The Impact of Climate Change: Projected Adaptation Costs for Boulder County, Colorado

Resilient Analytics

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Resilient Analytics, Inc

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Study Coordinator: Paul S. Chinowsky, PhD

Contact:
Resilient Analytics, Inc.
814 Trail Ridge Drive
Louisville, CO 80027
303-359-2401
pchinowsky@resilient-analytics.com
www.resilient-analytics.com

Executive Summary

Climate change trends are and will have a fiscal and human impact on Boulder County over the next several decades. The current study quantifies the potential impact on Boulder County over infrastructure, human, and natural sectors to provide a broad understanding of the potential impact of climate change. The study incorporates multiple climate scenarios projections through 2050 to provide a range of possible outcomes and fiscal impacts. The cost projections reflect a comparison of the environment in which the infrastructure or natural environments have historically existed or in which they were designed to operate with the projected future environment. The generation of these cost estimates reflects engineering and design-based guidelines that focus on the physical impacts of climate factors on the infrastructure and natural assets.

While a reactive or wait-and-see approach can be adopted, this policy approach is projected to result in notably higher maintenance costs as well as economic impacts from service interruptions across multiple sectors. Therefore, a proactive adaptation approach is recommended as a preferred alternative to reduce costs and subsequent economic impacts.

In summary, the estimated total cost of adaptation for mitigating only some of the potential effects of climate change across the geographic area of Boulder County through 2050 is conservatively placed at $96 million to $157 million for the median and high impact scenarios for the areas looked into with the City of Boulder incurring $16 million to $36 million of these adaptation costs. Additionally, increased demand for cooling in buildings will add another $3.1 million to $4.5 million in direct costs per year for median and high projections. Urban drainage improvements could increase this cost by an additional $16.2 million depending on county versus incorporated city responsibilities. These totals are presented with the understanding that different jurisdictions may be responsible for different impacts within this geographic area.

Additional costs not included in this total include: residential costs for installing air conditioners in residences where they are not currently installed, increasing water availability during extreme drought events, removal of dead trees resulting from future mountain pine beetle infestation, public health costs due to increased hospital costs, and additional economic costs due to business interruptions during infrastructure repair and replacement periods.

The timeline for incurring these costs begins within the current decade. Infrastructure assets such as bridges and primary roads have design lifespans that cover the entire scope of this study. Therefore, current maintenance and development plans should already include new design guidelines. Similarly, extreme heat events are projected to increase over the next decade. Thus, planning for public health issues should be an immediate concern.

While the focus of this study is on future climate projections and impacts, using the baseline we have chosen, a climate trend is already appearing and influencing the current period. Therefore, implementing adaptation policies to mitigate potential impacts should be considered as soon as possible to adapt systems that will be vulnerable under future and current climate conditions.

Contents

Introduction

The impact of climate change on Boulder County includes all aspects of daily life including impacts on infrastructure, human health, energy demands, and agriculture among others. Roads, buildings, and bridges are all susceptible to changes in operating conditions including drought, temperature, and precipitation. With several climate parameters already showing trends of change versus historic records such as increased temperatures, the time to consider decisions regarding potential impacts of climate change has already arrived. This analysis supports climate impact decision-making by providing a projected cost of climate impacts on assets geographically located in Boulder County through 2050 with an additional highlight on the City of Boulder. The cost projections reflect a comparison of the historic operating environment in which the infrastructure was built (temperature, precipitation, and flooding), and the projected future operating environment. In cases where the environmental conditions of the future operating environment diverge from the conditions in which the infrastructure was intended to operate, cost estimates are calculated to both repair the damages as well as put in place adaptations to mitigate the occurrence of these damages. This is done under multiple IPCC (Intergovernmental Panel on Climate Change) approved climate scenarios plus a historic baseline to get a range of potential cost scenarios. The analysis is completed on an annual basis to get an annual and cumulative total.

The analysis is based on an evaluation of cost through two distinct strategies, or policy approaches: reactive and proactive. The proactive strategy, *adapt*, is based on incorporating adaptation measures to make the infrastructure resilient to climate impacts by changing specific elements during design and construction. The adapt strategy focuses on changes to design standards to increase resilience. This is the preferred approach to addressing climate impacts as it minimizes the secondary effects of maintenance delays, health impacts, and economic implications. The reactive approach, *no-adapt*, does not anticipate future climate change impacts. Rather, any climate impact is addressed through increased maintenance on a yearly basis to repair damages that are anticipated to occur because of changing climate parameters. In both strategies, the calculated costs are based on the actions needed to maintain the original design-life of the infrastructure. To develop the subsequent costs presented here, a three-step process was incorporated in the study.

First, the projected climate impact on the specific region is examined. The study uses a combination of 1/4- and 1/16-degree grid-based climate scenarios to obtain the predicted future values of climate stressors including temperature and precipitation. These values are compared to historic climate data to obtain increments of change due to projected changes in climate parameters. The historic climate data represents the locally observed climate from 1980–2009[1]. The projection of this data forward into future years represents a baseline condition where no climate change would occur. The difference between this historic baseline and the climate model projections forms the basis for determining the difference between the design environment and the projected environment in the study.

Second, the study incorporates the Infrastructure Planning Support System (IPSS) to determine potential impacts on the specific elements being evaluated[2]. IPSS incorporates engineering-based analysis to determine specific impacts from individual climate stressors. These analyses are based on a combination of materials studies, case studies, and historical data. The system compares the historic climate data to which the infrastructure designs are assumed to be built, with the future operating climate conditions under which the elements will need to perform.

Finally, based on the type of impacts being analyzed, the potential cost of climate impacts is calculated through; 1) costs that are projected maintenance and retrofit costs and/or changes in design costs, or 2) costs that are projected to be incurred due to changes in climate conditions. The first case covers infrastructure elements such as roads and bridges. In these cases, the baseline costs are the maintenance costs that would be anticipated if the historic climate patterns were to remain consistent for future periods of operation. These costs associated with the historic climate levels are then compared with the additional maintenance and adaptation costs that are projected to be incurred due to changes in operating conditions. Specifically, maintenance and adaptation changes resulting from changes in precipitation and temperature are compared to the historic costs.

The second case covers areas such as cooling centers for heat events and wildfire mitigation which are incurred to protect assets such as homes or protect human health. Similar to the previous case, historic climate scenarios used to establish baseline expected costs. Projected changes in climate parameters are then used to determine increases in mitigation requirements such as increases in the need for cooling centers or increases in wildfire mitigation. In both cases, results are presented in terms of climate risk, adaptation strategies, and impact timelines.

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[1] Livneh, B., T. J. Bohn, D. W. Pierce, F. Munoz-Arriola, B. Nijssen, R. Vose, D. R. Cayan, and L. Brekke, 2015: **A spatially comprehensive, hydrometeorological data set for Mexico, the U.S., and Southern Canada 1950-2013**. Scientific Data, v. 2, article 150042 (2015).

[2] Chinowsky P, Arndt C (2012) Climate change and roads: A dynamic stressor–response model. Rev Dev Econ 16(3):448–462.

The overall process described here is reflected below in Figure 1. As illustrated, the same process is used for each element in the study.

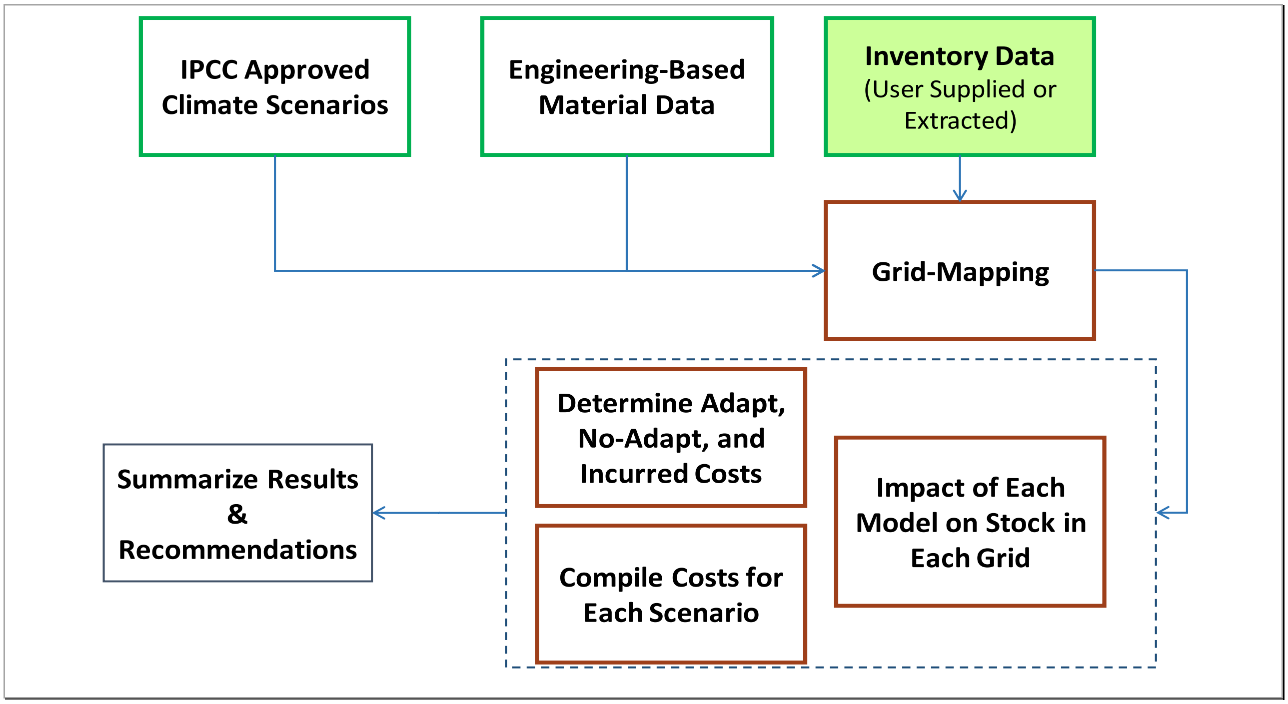

Figure 1: IPSS overall process diagram

Climate Data

The climate change projections utilized in this study were obtained from data generated by General Circulation Models (GCMs) approved by the Intergovernmental Panel on Climate Change. The GCMs provide climatological data for future climate change scenarios through 2100. The data used in this analysis include the available RCP 4.5 (mid-level impact) and 8.5 (high-level impact) scenarios for each GCM, which represent different scenarios of future development based on the accepted definitions of the Intergovernmental Panel Fifth Assessment Report[3].

To provide a robust analysis of possible climate change projections, all GCM data sets approved by the IPCC containing complete data projections for climate data on the region being studied were used in the current analysis. In total, 21 GCMs with 1/4-degree spatial data and 5 GCMs with 1/16-degree spatial data are used in the IPSS analysis. Each of these climate models contains two RCP scenarios (4.5 and 8.5)

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[3] Stocker, T. (Ed.). (2014). Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

to create the total set used for the analysis. Each scenario includes predictions for precipitation, humidity, and temperature.

Inventory Data

The inventories used in this study originate from Boulder County and City of Boulder sources unless otherwise specified. The individual offices with responsible oversight of data such as property assessments and road maintenance were consulted to provide accurate inventories as of the date of the study. A combination of database entries and GIS maps were used to locate infrastructure elements. Non-infrastructure data such as mortality rates were obtained using public data sources as detailed in the following sections.

Sector Impacts

The following sections detail the potential impacts of climate change on Boulder County elements. The impacts are based on documented, available science and multiple climate scenarios. The cost estimates are preliminary, conservative estimates based on an initial collection of available information. In each case, the methodology described above was used as the base approach to determining potential impacts and the costs of proactively adapting to mitigate damages. Individual descriptions are provided with additional detail to provide an overview of how specific costs were generated for the study. In each case, publicly available documents and sources are used for inventories, cost factors, and potential effects from climate factors.

References to papers and reports with greater detail on methodologies are provided to allow for validation of the results as well as comparisons to other studies. Additional documentation on the IPSS system is referenced to allow for greater understanding of the technical approach to generating costs.

The sectors included in this section are as follows:

- Wildfire – An analysis of potential increase in wildfire danger and the costs associated with mitigating damage to structures.
- Mountain Pine Beetle – An analysis of the potential for a reoccurrence of a mountain pine beetle infestation due to temperature changes in the Boulder County region.
- Drought – An analysis of the potential increases in drought conditions in the Boulder County region from 2020-2050.
- Human Health – An analysis of potential increases in mortality and morbidity rates due to extreme heat events, increased allergen exposure, and increased vector-borne disease exposure.
- Urban Drainage – An analysis of impacts on urban drainage and flooding due to changes in precipitation events.
- Roads – An analysis of impacts to road infrastructure from changes in temperature and precipitation throughout Boulder County.
- Bridges – An analysis of requirements to retain bridge safety due to increases in flow rates of streams over which bridges are located.
- Buildings – An analysis of potential changes in energy demand as well as physical damages to non-residential buildings located in Boulder County.

Points that should be considered when reading the results of the analysis:

- Conservative Results – The costs presented in the analysis may be conservative since the historic values from which the incremental climate costs are calculated are not a native baseline. Specifically, the historic costs are based on thirty years of climate data that may already have a climate impact signal.
- Existing Trends – Although the results in the study focus on upcoming decades, the current rise in temperature signals are resulting in increased costs in some sectors. Thus, the analysis should not be read as impacts that will appear a decade from now, but rather should be read as a continuation of current trends.
- Probabilities – The climate scenarios used in this analysis should be considered as independent. There is no linkage from one set of climate data to another. Therefore, the data should be read as trends rather than probabilities. The results may reflect that 65% of the models have a particular indication, but that should not be interpreted as a 65% probability. Rather, it is a body of evidence that is indicating a trend.
- Intensity Effects – Depending on the sector that is being addressed, precipitation impacts may focus on the intensity of an individual precipitation event, or focus on the total accumulation of precipitation over a given time period such as a month or year. This is important as a segment of models may project similar total precipitation amounts in the future, but the total may occur through fewer, but more intense, precipitation events. This is relevant for items such as urban drainage where the intensity of events is the driving parameter in infrastructure design.
- Costs versus Impacts – Where possible, potential costs are identified as impacts from climate change. These are areas where specific costs can be directly associated with damages to individual sector elements. For example, the impact on roads has an associated cost due to specific maintenance or adaptation efforts that will need to be put in place. However, there are sectors where impacts are indirect and the costs from these impacts will be absorbed in other sectors. For example, an increase in drought months affects wildfire probability as well as agriculture production and water supply. These secondary sectors absorb the impact costs and are not presented directly within the sector.

Wildfire

In the last 30 years Boulder County has witnessed numerous wildfires that have caused extensive damage to county lands and Boulder County structures. In total, wildfires have burned more than 16,000 acres and destroyed more than 260 structures[4]. Under projected climate scenarios, extended periods of drought and higher temperatures could lead to an increase in wildfire activity and result in greater damages.

To project potential wildfire damage, the Keetch-Byram Drought Index (KBDI) was used in conjunction with the historical fire record to project the number of annual wildfires and the corresponding damages. The analysis was conducted across the geographic area of Boulder County with the understanding that different jurisdictions may be responsible for different fire control efforts within this area. The KBDI is used in this study as it is the most widely used index for wildfire monitoring and prediction[5]. Other indices exist for drought-specific predictions such as the Palmer Drought Severity Index which is used in the drought sector. However, KBDI is used for wildfires to remain consistent with industry practices. The KBDI index is categorized into four different severity levels indicating the amount of risk for forest fires that exists for a given area (Table 1)[6].

KBDI Range	Fire Potential
0-200	Low
200-400	Moderate
400-600	High
600-800	Very High

Table 1: KBDI severity levels

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[4] "Wildfires." Boulder County, www.bouldercounty.org/disasters/wildfires/.

[5] Heim, Richard R. "A Review of Twentieth-Century Drought Indices Used in the United States." *Bulletin of the American Meteorological Society*, vol. 83, no. 8, 2002, pp. 1149–1165., doi:10.1175/1520-0477(2002)083<1149:arotdi>2.3.co;2.

[6] Srinivasan, Raghavan, and Balaji Narasimhan. "Estimation of KBDI (Drought Index) in Real-Time Using GIS and Remote Sensing Technologies." *2001 Sacramento, CA July 29-August 1,2001*, 2001, doi:10.13031/2013.3975.

