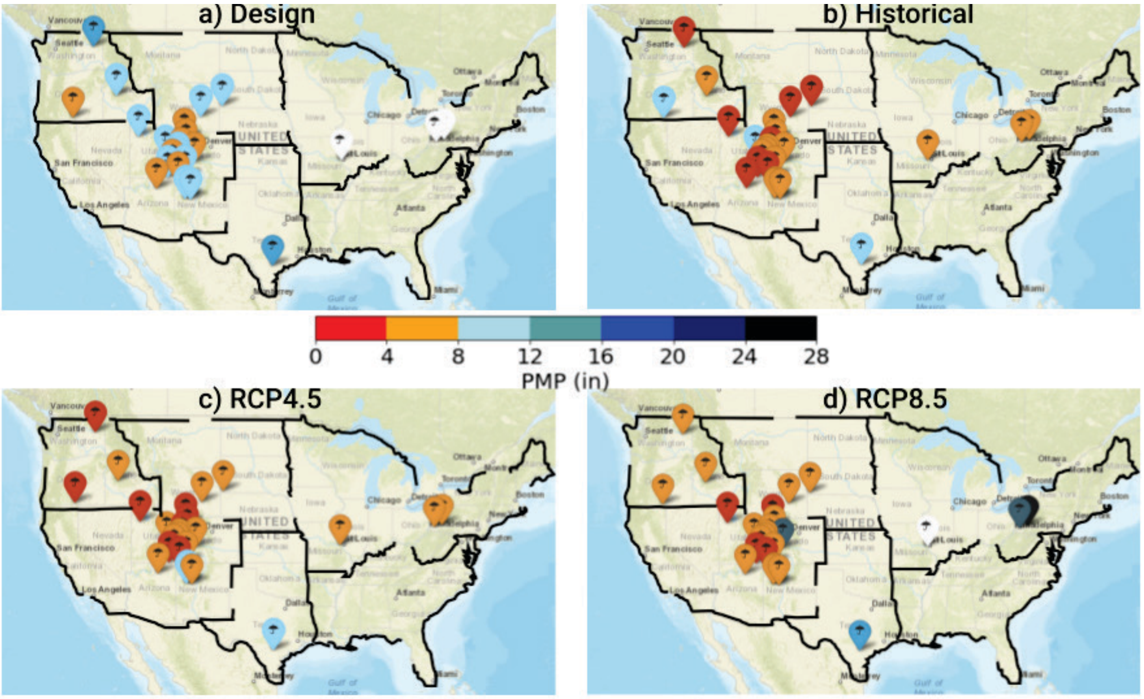


Figure 14. 24-hour Probable Maximum Precipitation at LM sites a) Design basis from site documents; b) Historical period (1950-2006); c) RCP4.5 projection period (2007-2099); d) RCP8.5 projection period (2007-2099). The white colors indicate the values are greater than 28 in.

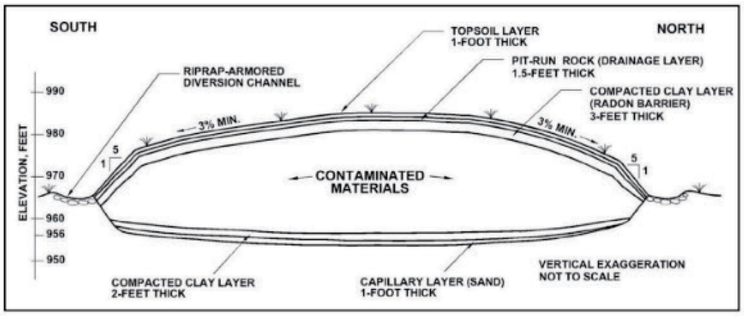
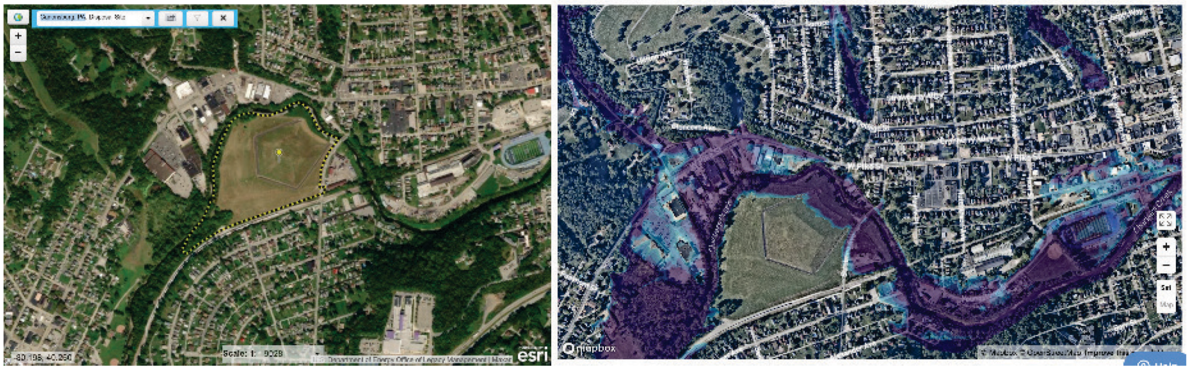


