MEMORANDUM

To: Brandon Coleman, City of Boulder

From: Cameron Wobus and Rachel Bash, Lynker Technologies

Subject: Incorporating Climate Change into flood control along South Boulder Creek: Summary of federal, state, and local guidance

Date: 31 December 2020

About the Authors

This memorandum was prepared by the water and environmental resources group at Lynker Technologies, LLC (Lynker), to support the City of Boulder in its decisions regarding flood risk on South Boulder Creek. Lynker's Boulder-based consulting group supports local, state and federal agencies with issues including water resources planning, climate change impact analysis, and environmental restoration and regulatory compliance. Over the past 30 years, Lynker's scientists and engineers have built and refined the City of Boulder's water supply planning model, provided litigation support to the City of Boulder in water court proceedings, and supported agencies and municipalities across Boulder County in flood recovery and adaptation planning.

Dr. Cameron Wobus, the lead author of this memorandum, is a broadly trained earth scientist with expertise in hydrology, geomorphology and climate change. Dr. Wobus has led climate change impact studies for water utilities, transportation departments, and federal agencies for more than a decade. Most recently, he led the flooding component of a multidisciplinary evaluation of how climate change and population growth could impact natural hazards in the State of Colorado. Dr. Wobus holds an MS in hydrology from Dartmouth College and a PhD in earth sciences from MIT.

Summary of Findings

Lynker prepared this memorandum to review how climate change might be considered and, if applicable, incorporated into engineering designs for flood control along South Boulder Creek. We focused this review on federal, state, and local agency guidance regarding how climate change should be incorporated into planning and engineering design. We also provide a brief, general review of academic literature describing how climate change could influence extreme precipitation and flooding.

A summary of our main findings is as follows:

- As global temperatures warm, the atmosphere can hold more water vapor. On average, this increase amounts to approximately 7% more water in the atmosphere per degree C of warming. Accordingly, the potential for extreme rainfall is generally expected to increase with continued global warming.
- Our survey of federal agency guidelines and documents shows that the agencies tasked with managing water resources or flood risk acknowledge that climate change should be considered into long-range planning. However, there is little to no prescriptive guidance on how to modify engineering designs to account for climate-induced changes in flood risk.
- State and local agencies in Colorado have also generally acknowledged the potential impact of climate change on flood risk, including guidelines for floodplain development.
- The State of Colorado's dam safety guidelines require that for new dam designs, inflow design floods must be adjusted upwards by 7% to account for the increased moisture holding capacity of a warming atmosphere by mid-century.

Introduction

As a part of ongoing dialogue regarding land use planning for the CU South property in South Boulder, the City of Boulder and the University of Colorado are evaluating how the University's development goals for the property can be balanced with the City's flood mitigation goals for South Boulder Creek. One issue to resolve in this discussion is the degree of flood protection for downstream residents that should be included in any development proposal. For example, there is uncertainty as to whether flood control structures should be built to mitigate a "100-year" (1% annual exceedance probability) or larger flood event, and whether any of the design elements of flood control structures should be adjusted to account for climate change. Striking this balance requires an understanding of the state of the science regarding current flood risk, and how climate change could affect flood risk in the future. It also requires a thorough review of federal, state and local guidance on this topic.

The City of Boulder has requested a review of available guidance from other agencies regarding how climate change can be incorporated into flood risk analyses for engineering design. This memorandum was developed for that purpose. This memo first provides a general overview of how climate change could influence flood risk in general, and for South Boulder Creek in particular. This is followed by a summary of relevant federal, state and local guidance on how climate change can be incorporated into flood risk assessment and engineering design.

This document was prepared as background to aid the City of Boulder with its engineering decisions. It was not intended to provide any quantitative recommendations regarding design for any particular structure or facility.

General Principles: How might Climate Change affect Flood Risk?

Precipitation extremes are expected to increase under a warmer climate, because a warmer atmosphere can hold more water vapor than a cooler one. This general physical principle has been understood for more than 150 years: Clapeyron (1834) and Clausius (1850) demonstrated that increases in surface heating increases atmospheric water-holding capacity, as well as increased land surface evaporation. The "Clausius-Clapeyron scaling" originally described in those two papers has been refined and described in the context of climate change multiple times since the original work (e.g. Trenberth et al., 2003; O'Gorman & Schneider, 2009; Barbero et al., 2018), and the average magnitude of this effect is now widely accepted to be approximately 7% per degree Celsius. In other words, the amount of water vapor the atmosphere can hold increases by approximately 7% for each degree of warming. Based on this change in atmospheric moisture holding capacity, the expectation is that, all else equal, future precipitation extremes would also generally be expected to increase by approximately 7% per degree Celsius.