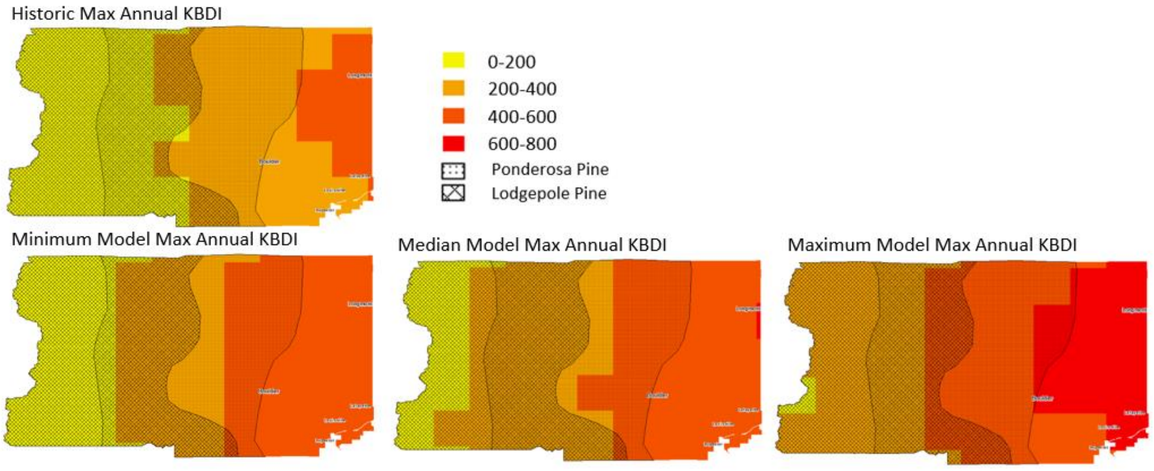

Figure 2: Boulder County maximum KBDI maps through 2050.

The historic and projected changes in KBDI for Boulder County are illustrated in Figure 2. As illustrated, the maximum KBDI increases for the majority of Boulder County under all climate models. This indicates that the level of threat for the County increases based on the projected changes from the climate models. The areas of ponderosa pine that are closest to the City of Boulder are especially vulnerable. Additionally, the threat level extends to higher elevations where a lower risk previously existed. This extension of the at-risk area could expose areas previously not prone to forest fires to new threats and potentially include areas where mitigation has not been as high a priority.

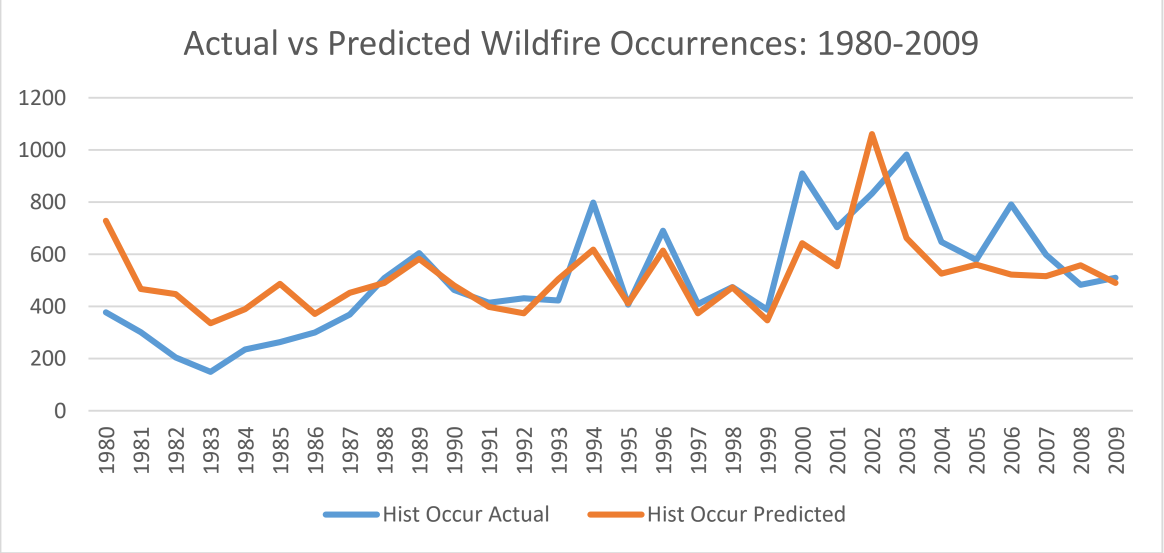

Figure 3: Historic, predicted, and actual wildfire occurrences

In order to estimate these changes in wildfire occurrences, a regression model was implemented to correlate the annual number of wildfire occurrences with the average spring-summer KBDI. In order to validate this relationship, the documented number of wildfires in Colorado was compared to the predicted number of wildfires based on the relationship with historic KBDI.

Figure 3 shows that the relationship established by KBDI and wildfire occurrences can accurately predict the number of wildfire occurrences in a given year. Overall, the average annual number of fire occurrences over the 30-year historical period differed by only 1.2%.

In order to predict the future changes in wildfire occurrences under climate change, the KBDI relationship was applied to the Localized Constructed Analogs (LOCA)[7] climate scenarios and compared to historical records. This group of scenarios was used as they project climate parameters at a 1/16th degree spatial unit. This allows for a finer analysis of areas which may be at risk. The results of this analysis are presented below (Table 2).

Wildfire Projections 2020 to 2049	Wildfire Occurrences	Wildfire Area (acres)	Percent Change
Historic	389	19,179	0%
CanESM2_4.5	450	22,212	16%
CCSM4_4.5	571	28,163	47%
GISS-E2-R_4.5	495	24,390	27%
HadGEM2-ES_4.5	668	32,937	72%
MIROC5_4.5	497	24,528	28%
CanESM2_8.5	463	22,826	19%
CCSM4_8.5	556	27,407	43%
GISS-E2-R_8.5	572	28,188	47%
HadGEM2-ES_8.5	722	35,609	86%
MIROC5_8.5	569	28,060	46%
RCP 4.5 Average	**536**	**26,446**	**38%**
RCP 8.5 Average	**576**	**28,418**	**48%**

Table 2: Wildfire projection results

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[7] "LOCA Statistical Downscaling." *LOCA Statistical Downscaling (Localized Constructed Analogs)*, loca.ucsd.edu/.

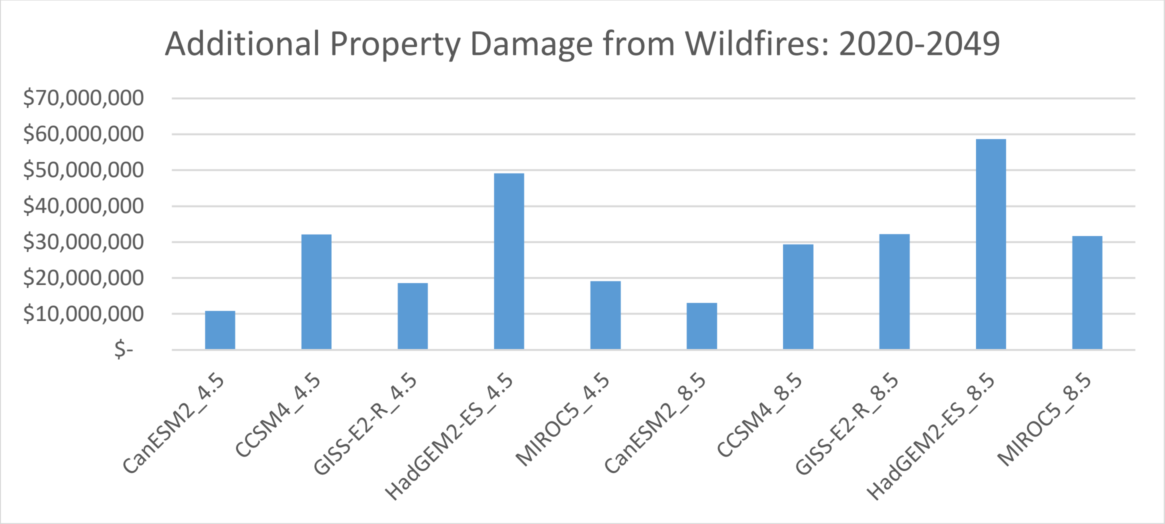

Figure 4: Additional property damage from wildfire projections

As illustrated, the number and area of wildfires increases in all scenarios from 2020-2049. The predicted cost of property damage also increases under all scenarios.

Figure 4 shows the estimated increased cost of property damage for each climate scenario over historic levels. Historically, the total Boulder County property damage involved the destruction of 260 structures between 1980-2009 for an estimated value of $68 million based on risk valuation[8].

It is projected that changes in climate conditions will result in an additional property damage cost of $10 million to $58 million over the historic average from 2020-2049 depending on the climate scenario. These costs only reflect the costs of household property damage. The costs do not include other direct and indirect costs of wildfire such as suppression and environmental damages.

Boulder County has over 5,900 households that are located in wildfire prone areas. The total value of those properties is over $1.5 billion[9]. Boulder County's Building and Land Use Codes require individuals constructing a new home or remodeling an older home to implement a Wildfire Mitigation Plan, which includes the creation and maintenance of effective defensible space. Current home owners are encouraged, but not required, to create and maintain a defensible space. Defensible space being the area between the house and where an oncoming wildfire can be potentially stopped from damaging the structure. The defensible space requires vegetation to be managed to reduce wildfire threat and allow

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[8] Botts, Howard, Jeffery, Tom, and Lindfors, Zach (2016). 2016 CoreLogic Wildfire Hazard Risk Report, CoreLogic.
[9] USBoundary.com - U.S. area boundary, data, graphs, tools and services, www.usboundary.com/.

firefighters to safely defend the house[10]. Currently, the Boulder Wildfire Mitigation program encourages homeowners to mitigate potential fire risk by providing cost-sharing towards mitigation efforts[11]. Empirical data from this program has found that an average cost for mitigating fire risk is $3,399 per household. This number will vary by household and circumstances, but it can serve as a planning number for estimating overall costs. Given the number of households that are currently in wildfire prone areas and the average cost to protect a household from wildfire, the total cost for household fire mitigation is estimated to be as high as $20.25 million.

In addition to the threat to homes, the geographic area covered by this study includes over 77,000 acres of forest that may require wildfire treatment according to the Colorado Wildfire Mitigation plan. This forest is managed under different jurisdictions depending on location, but the overall risk should be considered when evaluating increasing wildfire danger in Boulder County.

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[10] "Wildfire Mitigation FAQ." Boulder County, www.bouldercounty.org/disasters/wildfires/mitigation/frequently-asked-questions/.

[11] Boulder County Wildfire Partners - http://www.wildfirepartners.org/

Mountain Pine Beetle

From 1996 to 2010, 122,455 acres of forest were affected by the mountain pine beetle (MPB) in Boulder County[12]. Current research shows that warming temperatures and increasing drought conditions are driving MPB populations upwards[13]. This analysis is meant to give Boulder County a general vulnerability assessment to the MPB, given changes in climate and how they affect MPB populations.

The focus of MPB projections is the projected change in temperature as the single year lifespan of the MPB is directly influenced by temperatures at specific times during the year. Warmer temperatures favor beetle activity, increase the stress level for attacked tress, and speed the development of the beetle. Similarly, extreme cold temperatures in fall, winter and spring increase larval mortality. Cold temperatures in the fall and spring are particularly effective in killing larvae because the beetles are not completely cold-hardened. However, drought conditions can cause stress in trees which limits the trees resistance to the beetle. When warm temperatures and drought conditions both exist, local beetle populations can erupt due to multiple positive feedbacks[14].

Figures 5-7 summarize the trends in climate metrics that are important to MPB outbreaks. Specifically, this data represents the vulnerable grids within Boulder County in which ponderosa pine and/or lodgepole pines are present. See Figure 2 in the Wildfire section for pine species areas within Boulder County.

As illustrated, the minimum temperatures in October and March are significantly higher under climate projections than historic levels[15]. The historic time series being the average annual temperatures from 1980 to 2009 projected forward as a comparative baseline for the future climate. The historic baseline is an assumption that previously experienced temperatures are representative for the future if no climate change occurs. The trend away from the historic baseline may lead to less larval mortality and thus a stronger MPB population. MPB populations exist in one of four stages: endemic, incipient epidemic, epidemic and post epidemic. MPB normally exist as endemic populations. Under endemic conditions the MPB is restricted to suppressed and/or damaged trees in which they colonize in combination with other bark beetle species. Incipient epidemic populations are those that have

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[12] Mountain Pine Beetle on the Colorado Front Range, U.S. Forest Service. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5340091.pdf

[13] Bark Beetles and Climate Change in the United States | Climate Change Resource Center, www.fs.usda.gov/ccrc/topics/bark-beetles-and-climate-change-united-states.

[14] Chapman, Teresa B., et al. "Spatiotemporal patterns of mountain pine beetle activity in the southern Rocky Mountains." Ecology, vol. 93, no. 10, 2012, pp. 2175–2185., doi:10.1890/11-1055.1.

[15] Historic period is from 1980 to 2013 and is projected forward

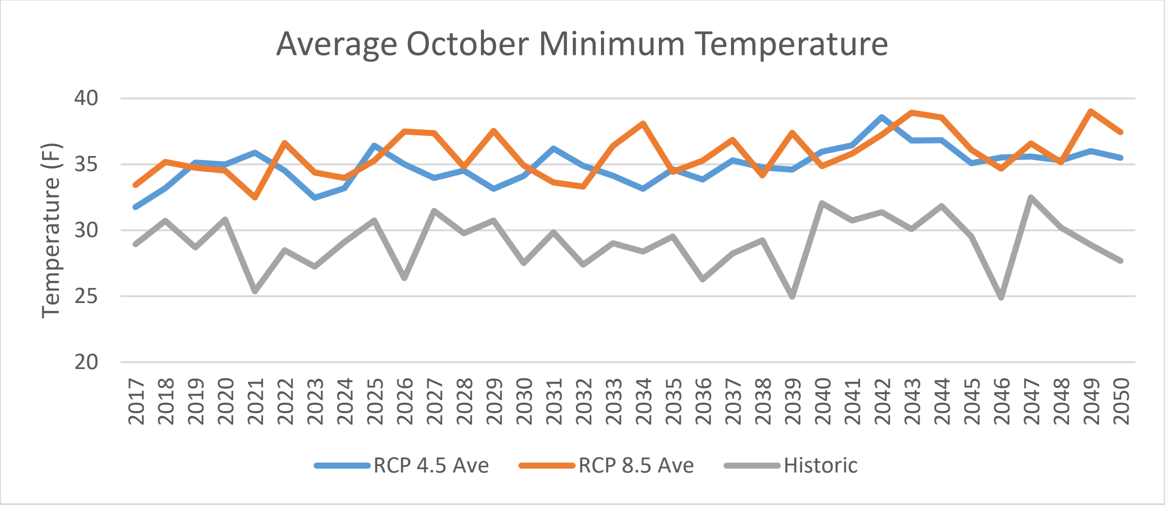

Figure 5: Fall temperature timeline

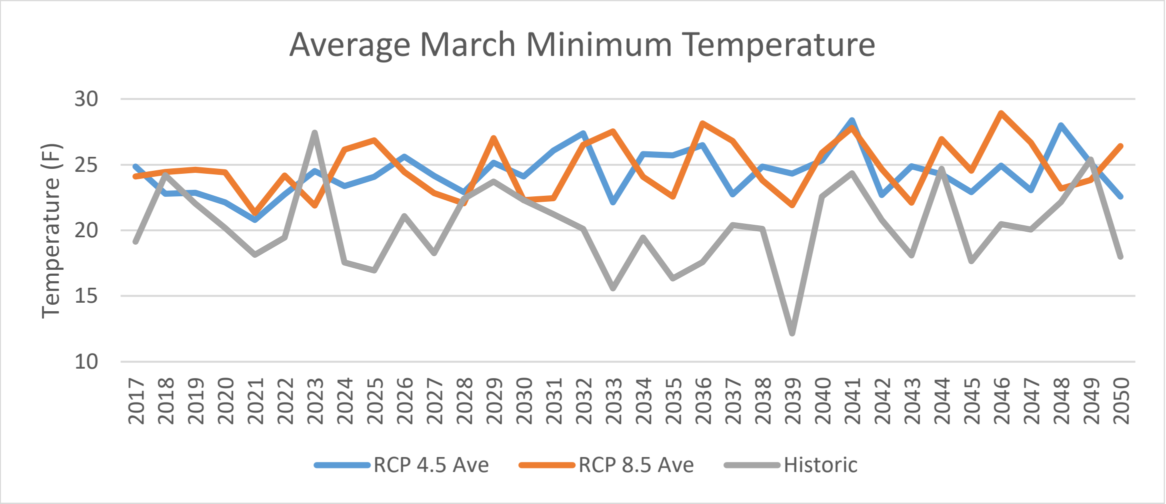

Figure 6: Spring temperature timeline

increased sufficiently enough to overcome the defenses of trees that are normally resistant to MPB endemic populations and other bark beetle species. If climatic conditions remain favorable for the incipient epidemic population, the MPB populations may spread rapidly across the landscape and become an epidemic population. At this point, the epidemic will persist until the majority of trees have been killed and the population enters post epidemic (population declines)[16].

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[16] L Carroll, A & Aukema, Brian & Raffa, Kenneth & A Linton, D & Smith, Greg & Lindgren, B Staffan. (2006). Mountain Pine Beetle Outbreak Development: the Endemic - Incipient Epidemic Transition. Working Paper, MPBI, Natural Resources Canada, Canadian Forest Service, Victoria, Canada. PO # 1.03. 21.