Figure 15. South-to-north cross section of the Canonsburg disposal cell.



(a) (b)

Figure 16. Canonsburg, PA: (a) the site boundary from the GEMS database and (b) the flooding extent from the First Street Foundation Flood Model. In (b), the light blue area is the flooding extent up to the depth of 1 meter, while the purple area is the one of larger than 1 meter.

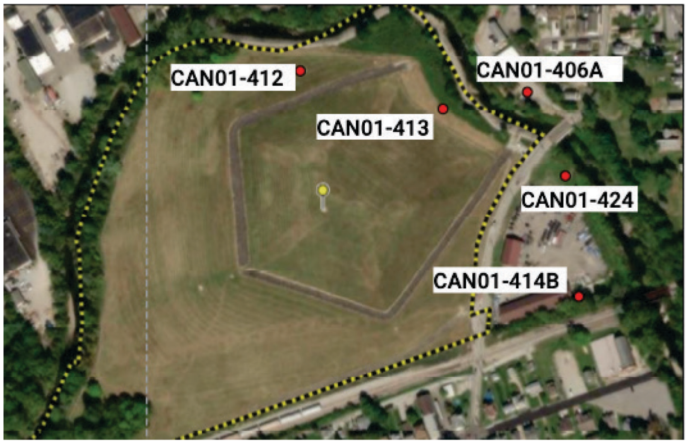


Figure 17. Aerial image of the Canonsburg, PA site and existing monitoring well locations.

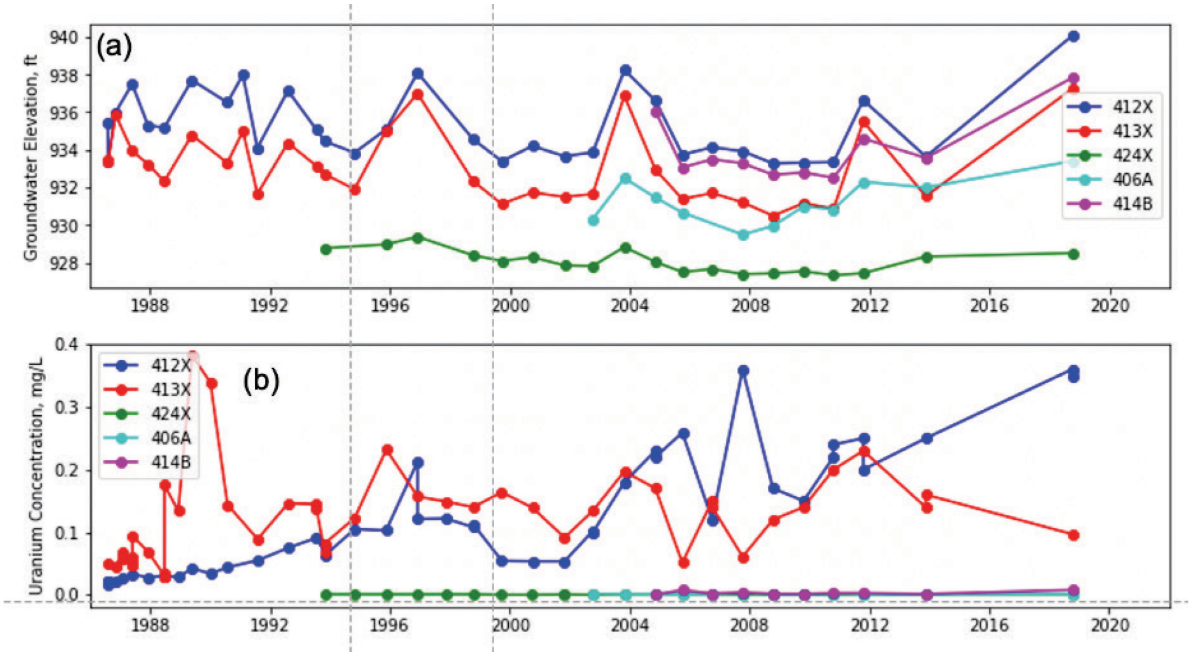


Figure 18. Canonsburg groundwater data: (a) groundwater table elevation, and (b) uranium concentrations