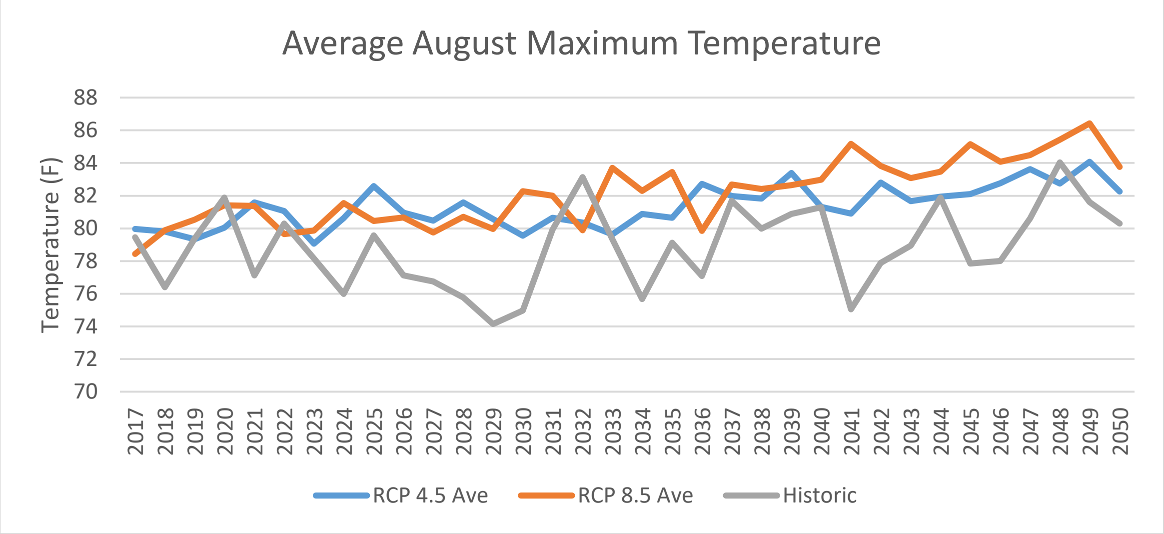

Figure 5: Summer temperature timeline

Warmer temperatures and drought conditions have been observed to increase the probability of MPB populations switching from endemic to incipient epidemic or epidemic population levels. These warmer and drier conditions cause greater stress in a stand of trees, therefore increasing the number of susceptible trees to MPB[16]. Figure 5 shows that the maximum August temperature for Boulder is projected to increase. Concurrently, drought conditions in Boulder County are also projected to increase (see Figure 2 in the Wildfire section). Of particular concern for Boulder County is the eastern area of ponderosa pine. These stands will likely see the worst drought conditions as well as higher seasonal temperatures.

The combination of these factors creates future climate conditions in Boulder County that are favorable to MPB populations to spread and become larger. Minimum temperatures in fall and spring will be warmer and therefore less likely to kill MPB larvae. Warmer summer temperatures and increased drought conditions will cause increased stress levels in the tree stands and may cause endemic MPB populations to become incipient epidemic or epidemic populations. As illustrated, these conditions could become a standard part of the Boulder County climate within a decade.

Drought

Climate change scenarios project an increase in the number and severity of droughts in many parts of Colorado. Warmer temperatures will amplify the evaporation of water from the soils, making periodic droughts worse than they would be under cooler temperatures[17].

The projected changes in drought conditions for Boulder County were developed using the Palmer Drought Severity Index (PDSI). PDSI is a drought indicator that incorporates soil characteristics, precipitation and evapotranspiration (based on temperature)[18]. PDSI is a widely used metric for drought and has been successful in quantifying long-term drought[19]. PDSI is reported in drought severity levels as detailed in Table 3[18].

PDSI Value	**Drought Severity Level**
-1 to -2	Mild Drought
-2 to -3	Moderate Drought
-3 to -4	Severe Drought
-4 or lower	Extreme Drought

Table 3: PDSI severity levels

The additional number of drought months that can be expected in Boulder County in the future can be predicted by comparing projections in the global circulation models (GCMs) from 2020-2049 to the GCM historical data from 1980-2009. Additionally, the average length of each drought can be estimated by tracking the consecutive months with projected drought.

Figures 8 and 9 illustrate the change in total drought months and the change in severity of drought months in Boulder County from 2020-2049. The predictions are illustrated using box plots to indicate the range of projections from the climate models. The plot for each severity level indicates the range of predictions from a low of the 5th percentile prediction to a high of the 95th percentile prediction. The box in the middle of each severity level indicates the central predictions of the models with the bottom of the box indicating the 25th percentile model and the top of the box indicating the 75th percentile. The median of the predictions is indicated by the horizontal line in the box. The range of predictions is

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[17] "Drought and Climate Change." Center for Climate and Energy Solutions, 1 Nov. 2017, www.c2es.org/content/drought-and-climate-change/.

[18] Palmer, W.C. 1965. Meteorological drought. Research Paper No. 45, U.S. Department of Commerce Weather Bureau, Washington, D.C.

[19] "Palmer Drought Severity Index (PDSI)." Palmer Drought Severity Index (PDSI) | NCAR - Climate Data Guide, climatedataguide.ucar.edu/climate-data/palmer-drought-severity-index-pdsi.

visualized by the total difference between the 5th and 95th percentile models and the difference between the 25th and 75th percentile models. The greater the difference between these points, the greater the variability in the climate model indicators from which the predictions are developed. The predictions can be compared to the historic prediction level by comparing the results to the asterisk located on each severity plot.

As indicated in Figure 8, the predicted number of drought months increases over the historic value at each severity level from 2020 to 2049. However, the primary message from Figure 8 is the pattern that illustrates that the number of mild droughts decreases for about 75% of the models. This is generally due to the fact that drought severity is switching to higher levels. Historic droughts that were mild are now intensifying to either moderate, severe, or extreme drought levels. For moderate, severe, and extreme droughts, the majority of models show a significant increase in drought months over 2020 to 2049. Specifically, 64%, 74% and 74% of models show an increase in moderate, severe, and extreme droughts, respectively. This creates the shift in the graph from mild to a greater predicted severity level.

Figure 9 shows that the total number of drought months (all severity levels summed) is expected to increase as well. 69% of models show that the total number of drought months will increase from 2020 to 2049. Models that show decreases in drought months can be attributed to the models projecting an increase in precipitation for the area.

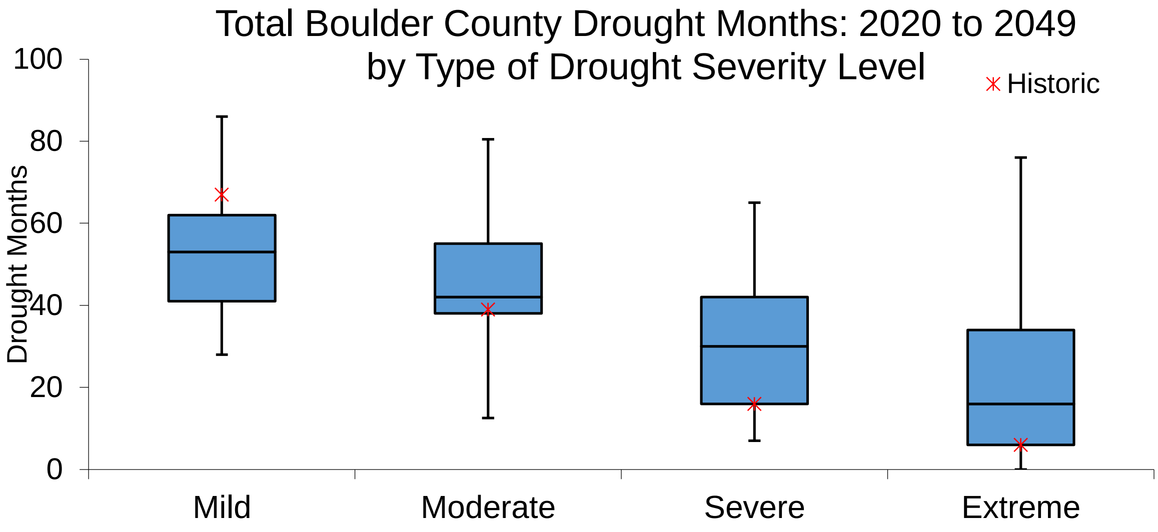

Figure 8: Drought month predictions across models by severity level

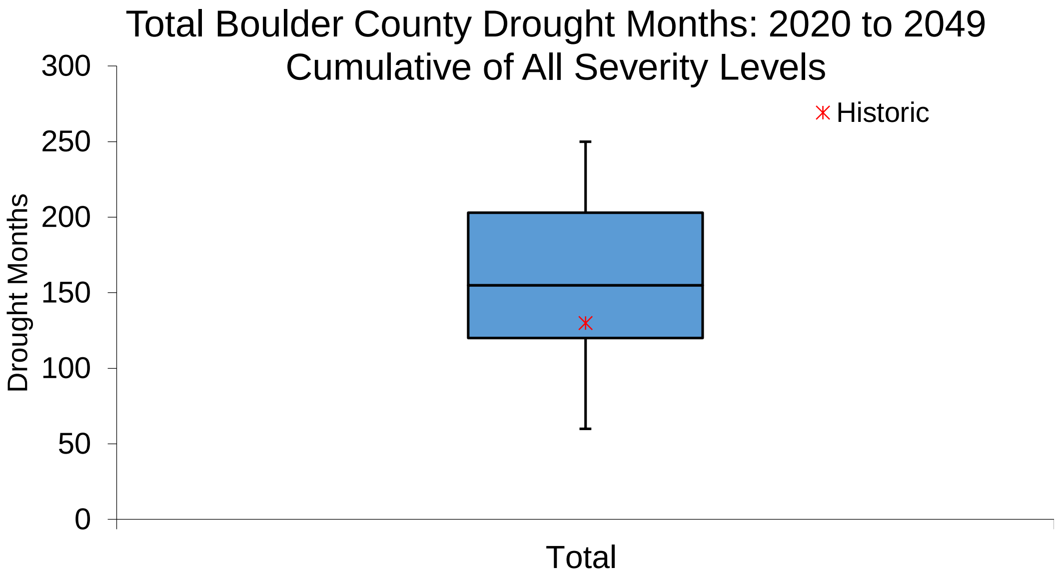

Figure 9: Total drought months cumulative of all severity types across all models

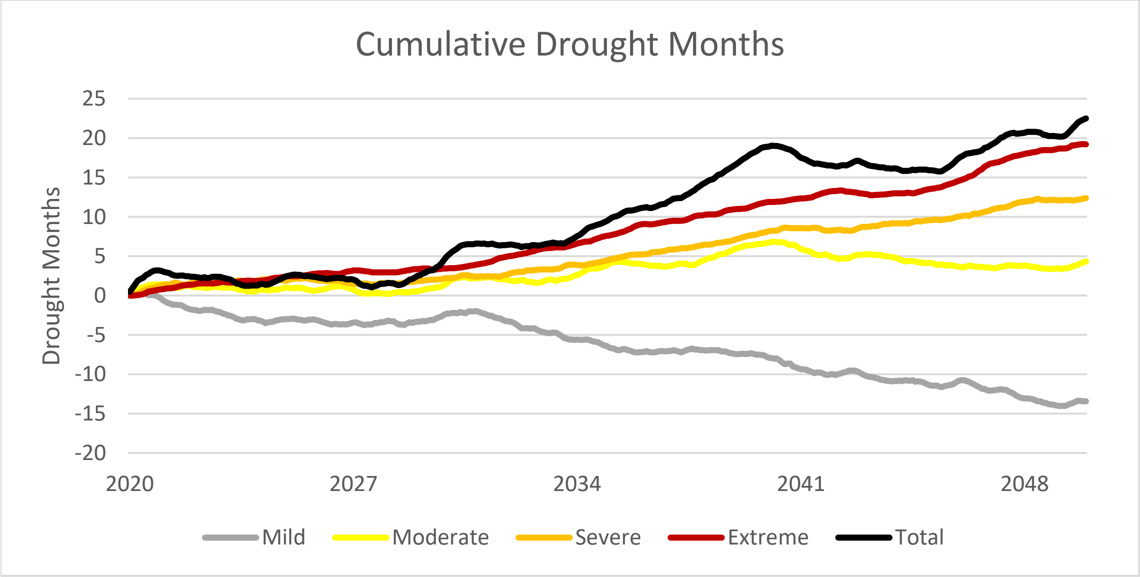

Figure10: Timeline of cumulative drought months by severity

The timing of when droughts are projected to become more frequent and severe is shown in Figure based on an average climate scenario. The graph utilizes additional projected drought months per year to illustrate the growth and timing of droughts in the area.

As illustrated, a notable change is projected about 2030 when an upward trend in additional drought months begins to occur. This is most likely attributed to a sharper increase in temperatures in Boulder County projected for that time period. However, the graph also illustrates that a trend already exists where the number of mild drought months is decreasing and more severe drought months are being experienced.

In summary, the majority of GCM models indicate droughts in Boulder County will become more frequent and more intense from 2020-2049. This climatic change could have a negative effect on agriculture, wildfires, energy and water availability in the area. Additional costs that may be incurred to mitigate the effects of these droughts include increasing water supply from external sources, compensating agricultural operations for reducing water-intensive crops, incentivizing homeowners to change landscape items to be more drought resistant, and increasing fire mitigation procedures to reduce wildfire hazards. Concurrently, the impact on usage from both underground aquifers and reservoirs will need to be examined to determine if traditional usage levels can be continued, or whether usage levels may have to be monitored to ensure long-term availability of water.

Human Health

The trend towards increasing temperatures in the Boulder County region has multiple human health impacts. Some of these are direct impacts such as the risk of heat stroke from extreme heat events. Others are indirect such as an increase in allergens due to an increase in the growing season for allergy-causing plants. In this section, we summarize some of the human health threats that must be considered as climate conditions change within Boulder County[20].

Heat Effects

Since record keeping began in 1895, heat waves in Boulder County have become more frequent and intense[21]. The continuance of this trend for increasing temperature trends is expected to lead to an increase in heat related deaths and illness. Extreme heat events compromise the body's ability to regulate its temperature or by inducing direct or indirect health complications[22]. The effect is especially notable on vulnerable populations including the very young, the elderly, and individuals with existing medical conditions. This analysis addresses the issue of morbidity and mortality from heat and estimates the number of deaths from 2020-2049 that can be attributed to extreme temperatures in Boulder County[23].

Mortality

An extreme heat event is defined as a day with a daily minimum temperature greater than or equal to the 99th percentile value from that location's distribution and where that temperature is greater than 68°F. Extreme temperature mortality is defined in the equation below[24].

$$\begin{aligned}&\mathit{Extreme\ temperature\ mortality}\\&\qquad = \mathit{Percent\ change\ in\ daily\ mortality\ for\ an\ extreme\ event}\\&\qquad * \mathit{average\ number\ of\ deaths\ per\ day} * \mathit{number\ of\ extreme\ heat\ events}\end{aligned}$$

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[20] USGCRP, 2016: The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha, M.C. Sarofim, J. Trtanj, and L. Ziska, Eds. U.S. Global Change Research Program, Washington, DC, 312 pp

[21] Walsh, J., and others, 2014: Ch. 2: Our Changing Climate. Climate Change Impacts in the United States: The Third National Climate Assessment, J.M. Melillo, Richmond, T. (T.C.), and Yohe, G.W., Eds., U.S. Global Change Research Program, 19-67

[22] Sarofim, M.C., S. Saha, M.D. Hawkins, D.M. Mills, J. Hess, R. Horton, P. Kinney, J. Schwartz, and A. St. Juliana. 2016. Chapter 2: Temperature-related death and illness. The impacts of climate change on human health in the United States: A scientific assessment. U.S. Global Change Research Program. https://health2016.globalchange.gov.

[23] The analysis is based on an analysis done by Mills et al 2013 who sought to do the same thing for 33 metropolitan areas in the United States.

[24] Mills, D., J. Schwartz, M. Lee, M. Sarofim, R. Jones, M. Lawson, M. Duckworth, and L. Deck, 2014: Climate Change Impacts on Extreme Temperature Mortality in Select Metropolitan Areas in the United States. Climatic Change, doi: 10.1007/s10584-014-1154-8.