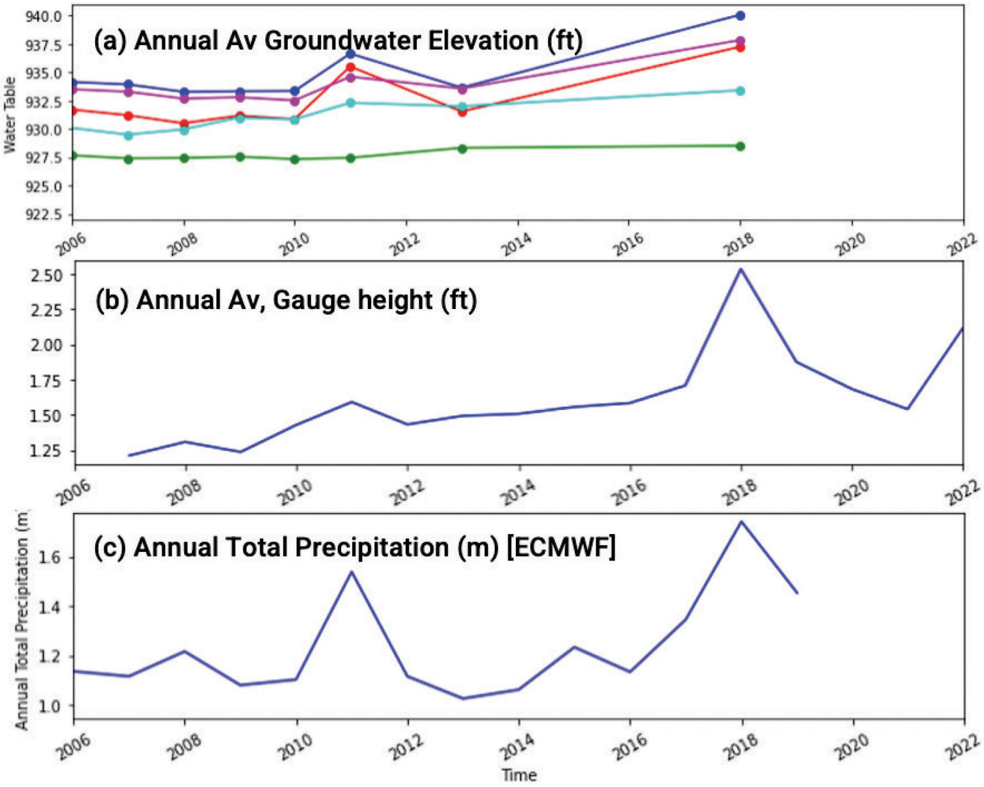


Figure 19. Canonsburg climate data: (a) Annual average groundwater table elevations (feet above mean sea level), (b) annual average gauge height of the surface water monitoring location, and (c) annual total precipitation (meter) from the ECMWF ERA5 data.

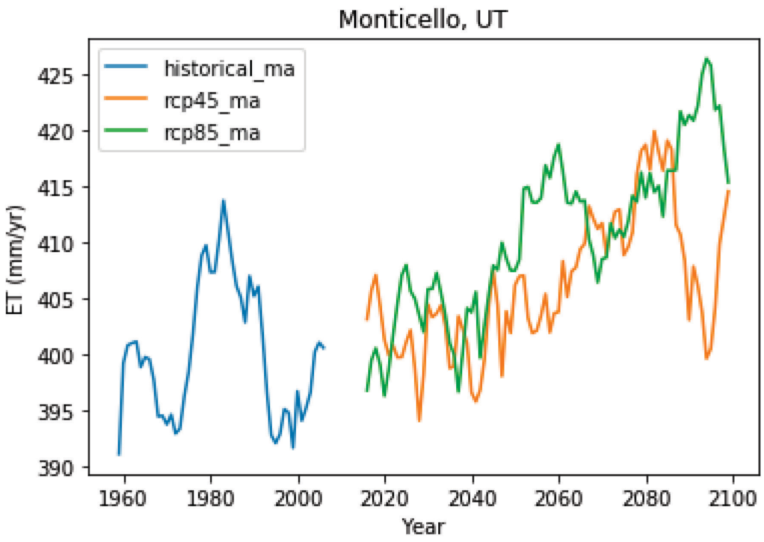


Figure 20. The 10-year moving average evapotranspiration time series in the historical, RCP4.5 and RCP8.5 scenarios at Monticello, UT. The ET data source is LOCA-CMIP5, obtained from https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html

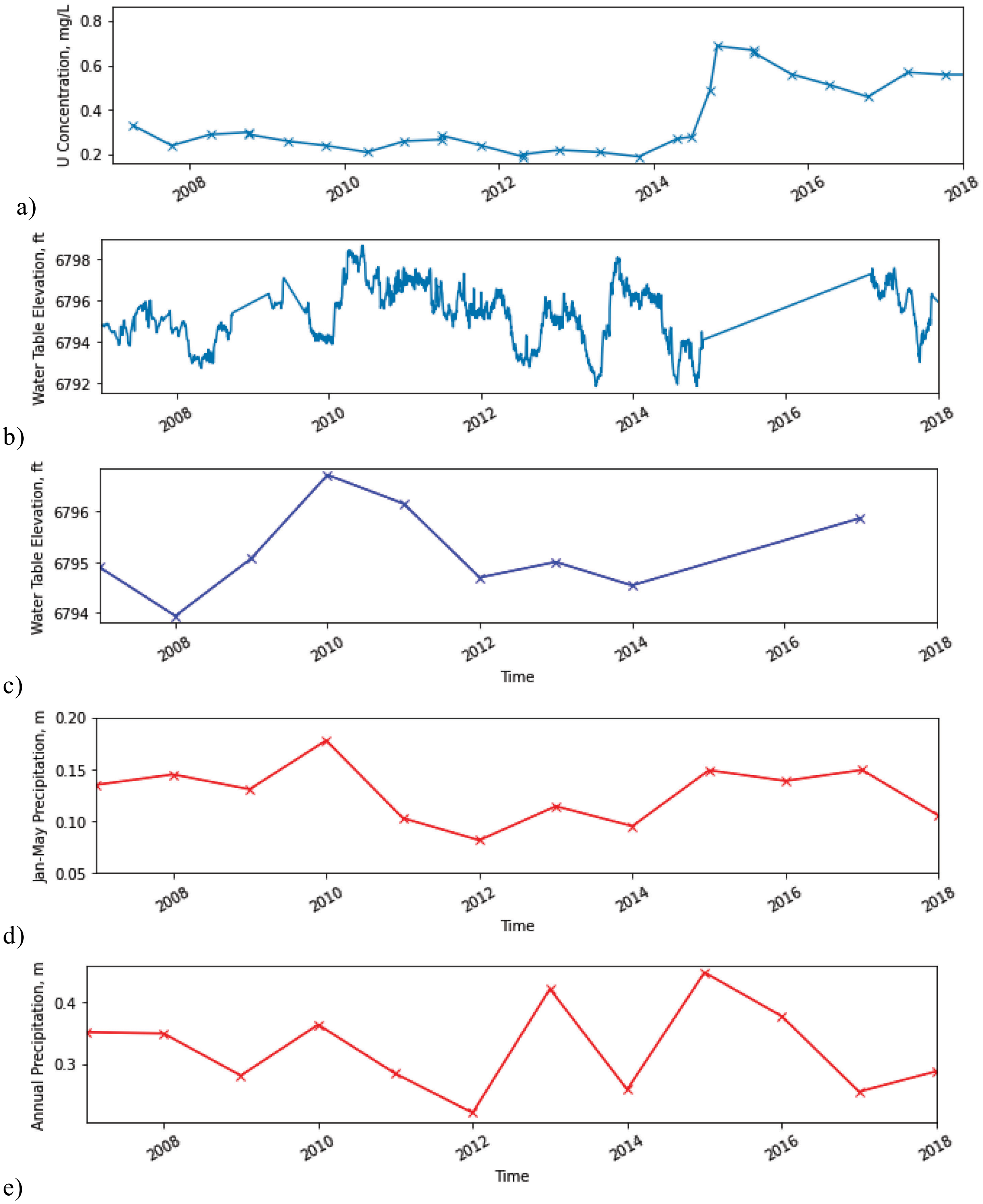


Figure 21. Groundwater datasets (Well 88-85 of Monticello, UT) in comparison with climate data: (a) uranium concentration, (b) water table elevation, (c) annual average water table elevation, (d) January-May precipitation and (e) annual total precipitation.