Historic (1980-2009) Extreme Heat Event Mortality Rate					
0.05	deaths per year	or	1 death every	**21.4**	years

Projected (2020-2049) Extreme Heat Event Death Rate						
Minimum	**0.27**	deaths per year	or	1 death every	**3.6**	years
Mean	**0.72**	deaths per year	or	1 death every	**1.4**	years
Maximum	**1.47**	deaths per year	or	1 death every	**0.7**	years

Table 4: Extreme heat event mortality summary

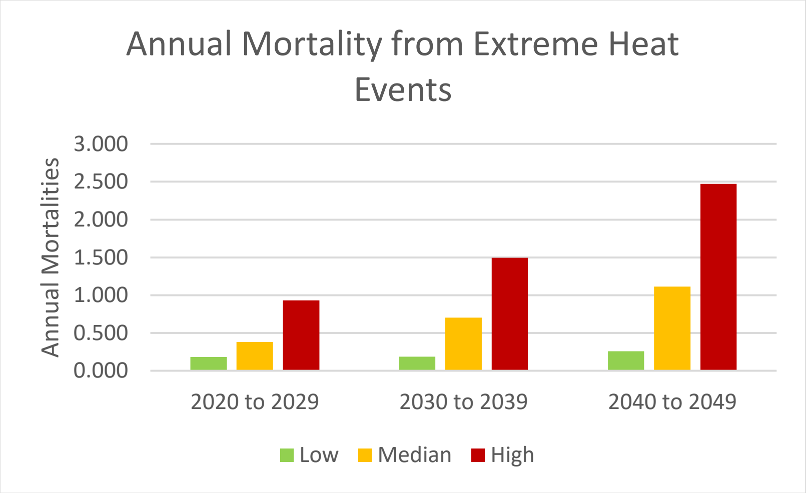

Figure11: Annual extreme heat event mortality projections

Annual mortality rates were developed based on Colorado Department of Public Health statistics for Boulder County[25]. The number of extreme heat events were calculated in Boulder County for an historic baseline from 1980-2009 and for climate projections from 2020-2049. Results from this analysis are documented in Table 4. The results do not account for changes in human behavior or population.

From 2020-2049 the baseline historic extreme heat event mortality rate is minimal with only 1 death expected over the time period from an extreme heat condition. However, the projected change in temperatures will increase this number to a projected mortality rate of 8 to 44 deaths depending on the scenario. As illustrated in Figure, the mortality rate increases significantly throughout that time period.

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[25] Boulder County Births and Deaths 2015. Colorado Department of Public Health and Environment, www.cohealthdata.dphe.state.co.us/chd/Resources/vs/2015/Boulder.pdf.

Morbidity

The issue of illness associated with heat events or the impact of heat on existing health conditions is one that receives attention, but cannot always be directly associated. Specifically, heat affects multiple areas of health including both specific effects such as heat stress, heat stroke, and heat exhaustion[26] and indirect effects on existing conditions such as diabetes and renal failure[27]. The direct effects are observable through increased emergency room visits during extreme heat events as well as impacts on outdoor workers. However, the indirect effects are the focus of public health agencies that are trying to intervene before extreme heat can cause fatal effects in patients with other illnesses. In studies focused on emergency room visits in multiple locations across the United States, health workers are attempting to pinpoint the heat parameters when vulnerable individuals become more susceptible to heat stress. While these studies are still being undertaken, the picture is becoming increasingly clear that extreme heat events are affecting elderly populations in particular who already have existing conditions[28].

As an indicator of the potential for heat-related illness in Boulder County, the projected number of extreme heat events is compared with historic levels. For the morbidity analysis, a slightly broader definition of heat event is used as suggested by the Center for Disease Control and Prevention (CDC). Specifically, based on the generally low levels of humidity found in Boulder County during the summer months, the definition of an extreme heat event is a day where the maximum temperature exceeds the 95th percentile of historic maximum temperatures[29]. For Boulder County, this historic temperature level is defined in this study as 91 degrees based on the historic record.

As indicated in Figure 12, the number of extreme heat events is projected to rise above the historic level by up to 56 days per year by the 2040 decade for a high impact scenario and 30 days per year for the median scenario. Each of these heat event days is a candidate for the heat-related illnesses described above. Given the double or triple increase in extreme heat events, Boulder County should plan on increased emergency room visits[28] as well as the potential for increased need for checking on vulnerable populations.

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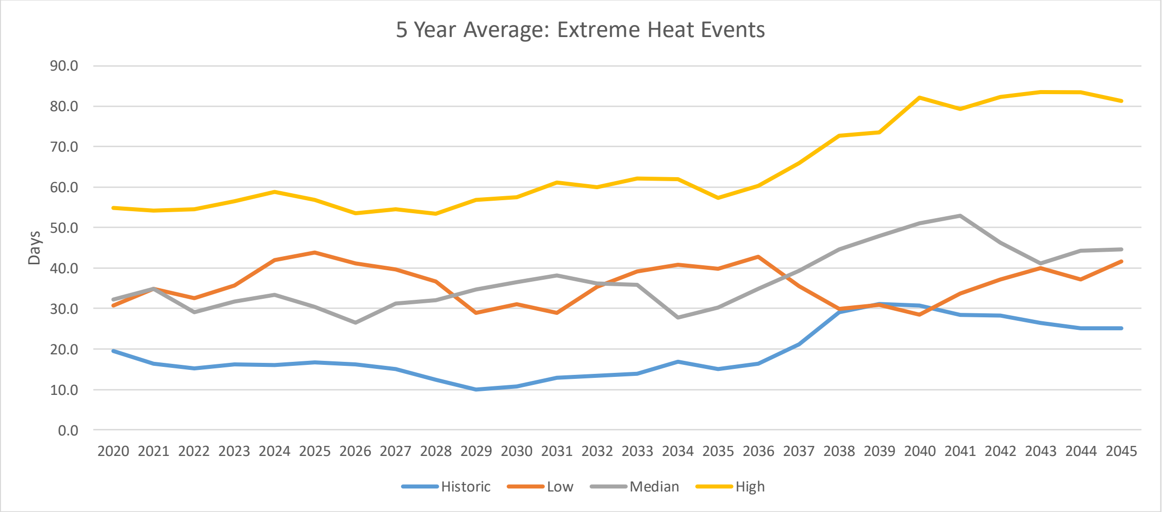
[26] California Department of Public Health (2007). Public Health Impacts of Climate Change in California: Community Vulnerability Assessments and Adaptation Strategies, Report No.1: Heat-Related Illness and Mortality.

[27] Li, Bo, Sain, Steve, Mearns, Linda O., Anderson, Henry A., Kovats, Sari, Ebi, Kristie L., Bekkedal, Marni Y.V., Kanarek, Marty S., and Patz, Jonathan A. (2012). "The Impact of Extreme Heat on Morbidity in Milwaukee, Wisconsin," Climatic Change, 110:959-976.

[28] EPA and CDC (2016). Climate Change and Extreme Heat.

[29] Centers for Disease Control and Prevention, "National Climate Assessment – Extreme Heat Events," CDC WONDER, https://wonder.cdc.gov/wonder/help/HeatWaveDays.html



Increase in Extreme Heat Events (Days above historic level)

	2020 to 2029	2030 to 2039	2040 to 2049
Low	8	5	14
Median	14	20	30
High	35	38	56

Figure 12: Number of projected extreme heat days in Boulder County. Number of days are average over the geographic area of Boulder County. Specific geographic locations may experience either greater or fewer days in a given year.

Mitigation

The mitigation of the potential impact of extreme heat events requires Boulder County to assist individuals who require access to additional cooling capacity during extreme heat events. This additional cooling could either occur in individual homes or through the establishment of cooling centers within the County. The approach to providing individual homes with additional cooling may focus on a program to provide air conditioners to vulnerable populations. The cost per household being in the range of $1,000. An additional option would be to open cooling centers during extreme heat events. The cost of such a center can vary depending on factors including existing facility availability, staffing rates, and number of individuals using the center. However, one study in Phoenix, AZ estimated the cost of running a cooling center at $500 per day[30]. The challenge is that these centers must be located in enough areas to facilitate vulnerable populations to access the center. A single center in the center of the geographic area is not sufficient to address all of the population.

To calculate a rough estimate of the cost for cooling centers, it is assumed that one cooling center is established for each 1/16th degree grid or approximately nine square miles in the City of Boulder and one cooling center is opened for every nine grids for the remainder of the County (approximately every 10 miles). Using the projected increase in extreme heat days and assuming the cooling centers will be open on each extreme heat day in each grid cell experiencing an extreme heat day, the County should plan for the median climate model projections from a risk perspective. This planning would translate to a cost of $4.62 million through 2050 ($154,000 average annual) to operate cooling centers in extreme heat events. The City of Boulder is projected to incur $2 million of these costs.

Allergens and Asthma

Although mortality and morbidity resulting from extreme heat events receives the greatest amount of focus in relation to climate change due to its direct impact, the indirect impacts on human health can prove to be considerably broader in impact. Of these, the impact on allergy and asthma sufferers may witness the largest impact. This is based on one of the key contributors to this issue – plants that release allergens as part of their growing season. Traditionally, the allergy season in Boulder County runs from spring to fall with different allergens contributing at different points during the allergy season.

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[30] Maricopa County Cooling Center Evaluation Project in Collaboration with Arizona State University and Arizona Department of Health Services, Maricopa County Department of Public Health Division of Disease Control Office of Epidemiology September 2015

The length of the season is based on when the last frost of winter occurs and when the first frost of fall occurs, together with the average temperature during this time period[31].

The projected increase in temperatures in the early spring and early fall is projected to change this traditional growing season and thus the length of time when individuals will be exposed to allergens[32] (Figure 13). As illustrated, the median and high impact scenarios project a continued increase in the growing season throughout the next three decades. The City of Boulder has a higher projected increase since it does not have the mitigating factor of the western County elevation.

Within Boulder County, key allergens including Oak trees, Ragweed, and Maple trees would have an increased impact on allergies and asthma due to the projection of longer growing seasons. The overall result of this projection being an earlier emergence of allergens as well as a longer exposure season. This extension of the allergy season may result in vulnerable populations contracting asthma at a greater rate according to medical research[33].

The potential impact for Boulder County is widespread, as individuals who suffer from seasonal allergies will have an extended period of exposure. Vulnerable populations will have enhanced impacts including a greater number of doctor visits to treat asthma symptoms. In general, an increase in growing season could result in an increased number of hospital and doctor visits which reduces worker productivity and increases public health costs.

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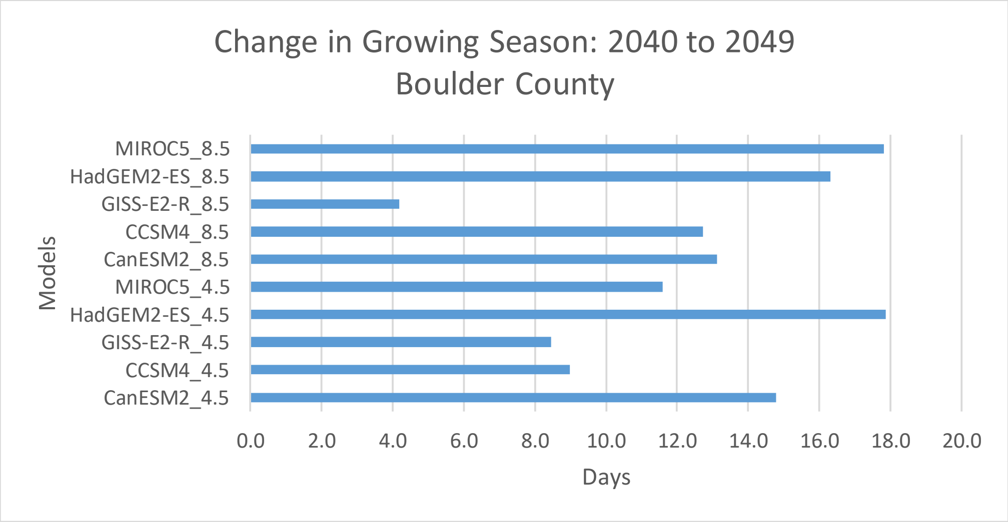
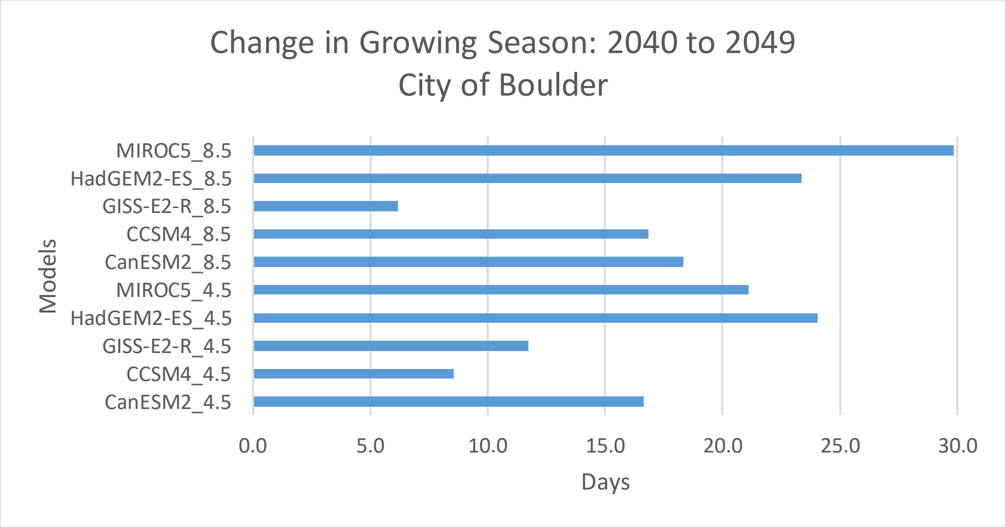
[31] Ziska, L., Knowlton, K., Rogers, C., Dalan, D., Tierney, N., Elder, M.A., Filley, W., Shropshire, J., Ford, L.B., Hedberg, C. and Fleetwood, P., 2011. Recent warming by latitude associated with increased length of ragweed pollen season in central North America. *Proceedings of the National Academy of Sciences*, *108*(10), pp.4248-4251.

[32] Goplen, J.J., Sheaffer, C.C., Becker, R.L., Moon, R.D., Coulter, J.A., Breitenbach, F.R., Behnken, L.M. and Gunsolus, J.L., 2018. Giant Ragweed (Ambrosia trifida) Emergence Model Performance Evaluated in Diverse Cropping Systems. *Weed Science*, *66*(1), pp.36-46.

[33] Luber, G., K. Knowlton, J. Balbus, H. Frumkin, M. Hayden, J. Hess, M. McGeehin, N. Sheats, L. Backer, C. B. Beard, K. L. Ebi, E. Maibach, R. S. Ostfeld, C. Wiedinmyer, E. Zielinski-Gutiérrez, and L. Ziska, 2014: Ch. 9: Human Health. Climate Change Impacts in the United States: The Third National Climate Assessment, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 220-256. doi:10.7930/J0PN93H5.





	2020 to 2029	**2030 to 2039**	**2040 to 2049**	**Average 2020 to 2049**
Boulder County: Low	-2.9	-0.5	4.6	1.7
City of Boulder: Low	-5.9	-0.7	6.4	1.6
Boulder County: Median	9.5	12.4	12.9	11.5
City of Boulder: Median	14.0	17.9	17.6	17.3
Boulder County: High	14.2	15.5	17.9	15.1
City of Boulder: High	25.2	24.6	29.3	23.6

Figure 13: Projected increase in growing season days for Boulder County and the City of Boulder.

Vector-Borne Disease

The third area of human health concern related to climate factors is the potential for increases in vector-borne diseases, many of which are referred to as mosquito-borne diseases. These health issues are related to increases in outbreaks due to exposure to infected mosquitoes. In the Boulder County region, a continuing concern is the spread of West Nile virus (WNV)[34] where WNV is transmitted by mosquitoes that have been in contact with infected birds.

The connection to climate change is the relationship of these infection rates to temperature and drought[35,36]. Specifically, during drought events, infected birds and mosquitoes have a greater likelihood to come into contact as available water supplies are reduced. As discussed previously, it is projected that the number and severity of drought events in the Boulder County region will increase as will the temperatures in the key spring and late summer months. The combination of these events will increase the likelihood of mosquito-bird interactions[37]. Ultimately, this could increase the likelihood of WNV cases among the population in Boulder County, although this does not capture the potential for additional human immunity.

The result of this increase in human terms is likely to include increased need for medical treatment with the accompanying impact on job productivity. Vulnerable populations will again face a greater risk of medical issues with the increased exposure to WNV. In addition to the potential medical and productivity impacts, Boulder County will need to consider mitigation options to reduce the broader spread of WNV. Additional spraying programs might be considered as well as other programs to reduce the potential contact between mosquitoes and birds during drought events.

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[34] Mosquitoes and West Nile Virus, Boulder County Public Health, https://www.bouldercounty.org/environment/water/west-nile-virus/

[35] Paull, S. H., Horton, D. E., Ashfaq, M., Rastogi, D., Kramer, L. D., Diffenbaugh, N. S., & Kilpatrick, A. M. (2017). Drought and immunity determine the intensity of West Nile virus epidemics and climate change impacts. *Proc. R. Soc. B*, *284*(1848), 20162078.

[36] Harrigan, R.J., H.A. Thomassen, W. Buermann, and T.B. Smith, 2014: A continental risk assessment of West Nile virus under climate change. Global Change Biology, 20, 2417-2425.

[37] Paz, S. (2015). Climate change impacts on West Nile virus transmission in a global context. *Phil. Trans. R. Soc. B*, *370*(1665), 20130561.

Urban Drainage

Changes in storm intensity associated with climate change could have significant impacts on urban drainage systems. Higher intensities could lead to overloaded urban drainage systems, which may lead to local flooding damages[38]. To determine whether these flooding events may occur more frequently in the future in Boulder County, standard engineering procedures were utilized to compare the impact of future precipitation projections with historic levels.

For this analysis, precipitation frequency data was assembled from NOAA's Precipitation Frequency Data Server[39]. From that data, rainfall intensity for 15, 30, and 60 minute durations were calculated according to equations 500.1 and 500.2 of the Boulder County Storm Drainage Criteria Manual[40]. The Boulder County Storm Drainage Criteria Manual defines a minor and a major storm as 5- and 100-year events. To remain consistent with the design manual, all calculations were done for both 5-year and 100-year events. The projected rainfall intensity curves from 2020 to 2050 are illustrated in Figure 14 and Figure 5.

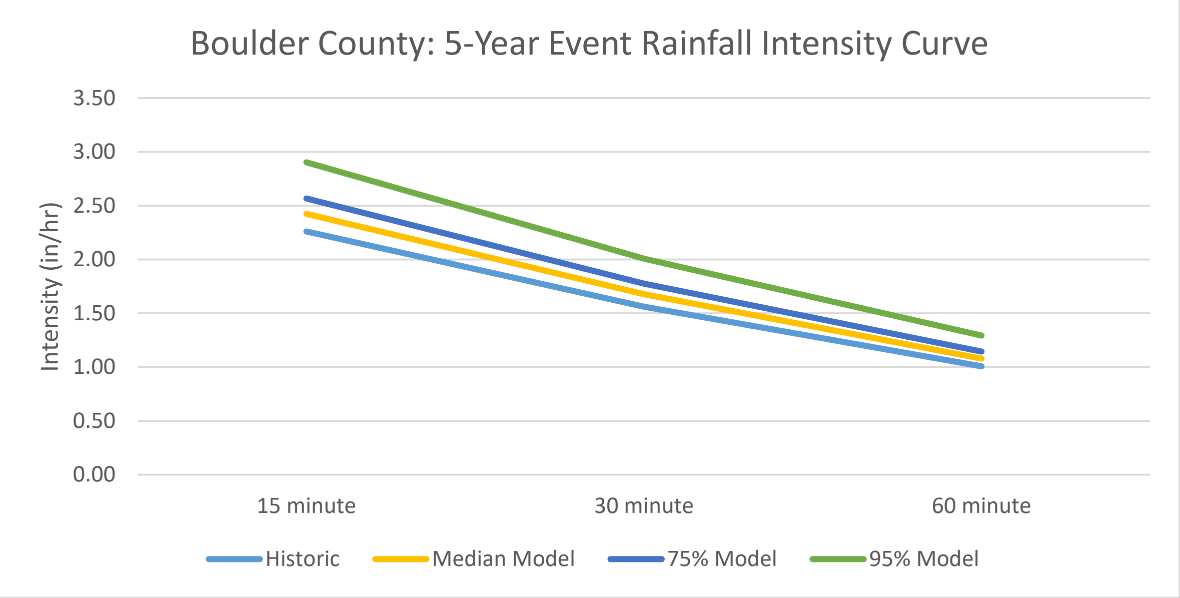

Figure 14: Minor storm rainfall intensity projections

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[38] Trtanj, J., L. Jantarasami, J. Brunkard, T. Collier, J. Jacobs, E. Lipp, S. McLellan, S. Moore, H. Paerl, J. Ravenscroft, M. Sengco, and J. Thurston, 2016: Ch. 6: Climate Impacts on Water-Related Illness. The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. U.S. Global Change Research Program, Washington, DC, 157-188, doi:10.7930/J03F4MH.

[39] US Department of Commerce, NOAA, NWS, Office of Hydrologic Development. PF Data Server-PFDS/HDSC/OWP, US Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, 7 Nov. 2005, hdsc.nws.noaa.gov/hdsc/pfds/.

[40] Boulder County Storm Drainage Criteria Manual. https://assets.bouldercounty.org/wp-content/uploads/2017/03/storm-drainage-manual-full-version.pdf

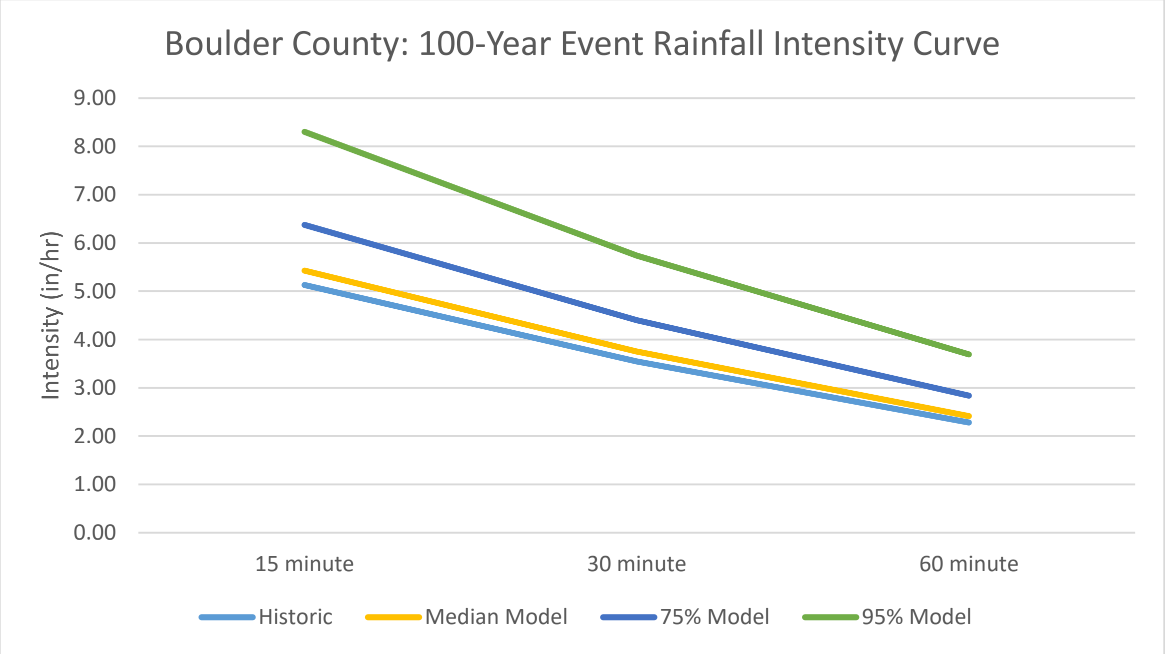

Figure 15: Major storm rainfall intensity projections

Rainfall intensity for both storms is projected to increase under the majority of models. 79% of models project an increase in minor storm rainfall intensity and 62% of models project an increase in major storm rainfall intensity. In particular, the 15-minute storm levels are projected to increase at a notable level indicating that future events will be characterized by more intense, short duration precipitation events.

The increase in precipitation intensity is important as storm drainage systems are designed based on these short-term events. As the 15-minute and 60-minute events increase in intensity, the capacity of the drainage systems to absorb the additional flow becomes a limiting factor. The consistency in the trends of the climate models illustrates that flooding due to the over-capacity of the drainage system increases in likelihood and accordingly the likelihood of flooding damages. Additionally, the ability for the natural acreage around the drainage systems to assist the process by absorbing excess water becomes limited as precipitation events saturate the ground. Therefore, with precipitation intensity likely increasing in Boulder County, additional maintenance investments as well as adaptation investments may be necessary to prevent potential damage from exceeding system capacity[41].

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[41] Detailed explanation of urban drainage can be found in Appendix A

5-Year Storm	**15 minute**	**30 minute**	**60 minute**
75th Percentile Model	15%	13%	13%
Median Model	6%	6%	7%
100-Year Storm			
75th Percentile Model	23%	24%	24%
Median Model	6%	6%	6%

Table 5: Risk Profile for Urban Drainage Planning

Table 5 presents a risk profile for the potential impact of increased precipitation intensity with increases over 5% over historic planning levels being a concern and increases over 10% being a high risk for flooding and damages. As illustrated, the 75th percentile model indicates a high risk for flooding and damage at each storm prediction level.

Numerous site-specific factors influence the effect of climate change on a given drainage system, the EPA provides guidance for adaptation costs based on average costs per square mile for 100 cities across the United States. Adaptive actions use best management practices to limit the runoff entering the urban drainage system to avoid damages[42]. These practices include temporary storage such as retention ponds or infiltration such as permeable pavement. All adaptation strategies are based on EPA guidelines and construction cost estimates.

In Boulder County, there are 78.61 square miles of incorporated city limits. Average costs to implement adaptive actions to the extent that they have not already been taken for all incorporated City limits is estimated to be $16.25 million based on generalized EPA cost guidelines. Table 6 shows an estimated cost breakdown by cities within Boulder County. The final costs of these adaptations would be determined based on an in-depth engineering analysis of site-specific conditions and local cost considerations.

It is also recommended that the projected changes in intensity be incorporated into new drainage structures that Boulder County plans to build. All structures related to drainage (including culverts) should be designed for the potential changes in intensity so that they can maintain the acceptable level of risk corresponding to the design manual criterion.

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[42] EPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, EPA 430-R-17-001.

City	**Area (square miles)**	**Cost (thousands)**
Boulder	25.23	$ 5,218
Erie	4.92	$ 1,017
Jamestown	0.57	$ 118
Lafayette	8.87	$ 1,833
Longmont	23.02	$ 4,761
Louisville	8.93	$ 1,846
Lyons	1.25	$ 258
Nederland	1.52	$ 314
Superior	3.72	$ 768
Ward	0.53	$ 109
Total	**78.61**	**$ 16,256**

Table 6: Urban drainage adaptation costs

Roads

Climate change poses many impacts to all types of road infrastructure. Specifically, as increases in precipitation and temperature occur relative to the historical standards used to design the roads, damages and degradation occur at higher rates than is budgeted for road maintenance and repairs.

Boulder County road infrastructure data was assembled from the Geospatial Open Data Site for Boulder County and the City of Boulder[43,44]. Using road attribute data, the road stock was categorized according to each segment's surface (paved and gravel) and level (primary, secondary and tertiary). A summary of roads included in the study can be seen in Tables 7a and 7b. Roads listed for the City of Boulder are included in the Boulder County numbers. The City of Boulder numbers are highlighted as specific impacts.

	Primary	**Secondary**	**Tertiary**	**Total**
Paved	40.4	512.0	531.3	1,083.7
Gravel	0.0	47.6	288.9	336.5

Table 7a: Boulder County road stock summary (miles) including City of Boulder roads

	Primary	**Secondary**	**Tertiary**	**Total**
Paved	0.0	39.5	255.1	294.6
Gravel	0.0	0.0	0.0	0.0

Table 7b: City of Boulder road stock summary (miles)

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[43] "Home | Boulder County Open Geospatial Data." Home | Boulder County Open Geospatial Data, gis-bouldercounty.opendata.arcgis.com/.

[44] "Open Data Catalog." City of Boulder Colorado, bouldercolorado.gov/open-data/tag/gis

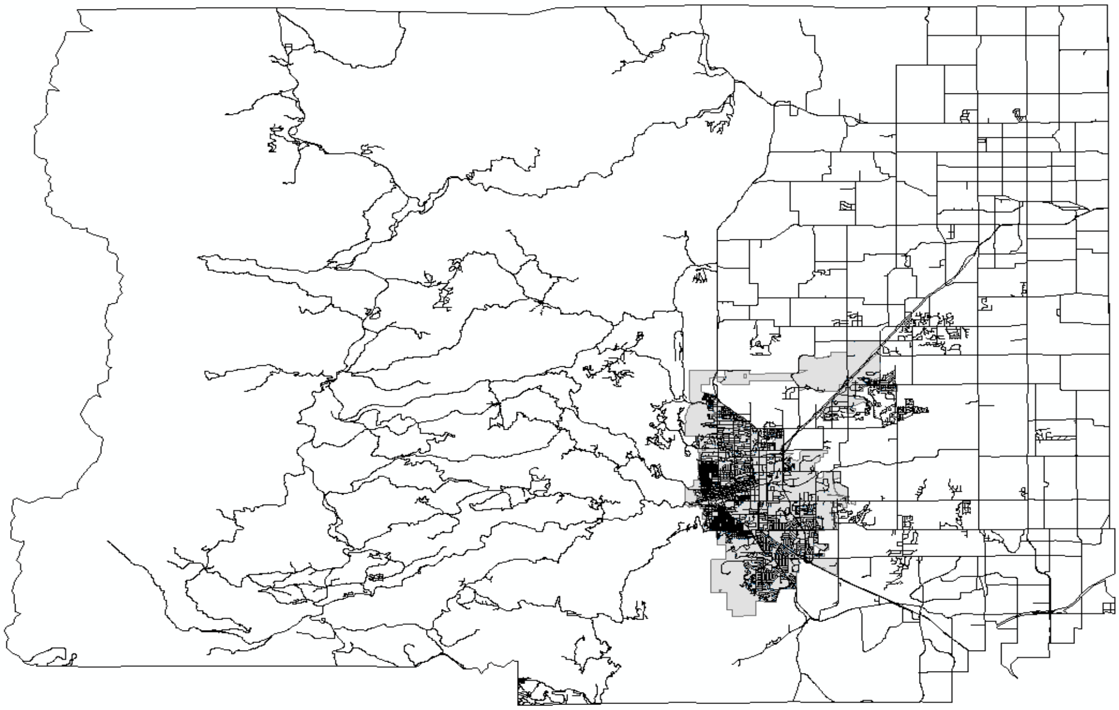

Figure 66: Map of Boulder County road stock. City of Boulder roads are located within the gray shaded area

In total, the analysis includes 1,420 miles of road in Boulder County of which 294.6 are in the City of Boulder. Figure 66 shows a map view of the road stock for reference.

A summary of cost results from the analysis are presented in Tables 8a and 8b. Tables 8a and 8b present the cumulative costs of each road type for the median model through 2050 for Boulder County and the City of Boulder. Paved roads dominate costs due to the higher construction costs and the greater sensitivity to increases in temperature resulting in increasing maintenance and damages. Additionally, tertiary roads have the greatest cost in the City of Boulder which is reflective of the road inventory within the City of Boulder.

	Primary	Secondary	Tertiary	TOTAL
Paved	$ 3.4	$ 7.7	$ 19.9	$ 31.1
Gravel	$ -	$ 3.6	$ 10.5	$ 14.1
TOTAL	$ 3.4	$ 11.3	$ 30.4	$ 45.2

Table 8a: Cumulative costs in Boulder County through 2050 by road type (MUSD)

	Primary	Secondary	Tertiary	TOTAL
Paved	$ -	$ 1.3	$ 9.7	$ 11.0
Gravel	$ -	$ -	$ -	$ -
TOTAL	$ -	$ 1.3	$ 9.7	$ 11.0

Table 8b: Cumulative costs specifically for City of Boulder through 2050 by road type (MUSD)

Figures 17a and 17b include three options for addressing climate change impacts. The reactive approach includes costs incurred if a maintenance only approach is taken where damages are addressed only after they occur. A proactive approach is an adaptation approach where measures are put in place to proactively mitigate potential damages. And finally, an optimized approach determines based on financial measures when adaptation and maintenance should be combined to achieve a minimum cost. Appendix B lists the reactive and proactive measures that are considered in the road analysis for paved, gravel, and unpaved roads.

Figure 17 shows the range of costs for all models based on the primary climate factors. Projections show that temperature and precipitation will be of primary concern for both the Boulder County and City of Boulder road stocks. Increases in temperature will exceed design standards and create excess cracking that must be repaired. Similarly, increases in precipitation will increase the cracking by impacting the strength of the roadbed as well as causing additional erosion along the edges of some roadways.

A primary difference between the City and County effects is in the level of impact projected by precipitation changes. The Boulder County road stock has a greater proportion of potential impacts from precipitation in comparison to the other stressors than is seen for the City of Boulder. This is due to the number of gravel roads and mountain roads in the Boulder County road stock. The per-mile costs discussed below give a greater indication of the relative impact on the roads from each stressor.