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Appendix A

README: Climate Data and Visualization for LM

A.1 Overview

This folder includes the climate datasets (historical/projection) and visualization for the 71 DOE-LM sites identified through the LM Site Questionnaire that were deemed to have some level of potential shifting associated with future climate change in terms of altering system performance and/or exceeding design requirements. We use the Coupled Model Intercomparison Project (CMIP) climate models (Taylor et al., 2012), which are the standard global climate model ensembles used in the US Global Change Research Program and the Intergovernmental Panel on Climate Change (IPCC). Both historical and future projection datasets (Thrasher et al., 2012) are downscaled to 28 km (0.25 degree) from the coarser 1-degree resolution GCM output.

We define the shifting score based on the historical mean, projected mean, and historical standard deviation, when the climate metrics follow a statistically normal distribution, following the approach of Werth (2016). When the distribution is skewed, we define the shifting score based on the distribution quantile.

A.2 Detailed information

- Data source: https://developers.google.com/earth-engine/datasets/catalog/NASA_NEX-GDDP#image-properties
- Scripts and tools we used to download the datasets: https://pypi.org/project/climate-resilience/
- Climate scenarios:
    - Historical (1950-2005, referred as “historical” in our dataset)
    - Projection RCP4.5 (2006-2099, referred as “rcp45” in our dataset)
    - Projection RCP8.5 (2006-2099, referred as “rcp85” in our dataset)
- Climate models: 21 global climate models, including 'ACCESS1-0', 'bcc-csm1-1', 'BNU-ESM', 'CanESM2', 'CCSM4', 'CESM1-BGC', 'CNRM-CM5', 'CSIRO-Mk3-6-0', 'GFDL-CM3', 'GFDL-ESM2G', 'GFDL-ESM2M', 'inmcm4', 'IPSL-CM5A-LR', 'IPSL-CM5A-MR', 'MIROC-ESM', 'MIROC-ESM-CHEM', 'MIROC5', 'MPI-ESM-LR', 'MPI-ESM-MR', 'MRI-CGCM3', 'NorESM1-M'
- Climate variables:
    - Average annual total precipitation (mm/day)
    - Average daily maximum two-meter surface temperature (tasmax, Celsius degree)
    - Extreme precipitation days, defined as the number of days with precipitation in the top 1% of all days having recordable precipitation (EPA definition)
    - Maximum daily precipitation (mm/day): defined as the maximum daily precipitation in each year
    - Standardized Precipitation-Evapotranspiration Index (SPEI): a diagnostic of long-term drought severity index. They are calculated in monthly temporal frequency.

    Negative values indicates drier. The data are provided by Florida Institute of Technology.
    - Extreme degree days: similar definition to the growing degree days https://mrcc.purdue.edu/gismaps/info/gddinfo.htm#:~:text=Growing%20Degree%20Days%20(GDD)%20are,or%20base%20temperature%20(TBASE) with Tbase = 93F.
    - Heating degree days: the definition can be found at https://www.eia.gov/energyexplained/units-and-calculators/degree-days.php#:~:text=Heating%20degree%20days%20(HDD)%20are,for%20the%20two%2Dday%20period.
    - Cooling degree days: the definition can be found at https://www.eia.gov/energyexplained/units-and-calculators/degree-days.php#:~:text=Heating%20degree%20days%20(HDD)%20are,for%20the%20two%2Dday%20period.
    - Wildfire: The wildfire data are EU classes (low, medium, high, etc.) based on the CFWI (Canadian Fire Weather Index). The wildfire data are provided by the Argonne National Laboratory.
    - Flooding (will be available soon if historical data can be found that is of relevance to the study)
    - Groundwater elevation and uranium concentrations (will be available soon if historical data can be found that is of relevance to the study)