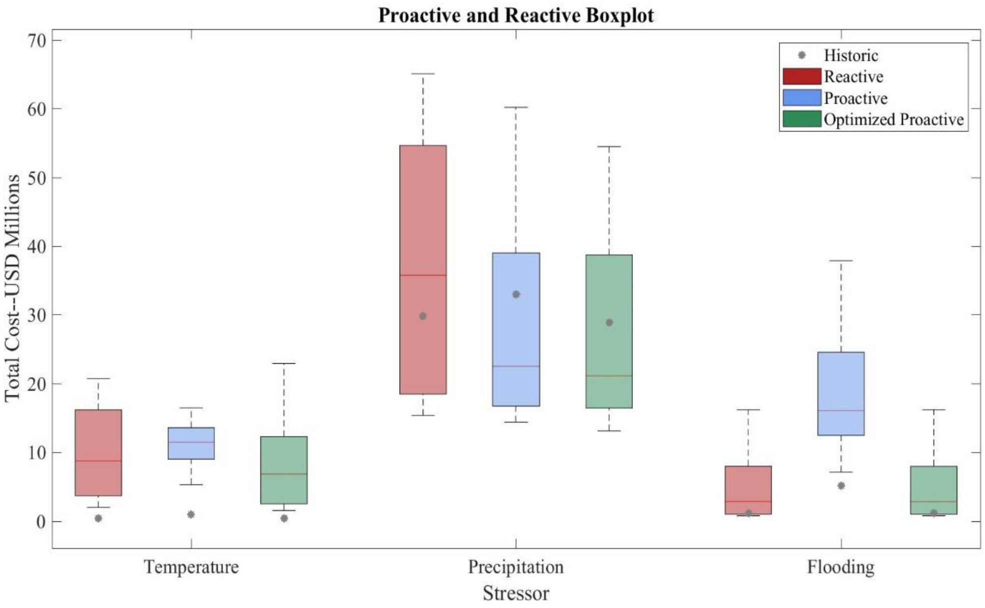

Figure 17a: Proactive and reactive boxplot by stressor through 2050 for Boulder County

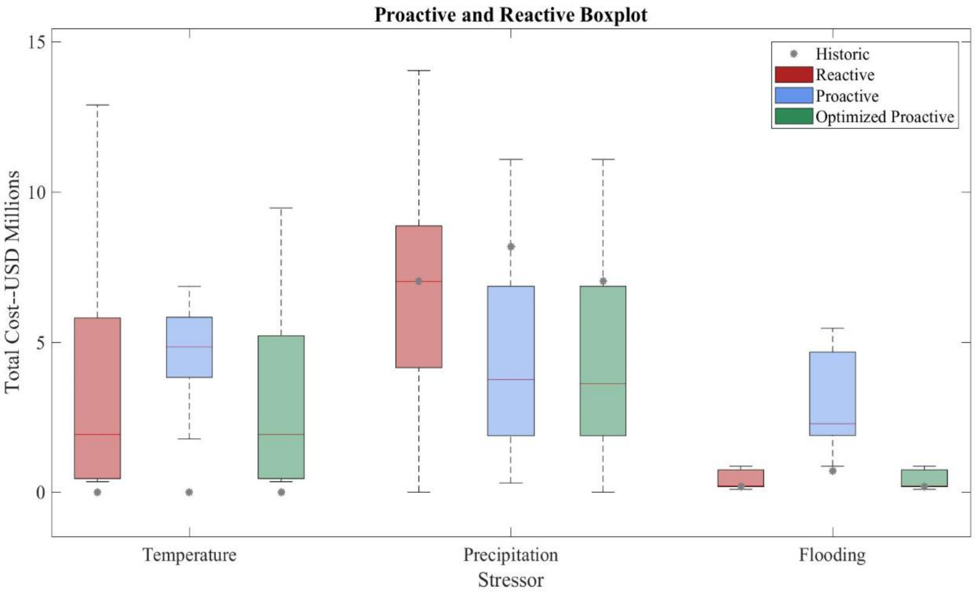

Figure 17b: Proactive and reactive boxplot by stressor through 2050 for the City of Boulder

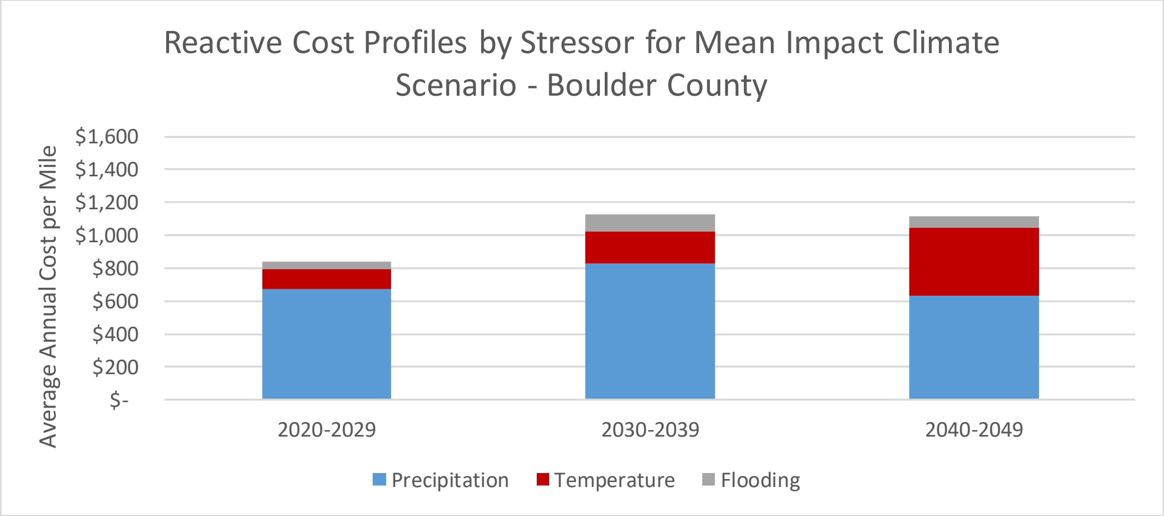

Figure 18a: Average annual reactive decadal costs by stressor (per mile) – Boulder County

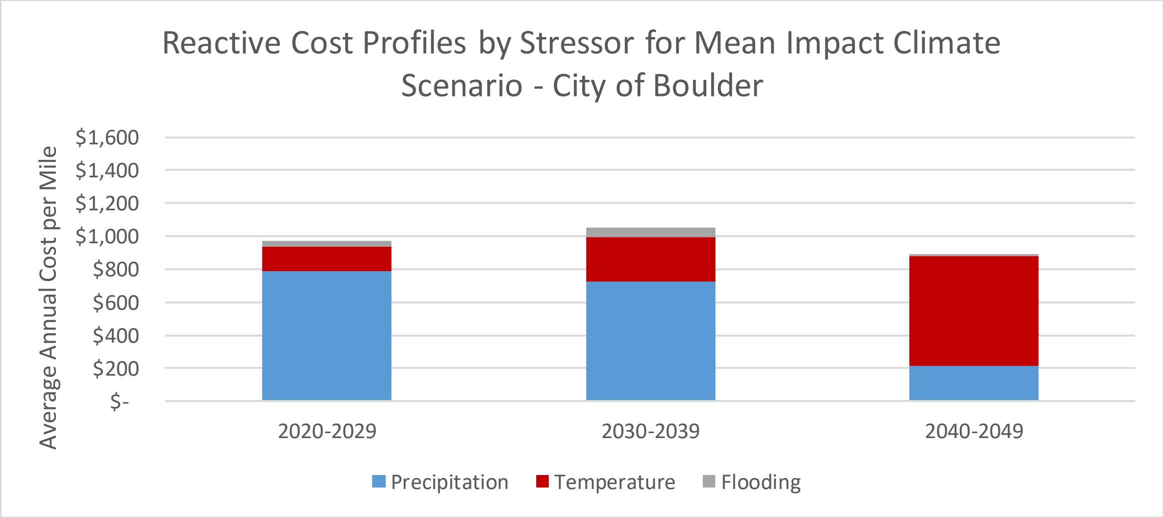

Figure 18b: Average annual reactive decadal costs by stressor (per mile) – City of Boulder

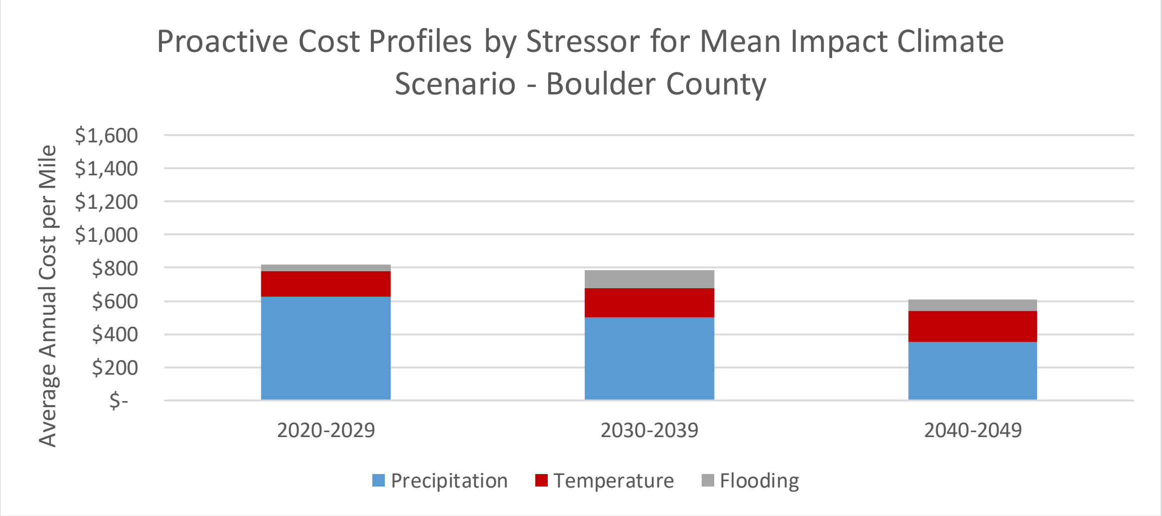

Figure 19a: Average annual proactive decadal costs by stressor (per mile) – Boulder County

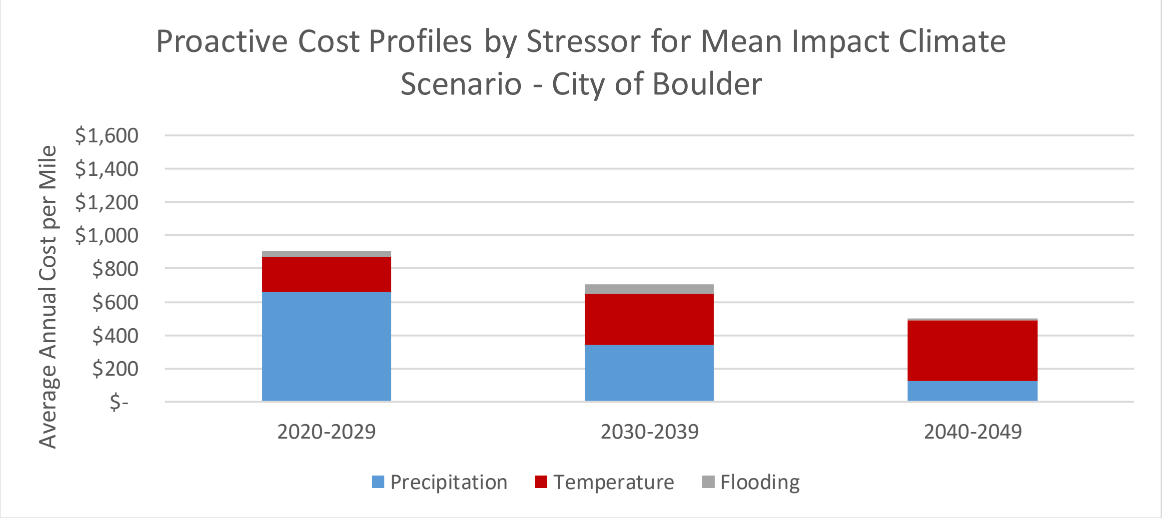

Figure 19b: Average annual proactive decadal costs by stressor (per mile) – City of Boulder

Scenarios	Optimized Proactive Costs (MUSD)		Reactive Costs (MUSD)	
	Projected Costs	*Change Versus Historic*	*Projected Costs*	*Change Versus Historic*
Historic	*$ 30*	--	*$ 31*	--
Low Impact Scenario	*$ 16*	$ (14)	*$ 19*	$ (12)
Median Impact Scenario	*$ 32*	$ 2	*$ 45*	$ 14
High Impact Scenario	*$ 77*	$ 47	*$ 99*	$ 68

Figure 20a: Total reactive and proactive costs through 2050 – Boulder County

Scenarios	Optimized Proactive Costs (MUSD)		Reactive Costs (MUSD)	
	Projected Costs	*Change Versus Historic*	*Projected Costs*	*Change Versus Historic*
Historic	*$ 7*	--	*$ 7*	--
Low Impact Scenario	*$ 1*	$ (6)	*$ 1*	$ (6)
Median Impact Scenario	*$ 8*	$ 1	*$ 11*	$ 4
High Impact Scenario	*$ 16*	$ 9	*$ 22*	$ 15

Figure 20b: Total reactive and proactive costs through 2050 – City of Boulder

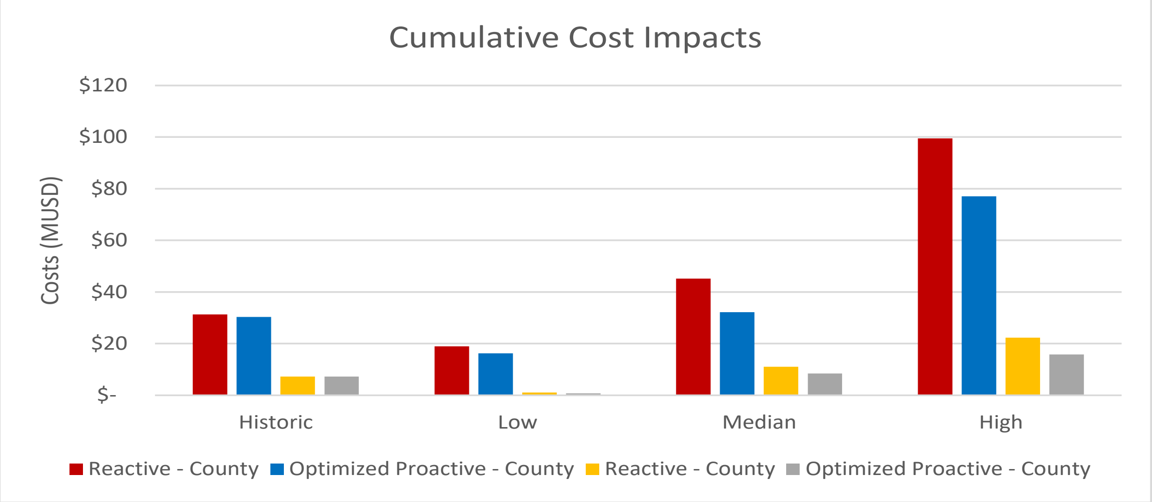

Figure 20c: Cumulative cost impacts by approach for historic, low, median, and high impact scenarios.

Figures 18 and 19 show the average costs by decade and stressor. **Error! Reference source not found.**8 s hows that climate related maintenance costs increase from an annual average of $920,000 for the historic climate ($650 per mile) for Boulder County to an average of $1.6 million per year by the 2030 era ($1,130 per mile) due to climate impacts. An increase of $480 per mile, per year. For the City of Boulder, these costs are $212,000 for the historic climate ($720 per mile) increasing to $310,000 per year ($1,050 per mile). An increase of $330 per mile.

Adaptation can reduce the potential impact of climate change (see Figure 19). The proactive adaptation policy approach is projected to reduce the annual average costs in comparison to a reactive approach in the 2030s and 2040s after the initial investment is complete. By the 2040 decade, the per-mile maintenance cost drops to about $600 for Boulder County and $500 for the City of Boulder. Overall, the proactive investment is projected to save $12 million and $21 million for the median and high impact models respectively for Boulder County (Figure 20a). This number represents the difference between the proactive approach and the reactive approach when comparing the increases versus historic projections. The City of Boulder is projected to save $3 million and $6 million for the median and high impact scenarios (Figures 20b and 20c).

Similar to each of the projections in this study, there is variance in potential costs based on the climate scenario adopted. The potential to over or under spend is a risk that exists for every location and for every infrastructure element. Designing for the worst climate scenario could lead to overspending and designing for the mildest climate scenario could result in underspending. **Error! Reference source not f ound.**21 shows that an optimal range of proactive investment can be determined based on the amount of adaptation investment made and the potential for over or underspending to occur based on that investment (regret). As illustrated in **Error! Reference source not found.**21, when the climate scenarios a nd their associated costs are placed on a graph in comparison to the potential regret that can occur with that expenditure, a preferred approach can be decided upon as a starting point for discussions. As illustrated, for Boulder County, an adaptation expenditure of approximately $32 million, an additional $2 million investment over historic expenditures, by 2050 would be the preferred approach to limit the risk of over/under spending. The same analysis for the City of Boulder equates to an $8 million expenditure, an additional $1 million investment over historic expectations.

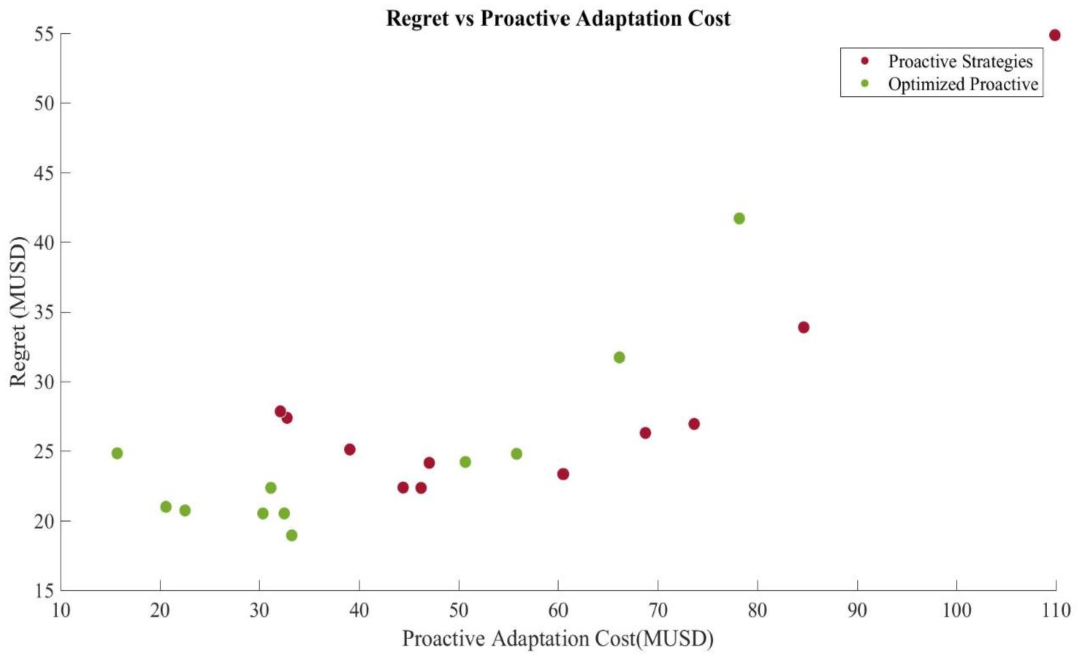

Figure 21a: Optimized regret and proactive scatter plot – Boulder County

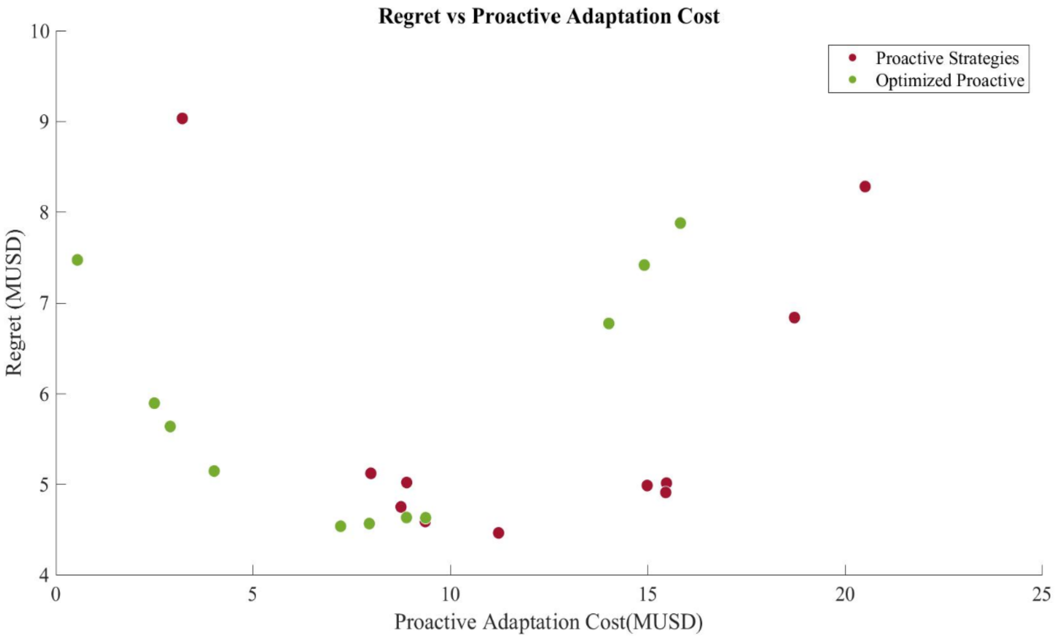

Figure 21b: Optimized regret and proactive scatter plot – City of Boulder

Bridges

Bridges are a vital part of the transportation infrastructure. With climate change, increased flooding and stream flow are expected to put stress on bridges by increasing the frequency of bridge scour[45]. Scour occurs where water flows by the bridge piers or abutments. The movement of the water removes soil that surrounds and supports the pier or abutment creating scour holes. The greater the flow of water, the more vulnerable the bridge pier or abutment will be to scour. If the flow of water exceeds what the bridge piers or abutments were designed to resist, the exposed soil at the base of the piers can experience excessive scouring to the point of placing the bridge in danger of failure.

In this analysis, impacts on bridge performance from climate change are estimated based on changes in peak river flow[46] and the potential for resulting increases in scour. The model estimates the changes in peak flow rates for the 100-year return period flood based on changes in maximum daily precipitation. The 100-year return period flood being the standard design criteria used for many highway bridges. In cases where the flow rates exceed the current design expectation, the bridges are considered vulnerable to excessive scour. Depending on the level of increase in flow rate, the necessary adaptation for the bridge will either be to install diversionary measures such as rock around the base of the pier, or in cases of large increases, to install additional concrete around the pier and its foundation to provide additional stability. The costs of this adaptation are reflected in this analysis.

To conduct the analysis of Boulder County, a spatial unit defined by an eight-digit hydrological code (HUC) was incorporated. Boulder County lies in the St. Vrain HUC number 10190005. Using this spatial unit, 238 bridges in Boulder County were analyzed. The bridge stock was assembled from the National Bridge Inventory[47]. Table 9 summarizes the results of this analysis.

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[45] Neumann, J., J. Price, P. Chinowsky, L. Wright, L. Ludwig, R. Streeter, R. Jones, J.B. Smith, W. Perkins, L. Jantarasami, and J. Martinich, 2014: Climate change risks to U.S. infrastructure: impacts on roads, bridges, coastal development, and urban drainage. *Climatic Change*, 131, 97-109, doi: 10.1007/s10584-013-1037-4.

[46] Wright L, Chinowsky P, Strzepek K, Jones R, Streeter R, Smith JB, Mayotte J-M, Powell A, Jantarasami L, Perkins W (2012) Estimated effects of climate change on flood vulnerability of U.S. bridges. Mitig Adapt Strateg Glob Change 17(8):939–955

[47] National Bridge Inventory, Office of Bridges and Structures, US Department of Transportation.

Model	Era 1 Flow Ratio	Era 2 Flow Ratio	Era 1 Cost (MUSD)	Era 2 Cost (MUSD)
CanESM2_4.5	0.70	1.03	$ -	$ -
CanESM2_8.5	1.20	1.17	$ 114.7	$ -
CCSM4_4.5	0.89	1.39	$ -	$ 114.7
CCSM4_8.5	0.60	1.12	$ -	$ -
GISS-E2-R_4.5	1.23	0.80	$ 114.7	$ -
GISS-E2-R_8.5	0.88	1.36	$ -	$ 114.7
HadGEM2-ES_4.5	1.02	0.81	$ -	$ -
HadGEM2-ES_8.5	1.12	1.10	$ -	$ -
MIROC5_4.5	1.02	1.40	$ -	$ 114.7
MIROC5_8.5	0.81	1.58	$ -	$ 114.7
Model Average			$ 22.9	$ 45.9

Table 9a: Bridge flow and cost summary – Boulder County

Model	Era 1 Flow Ratio	Era 2 Flow Ratio	Era 1 Cost (MUSD)	Era 2 Cost (MUSD)
CanESM2_4.5	0.70	1.03	$ -	$ -
CanESM2_8.5	1.20	1.17	$ 30.1	$ -
CCSM4_4.5	0.89	1.39	$ -	$ 30.1
CCSM4_8.5	0.60	1.12	$ -	$ -
GISS-E2-R_4.5	1.23	0.80	$ 30.1	$ -
GISS-E2-R_8.5	0.88	1.36	$ -	$ 30.1
HadGEM2-ES_4.5	1.02	0.81	$ -	$ -
HadGEM2-ES_8.5	1.12	1.10	$ -	$ -
MIROC5_4.5	1.02	1.40	$ -	$ 30.1
MIROC5_8.5	0.81	1.58	$ -	$ 30.1
Model Average			$ 6.0	$ 12.1

Table 9b: Bridge flow and cost summary – City of Boulder

As illustrated, two eras are identified when bridge adaptations may be put in place, 2020-2049 and 2050-2079. The second era is included in this table because bridges have a design lifetime than often ranges from 50-100 years. The costs indicated in the table represent the necessary costs for upgrading the bridges identified as vulnerable to scour. The costs include diversionary approaches or concrete strengthening depending on the increase in flows identified for the body of water that the bridges cross. Since this adaptation should only be required once during the lifetime of a bridge, the cost may occur in either the first or second era depending on the individual model and its projection of when increases in precipitation will occur. As illustrated, 6 of the 10 models used for the bridge analysis indicate that costs will be required to modify the bridges to prevent failure from scour. In each case, the models indicate that $114.7 million will be required to upgrade the affected bridges in Boulder County (Table 9a). The specific projected cost for the City of Boulder is $30.1 million. On average, this equates to $478,000 per bridge in adaptation expenses.

As illustrated, bridge expenses may be overlooked if only the first era is considered. It is necessary is to look at both the first and the second era to fully understand the potential impact of climate change. Additionally, bridge adaptation is dependent on the projected increases in water flow. This accounts for the “all or nothing” results for the models. Where the models indicate the required increase, the adaptation costs are incurred. However, where the models do not indicate an increase, no costs are incurred. Given that all models are equally probably as a starting assumption, the average of the models could be used as an initial planning number for future costs.

Buildings

Changes in precipitation and temperature will have significant effects on building operating costs. More frequent rain events can cause damage to the roof structure and increasing temperatures will alter the energy consumption. By understanding and predicting these changes, structures can be adapted to mitigate potential problems associated with climate change.

In this analysis, 4,895 buildings located in Boulder County were analyzed. The stock was assembled from the Boulder County Assessor website[48]. In total 68.3 million square feet of building area was analyzed. Department of Energy (DOE) Commercial Reference Buildings were used to estimate the energy intensities for each building in the study. Using climate projections and building energy intensities, a degree-day based method was used to predict the changes in building energy consumption. Heating degree days (HDD) and cooling degree days (CDD) are units used to determine the heating and cooling load for a specific building. Figure 2 and Figure 3 show the general trend in heating and cooling degree days for Boulder County.

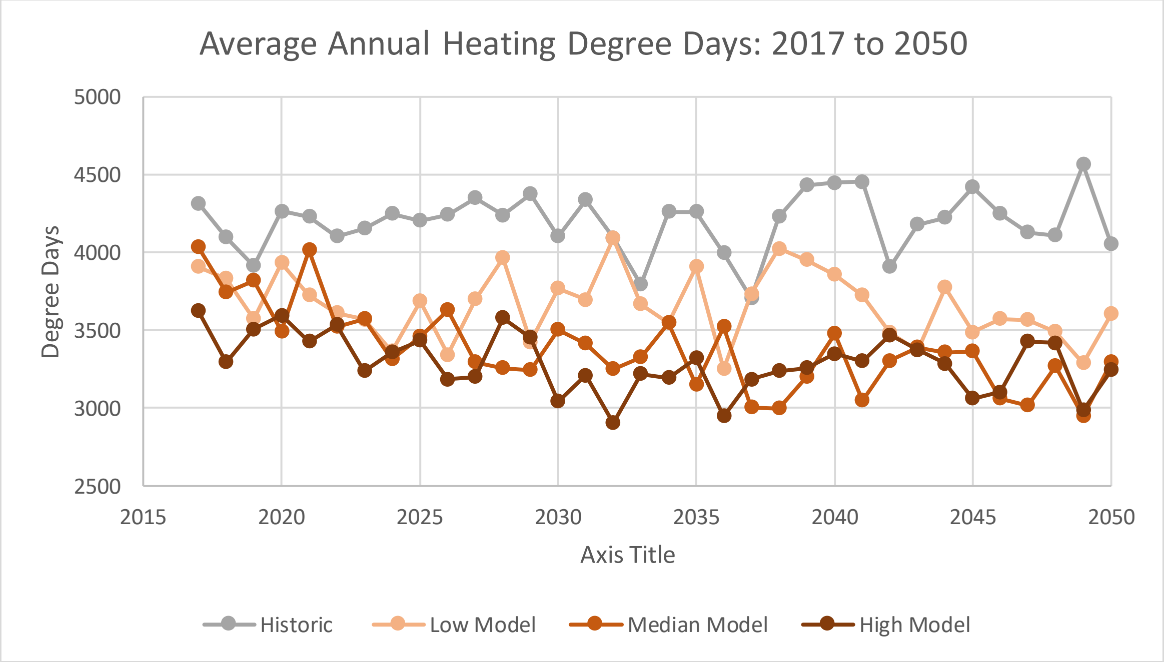

Figure 22: Heating degree day timeline

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[48] "Data Download." Boulder County, www.bouldercounty.org/property-and-land/assessor/data-download/.

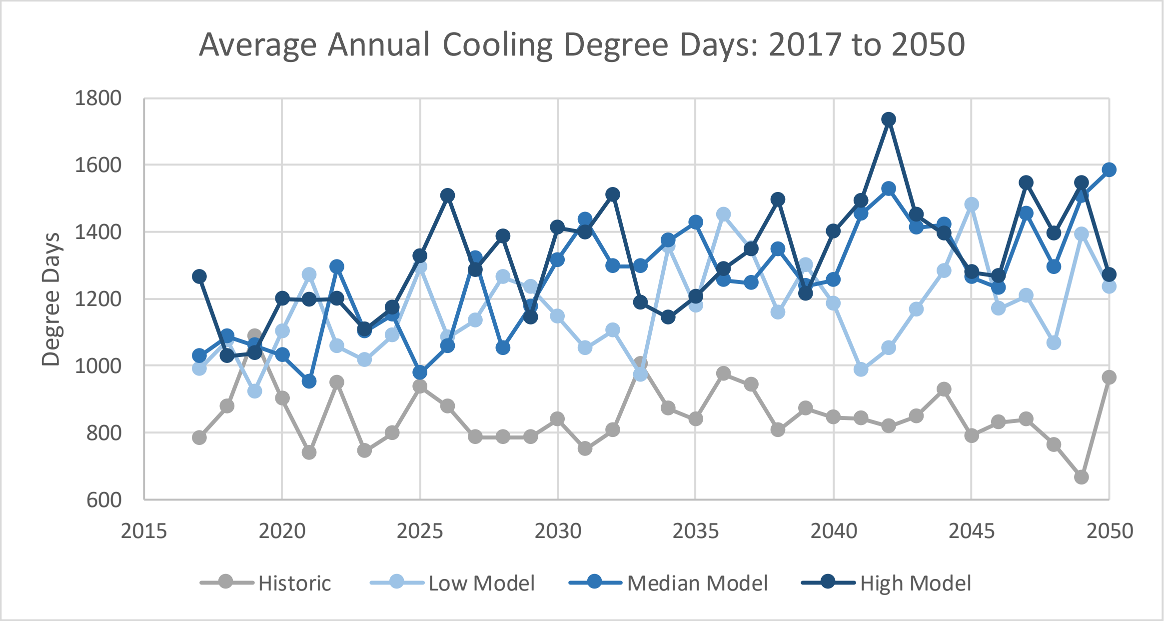

Figure 23: Cooling degree day timeline

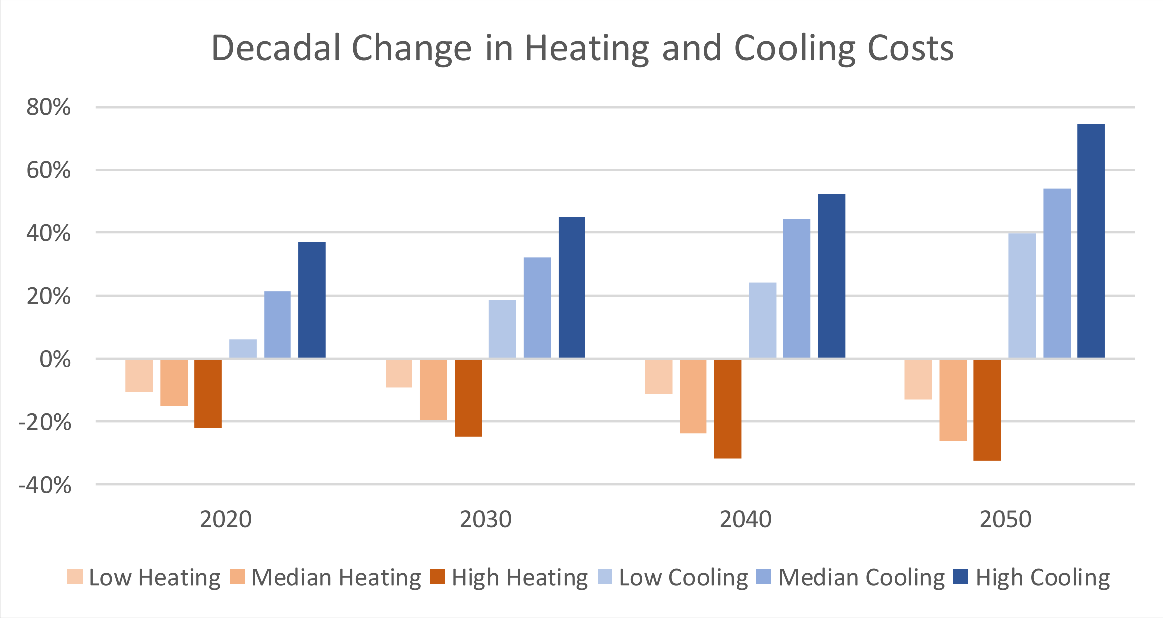

Figure 24: Percent changes in heating and cooling costs by decade

Figures 22 and 23 show a clear trend that CDDs are projected to increase and HDDs are projected to decrease. Currently, Boulder County is heating dominated, meaning that the majority of building energy costs are due to heating in the colder months. This begins to change as we approach 2050. Demand for cooling begins to increase significantly and heating demand declines. Figure 4 shows the changes in heating and cooling costs by decade. Cooling costs are projected to increase by 40% to 75% by 2050 and heating costs are projected to decrease by 13% to 32%.