- Climate metrics:
    - Hist_mean: The mean of each climate variable over 56 years of the historical period (1950-2005)
    - Hist_std: The standard deviation of each climate variable over 56 years of the historical periods
    - 1990_2019_mean: The mean of each climate variable over the recent 30 years (1990-2019). The period of 1990-2005 uses the “historical” scenario, the period of 2007-2019 uses the “rcp85” scenario.
    - Rcp45_mean: The mean of each climate variable over the 94 years of the rcp45 scenarios (2006-2099)*
    - Rcp45_max: The maximum of each climate variable over the 94 years of the rcp45 scenarios (2006-2099)**
    - Rcp85_mean: The mean of each climate variable over the 94 years of the rcp45 scenarios (2006-2099)
    - Rcp85_max: The maximum of each climate variable over the 94 years of the rcp45 scenarios (2006-2099)
    - Shifting_rcp45: The shifting of each climate variable in the rcp45 scenario compared to the historical period. The shifting_index is defined as the z-score,

    which is computed as (rcp45_mean - hist_mean)/hist_std. The shifting_index is quantified as ***
        - shifting_index < 0, labeled as 0 or “negative” (rcp45_mean < hist_mean)
        - 0<shifting_index<1, labeled as 1 or “low” (hist_mean < rcp45_mean < hist_mean + 1* hist_std)
        - 1<shifting_index<2, labeled as 2 or “medium” (hist_mean + 1* hist_std < rcp45_mean < hist_mean + 2* hist_std)
        - shifting_index > 2, labeled as 3 or “high” (rcp45_mean > hist_mean + 2*hist_std)
    - Shifting_rcp85: Same for shifting_rcp45, but with rcp85_mean for rcp85 scenario.

Exceptions:

* The rcp26_mean and rcp26_max are presented because our SPEI dataset only has historical, rcp26 and rcp85 scenarios

** The minimum value is reported here for SPEI because negative value indicates drier condition by the definition of SPEI.

*** For the extreme precipitation days and maximum daily precipitation, we used the median value because these two climate variables are not normally distributed. The shifting_index is computed by the median, 70 percentile and 95 percentile of the historical period to be consistent with the shifting index for other variables

        - shifting_index < 0, labeled as 0 or “negative” (rcp45_median < hist_median)
        - 0<shifting_index<1, labeled as 1 or “low” (hist_median < rcp45_median < hist_70percentile)
        - 1<shifting_index<2, labeled as 2 or “medium” (hist_70percentile < rcp45_median < hist_95percentile)
        - shifting_index > 2, labeled as 3 or “high” (rcp45_median > hist_95percentile)

- Calculation methods:
    - The ensemble mean among 21 climate models are calculated and reported (for average total precipitation, average daily maximum temperature and average SPEI)
    - For extreme precipitation days and maximum daily precipitation, the climate variables are computed for each individual climate model first, then the mean of those ensemble models are reported. This is because the daily extreme precipitation will be diminished if ensemble mean is used for computing those variables directly.

- Sites: Please see the appendix at the end of this README, and please refer to the LMsites_handoff.csv file for more information
- File organization:
    - LMsites_handoff.csv
    - Climate variable database
        - Annual_average_tmax_stats.csv
        - Annual_total_precipitation_stats.csv
        - Drought_index_stats.csv
        - Extreme_precipitation_days_stats.csv
        - Maximum_daily_precipitation_stats.csv
        - Extreme_degree_days_stats.csv
        - Heating_degree_days_stats.csv
        - Cooling_degree_days_stats.csv
    - One directory per site
        - Aggregated climate metrics in the historical and projection periods for five climate variables in csv format (stat_matrix.csv)
        - Color-coded shifting_index in HTML format (stat_matrix_static_colors.html, you may need to download it and open with any browser)
        - Visualization of annual total precipitation (annual_total_precipitation_timeseries.png)
        - Visualization of annual average Tmax (annual_average_tmax_timeseries.png)
        - Visualization of extreme precipitation days (extreme_precipitation_days_timeseries.png)
        - Visualization of maximum daily precipitation (maximum_daily_precipitation_timeseries.png)
        - Visualization of drought index (drought_index_timeseries.png)
    - Wildfire
        - LM_CFWI_euClass_RCP85_RCP45.csv
        - LM_extracted_CFWI_timeseries_RCP4.5_annual_mean.csv
        - LM_extracted_CFWI_timeseries_RCP8.5_annual_mean.csv