By 2050, annual cooling costs for Boulder County buildings are predicted to increase by $3.3 million to $6.2 million. This cost does not include the cost of installing new air conditioning systems that could handle the additional cooling capacity. The additional cost of installing new and larger cooling systems would be significant in both residential and non-residential buildings. Annual savings from decreasing heating costs are projected to be $2.2 million to $5.6 million. On average, total energy costs could decrease by 7% or increase by 3% depending on the rate of temperature increase by 2050.

A second focus of the building analysis is on the potential damage to roofing materials. For these structures, roofing is designed based on projected amounts of water that will exist on the roof from rain events. Based on these projections, the size of roofing drainage systems is calculated. A failure to adequately size the roofing drain will result in water damage to the roof structure and potentially result in leaks that damage upper floors in the buildings. For proactive adaptation, drainage structures are redesigned and installed to handle the additional capacity. The average total cost of roofing proactive adaptation for Boulder County buildings is projected to be between $3 million and $19 million through 2050 for the median and high impact scenarios. A segment of these costs will be incurred by the City of Boulder depending on building ownership.

Timeline

The timeline for incurring the adaptation costs introduced in this report begins within the current decade. The current trends in temperature in particular illustrate that a change from the historic baseline is already occurring. The predictions from the climate models only increase and enhance the effects from the current trends. Infrastructure assets such as bridges and primary roads have design lifespans that cover the entire scope of this study. Therefore, current maintenance and development plans should already include new design guidelines. Similarly, extreme heat events are already occurring and will only increase over the next decade. Thus, planning for cooling centers should be an immediate concern. Similar concerns exist for increases in drought and wildfire occurrence.

As illustrated in the previous sections, each sector has individual timeline concerns depending on the climate factors that impact its operating environment or natural balance. Additionally, for infrastructure elements, the design life of the elements affects the adaptation timeline. Assets with extended design lifetimes such as bridges require adaptation measures in the near term while those such as gravel roads with a significantly shorter design life can be delayed until regular climate threats materialize.

From a decadal perspective, the following considerations should be made for adaptation policies based on the climate scenario projections.

- **2020-2030**: The continued trend towards increased temperatures guides decisions in this first decade. Of particular concern are adaptations to reduce wildfire threats, reduce human health concerns, and address buildings that require increased cooling capacity. Additionally, design guidelines for new construction should be modified to consider changing temperature conditions.
- **2030-2040:** The second decade will see the notable increase in temperatures as well as increases in short-term precipitation event intensity. These changes will require significant attention to human health concerns, wildfire mitigation, road maintenance and design changes, urban drainage adaptation, and mountain pine beetle mitigation.
- **2040-2050:** The final decade will witness the full impact of projected climate impacts. At this time, all sectors reviewed in this study will be experiencing the effects of climate impacts.

In summary, while the focus of this study is on future climate projections and impacts, using the baseline we have chosen, a climate trend is already appearing and influencing the current period. Therefore, implementing adaptation policies to mitigate potential impacts should be considered as soon as possible to adapt systems that will be vulnerable under future climate conditions.

Summary

In summary, climate change will continue to build on trends that are already appearing and have a fiscal and human impact on Boulder County over the next several decades. This study has documented these effects over a number of sectors to determine the potential impacts from a broad set of climate scenarios. Utilizing inventories from current Boulder County assets, the study provides an estimate of the costs associated with climate change including the potential cost of adaptation for mitigating the impact of climate change.

The impacts are based on documented, available science and multiple climate scenarios. The cost estimates are preliminary, conservative estimates based on an initial collection of available information.

In summary, the estimated total cost of adaptation for mitigating only some of the potential effects of climate change across the geographic area of Boulder County through 2050 is conservatively placed at $96 million to $157 million for the median and high impact scenarios for the areas looked into with the City of Boulder incurring $16 million to $36 million of these adaptation costs. Additionally, increased demand for cooling in buildings could add another $3.1 million to $4.5 million in direct costs per year for median and high projections. Urban drainage improvements could increase this cost by an additional $16.2 million depending on County versus incorporated city responsibilities. These totals are presented with the understanding that different jurisdictions may be responsible for different impacts within this geographic area.

Additional costs not included in this total include: residential costs for installing air conditioners in residences where they are not currently installed, increasing water availability during extreme drought events, removal of dead trees resulting from future mountain pine beetle infestation, public health costs associated with emergency room visits, and additional economic costs due to business interruptions during infrastructure repair and replacement periods.

A summary of the costs and findings included in this study can be seen below.

- **Wildfire –** The analysis projected the increase in burn area from 2020-2050 using the Keetch-Byram Drought Index and historic fire data. Additional property damage costs as well as fire mitigation costs were estimated.
    - Wildfire area is projected to increase by 38% and 48% for RCP 4.5 and RCP 8.5 models respectively from 2020 to 2050. Mitigation to prevent additional property damage, which only includes privately owned homes, is projected at up to $20.25 million.

- **Mountain Pine Beetle –** A climate vulnerability assessment for the mountain pine beetle (MPB) was conducted for Boulder County. Projections in temperature and drought conditions were coupled with local forest data to draw vulnerability conclusions.
    - Minimum temperatures in fall and spring will be warmer and therefore less likely to kill MPB larvae.
    - Warmer summer temperatures and increased drought conditions will cause increased stress levels in the tree stands and may cause endemic MPB populations to become incipient epidemic or epidemic populations.
    - The eastern area of ponderosa pine stands will likely see the highest temperature and worst drought conditions, making them the most vulnerable area in Boulder County.

- **Drought –** The Palmer Drought Severity Index (PDSI) was used to predict the changes in drought conditions over Boulder County. This analysis projected the change in drought months and drought severity from 2020 to 2050.
    - 69% of models show that the total number of drought months will increase from 2020-2049.
    - The severity of droughts is expected to increase. 74% of models show that the number of severe and extreme droughts will increase from 2020 to 2050.
    - A notable upward trend in additional drought months is expected to occur around 2030.

- **Human Health –** Annual extreme heat mortality rates were projected through 2050 to give insight on the effects of warming temperatures on human health. The results do not account for changes in human behavior, immunity, or population.
    - Annual mortality rates are expected to increase, resulting in one mortality from extreme heat every 0.7 to 3.6 years. This is a significant increase from the historical value of one mortality every 21 years.
    - It is estimated that Boulder County could incur $4.6 million in cooling center operating costs during extreme heat events between 2020 and 2050. The City of Boulder will incur $2 million of those costs.
    - The increasing temperatures will extend the growing season for allergen creating plants which will subsequently increase allergy and asthma symptoms across the County.

    - Increased drought events will increase the likelihood of West Nile virus cases as mosquitoes and infected birds have a greater likelihood of contact.

- **Urban Drainage –** Changes in storm intensity and flow were projected through 2050 to give insight into the vulnerability of the Boulder County urban drainage system.
    - 79% of models project an increase in minor storm rainfall intensity and 62% of models project an increase in major storm rainfall intensity. In particular, the 15-minute storm levels are projected to increase at a notable level indicating that future events will be characterized by more intense, short duration precipitation events.
    - Adaptation investments to prevent potential damage from projected increases in storms and subsequent exceeding of system capacities are estimated to be $16.2 million for all incorporated cities within Boulder County.

- **Roads –** The analysis of road impacts was based on a County-wide inventory of over 1,420 miles of roads within the County's geography boundaries. The City of Boulder accounts for 295 miles of these roads. The inventory included three categories of roads including primary roads, secondary roads such as Arapahoe Ave and McCaslin Blvd, and tertiary roads which are neighborhood roads. The analysis also distinguished between paved and gravel roads, each of which have unique damage considerations.
    - The cumulative increase in maintenance costs versus the historic level for Boulder County by 2050 is projected to be $14 million and $68 million for the median and high projections respectively. The City of Boulder will incur $4 million and $15 million of these costs respectively.
    - The projected cost per mile of road per year for road maintenance using the average annual cost from the 2030 decadal projections increases from $650 per mile historically to $1,130 per mile.
    - An optimum proactive scenario places the adaptation investment at $32 million ($8 million of which is the City of Boulder) to minimize over or under-spending on adaptation investment.
    - Proactive adaptation will save $12 million for a median projection and $21 million for a high-end projection by 2050. These costs are $3 million and $6 million for the City of Boulder.

- **<u>Bridges</u>** – The inventory of bridges included bridges throughout Boulder County. 238 distinct bridges were analyzed for climate change vulnerability.
    - 60% of the climate scenarios used project that increased flow will result in a need to upgrade bridges.
    - A planning estimate of $68 million can be used for estimating needed improvements to Boulder County bridges (based on an average cost of $478,000 per bridge). $18 million can be used for the City of Boulder.

- **<u>Buildings</u>** - The current analysis includes 4,895 buildings located across Boulder County. The analysis covers 16 different categories of commercial, industrial, and multi-family structures. The analysis does not include the cost of installing air conditioning in the buildings studied. The additional cost of installing cooling systems would be significant in both residential and non-residential buildings. It is also important to note that the cooling demand for electricity may not be able to be met by current energy production capacity.
    - Buildings in Boulder County will experience a cumulative increase in cooling costs of 31% to 45% by 2030. Similarly, the buildings will experience a cumulative increase in cooling costs of 54% to 75% by 2050. Total additional cooling costs are projected at $2.5 million to $3.7 million by 2030.
    - Savings of 19% - 25% on heating costs are possible by 2030 due to reduced heating demand in winter months.
    - Proactive investment to combat potential damage from increased precipitation total $3 million to $19 million by 2050.

Appendix A: Urban Drainage Flow Calculation

In order to calculate the effect of precipitation changes on the urban drainage system, the flow was calculated using the rational method according to Section 602 of the Boulder County Storm Drainage Criteria Manual. Basic assumptions were made for area and runoff coefficient in order to show the general effect of climatic changes on the flow. Area was assumed to be 1 acre and three runoff coefficients (.4, .6 and .8) were used in order to capture a range of surface. After flow (cfs) was calculated, flow ratios were developed based on the ratio of GCM flow to historic flow. This metric gives us insight into how much the flow ratios are projected in increase/decrease for each model. Table #A-1 shows the results of this analysis.

Flow Ratios	**5th Percentile**	**25th Percentile**	**50th Percentile**	**75th Percentile**	**95th Percentile**
5 Year Storm	0.88	1.01	1.07	1.14	1.26
100 Year Storm	0.72	0.91	1.06	1.24	1.55
% Increase	**5th Percentile**	**25th Percentile**	**50th Percentile**	**75th Percentile**	**95th Percentile**
5 Year Storm	-12.1%	0.6%	7.3%	13.6%	25.8%
100 Year Storm	-27.6%	-8.7%	5.7%	24.1%	54.9%

Table A-1: Projected flow ratios for the 5-year and 100-year storms for multiple climate scenarios.

The percent change in flow for the minor and major storm are projected to increase under the majority of models. For minor and major storms the median flow is projected to increase by 7.3% and 5.7% respectively. Under the 95th percentile model the flow is project to increase for the minor and major storm by 25.8% and 54.9% respectively. With precipitation intensity and flow likely increasing in Boulder County, adaptation investments may be necessary in order to prevent potential damage from exceeding system capacity.

Appendix B: Adaptation Measures for Roads

Stressor	Adaptation Measure for Roads	Full reference information for peer-reviewed publication where approach has been applied or presented
Precipitation	Reactive measure: Paved: Increase patching to address cracking from surface failure and fill subbase where erosion has destabilized local foundation Gravel: Regrade road localized to precipitation, fill subbase and reapply gravel top layer. Unpaved: Regrade road localized to precipitation, fill subbase and reapply top layer when appropriate.	Schweikert, Amy, Chinowsky, Paul, Kwiatkowski, Kyle, and Espinet, Xavier (2014). "The Infrastructure Planning Support System: Analyzing the Impact of Climate Change on Road Infrastructure and Development," Transport Policy, 35(9): 146-153. Chinowsky, Paul S., Schweikert, Amy, Strzepek, Niko, and Strzepek, Kenneth (2014). "Infrastructure and Climate Change: A Study of Impacts and Adaptations in Malawi, Mozambique, and Zambia" Climatic Change, 1-14.
	Proactive measure: Paved: Increase base strength (thickness and/or quality) to increase protection of subgrade layers as well as drainage. Should increase an additional 2.5 – 6 in depending on specific location Gravel: Increase gravel wearing course thickness to increase cover and protect subgrade layers. Generally increase by 2.5 – 6 in to handle increase in moisture Unpaved: Upgrade to paved road	Schweikert, Amy, Chinowsky, Paul, Kwiatkowski, Kyle, and Espinet, Xavier (2014). "The Infrastructure Planning Support System: Analyzing the Impact of Climate Change on Road Infrastructure and Development," Transport Policy, 35(9): 146-153. Chinowsky, Paul S., Schweikert, Amy, Strzepek, Niko, and Strzepek, Kenneth (2014). "Infrastructure and Climate Change: A Study of Impacts and Adaptations in Malawi, Mozambique, and Zambia" Climatic Change, 1-14.
Flooding	Reactive measure: Paved: Replace damaged road over affected area where washout occurred. Replace culvert if required. Includes	Schweikert, Amy, Chinowsky, Paul, Kwiatkowski, Kyle, and Espinet, Xavier (2014). "The Infrastructure Planning Support System: Analyzing the Impact of Climate Change on Road Infrastructure and Development," Transport Policy, 35(9): 146-153.

	replacing subbase and asphalt surfacing. Gravel: Replace damaged road over affected area where washout occurred. Replace culvert if required. Includes replacing subbase and gravel surfacing. Unpaved: Repair washed out area including regrading where required. Replace subbase if appropriate.	
	Proactive measure: Paved: Increase size of culverts to accommodate new flood projections. Gravel: Increase size of culverts to accommodate new flood projections. Increase depth of base layer. Unpaved: Increase base thickness to enhance drainage.	Schweikert, Amy, Chinowsky, Paul, Kwiatkowski, Kyle, and Espinet, Xavier (2014). “The Infrastructure Planning Support System: Analyzing the Impact of Climate Change on Road Infrastructure and Development,” Transport Policy, 35(9): 146-153.
Heat	Reactive measure: Paved: Additional patching required each year to fill cracks resulting from pavement weakening Gravel: N/A Unpaved: N/A	Schweikert, Amy, Chinowsky, Paul, Kwiatkowski, Kyle, and Espinet, Xavier (2014). “The Infrastructure Planning Support System: Analyzing the Impact of Climate Change on Road Infrastructure and Development,” Transport Policy, 35(9): 146-153. Chinowsky, Paul S., Schweikert, Amy, Strzepek, Niko, and Strzepek, Kenneth (2014). “Infrastructure and Climate Change: A Study of Impacts and Adaptations in Malawi, Mozambique, and Zambia” Climatic Change, 1-14.
	Proactive measure: Paved: Redesign of base asphalt binders with higher softening points (including polymer modification) for surface seals	Schweikert, Amy, Chinowsky, Paul, Kwiatkowski, Kyle, and Espinet, Xavier (2014). “The Infrastructure Planning Support System: Analyzing the Impact of Climate Change on Road Infrastructure and Development,” Transport Policy, 35(9): 146-153.

	and asphalt. Local mix may be available in addition to standard mix. Gravel: N/A Unpaved: N/A	Chinowsky, Paul S., Schweikert, Amy, Strzepek, Niko, and Strzepek, Kenneth (2014). "Infrastructure and Climate Change: A Study of Impacts and Adaptations in Malawi, Mozambique, and Zambia" Climatic Change, 1-14.