While this general information is useful in principle, it is substantially more difficult to translate into engineering practice due to the complexities inherent in the climate system. For example, studies have shown that for certain types of convective storms, increases in precipitation can exceed 7% per degree C (e.g., Lenderink & van Meijgaard, 2008; Westra et al., 2014). Large-scale atmospheric circulation also plays a significant role in determining how extreme precipitation might change regionally. In many cases, climate models do not agree on how those atmospheric circulation changes will affect specific locations, including Colorado (e.g., Mahoney et al., 2018). Finally, even if there were model agreement on future changes in precipitation extremes, those changes do not always translate directly into extreme flooding. This is because factors like land cover and soil moisture will affect how quickly rainfall is routed towards rivers and streams (Sharma et al., 2018).

On a local level, studies following the Colorado flood in 2013 provide a concrete example of how complex these issues can be, even for a specific flood event. The 2013 flood inspired a series of studies on whether climate change might have contributed to the severity of the event, and whether storms like this might become the "new normal." But research into the mechanisms for this event, and how climate change could have influenced it, had mixed conclusions. For example, Hoerling et al. (2018) found that the probability of a 2013-type event occurring in Colorado may have actually decreased due to climate change, because of changes in atmospheric circulation and moisture availability. In contrast, Pall et al. (2017) evaluated how the total rainfall during the 2013 flood might have been influenced by warming, and concluded that the total precipitation might have been as much as 30% lower without the human-driven climate warming over the late 20th and early 21st century. The differences in the outcomes from these two studies underscore the complexities inherent in diagnosing the causes of past events, and the difficulty in projecting future flooding extremes. Moreover, the uncertainty in how climate change might influence flood severity in Colorado contributes to the challenge in developing cost-effective engineering solutions to protect Boulder residents from highly uncertain future flood conditions.

Federal Guidance regarding Climate Change and Flood Risk

Over the past several years, federal agencies who deal with water infrastructure have acknowledged the need to incorporate climate science into planning and engineering design. Many of the agencies tasked with water infrastructure and disaster mitigation – including the US Geological Survey, the National Oceanic and Atmospheric Administration, the US Army Corps of Engineers, the Federal Emergency Management Agency, the US Bureau of Reclamation, and the US Department of Transportation – have developed guidance on how to consider climate change in flood risk for their agencies. This section summarizes some of this federal guidance.

US Geological Survey (USGS)

The USGS is the federal agency in charge of collecting, quality controlling, and disseminating streamflow monitoring data for the nation's rivers and streams. USGS also publishes guidelines for flood frequency analysis that are used across the federal government. Prior to 2019, formal guidelines for flood frequency analysis had not been updated since the publication of Bulletin 17B (USGS, 1981). That Bulletin explicitly stated that climate change need not be included in flood frequency analysis:

> There is much speculation about climatic changes. Available evidence indicates that major changes occur in time scales involving thousands of years. In hydrologic analysis it is conventional to assume flood flows are not affected by climatic trends or cycles. Climatic time invariance was assumed when developing this guide. (USGS, 1981)

Since the publication of Bulletin 17B, the USGS has gradually made more specific reference to the hydrologic impacts of climate change in its guidance. For example, in 2009 the USGS was one of four federal agencies who developed a report entitled "Climate Change and Water Resources Management: A Federal Perspective" (Brekke et al., 2009). This report summarized the state of the science at that time, and included general guidance on incorporating climate change into flood risk analyses:

> … simulated hydrologic projections consistent with climate projections might be surveyed for annual series of maximum flood events (or other hydrologic extremes of interest). Such information might be generated relative to an ensemble of climate projections to incorporate projection uncertainty into the estimation of projected flood-frequency distributions, evolving through time. (Brekke et al., 2009, p. 20)

Brekke et al., (2009) however, underscored the uncertainties in climate change projections, and the potential cost implications of revising water and flood management plans to adapt to an uncertain future:

> When contemplating the value of incorporating climate projections into […] river operations, managers must weigh potential benefits, given uncertainties in climate information, against the known and immediate costs of revision to operations. (Brekke et al., 2009, p. 29)

In 2019, the USGS updated the flood frequency analysis guidelines in Bulletin 17B, with the release of Bulletin 17C. Most of the major changes to the flood frequency analysis guidelines in Bulletin 17C focused on new techniques for calculating flood extremes and confidence intervals. However, Bulletin 17C also included a more direct discussion of climate change:

> In those situations where there is sufficient scientific evidence to facilitate quantification of the impact of climate variability or change in flood risk, this knowledge should be incorporated in flood frequency analysis by employing time-varying parameters or other appropriate techniques. All such methods need to be thoroughly documented and justified. (England et al., 2019)

Bulletin 17C summarizes methods for evaluating whether there are trends in historical data. However, while the report explicitly notes that future climate change should be considered in flood frequency analysis when there is sufficient scientific evidence to do so, it does not provide specific guidance on how this should be done, noting only that "additional work in this area is warranted" (England et al., 2019).

National Oceanic and Atmospheric Administration (NOAA)

The National Weather Service, as part of NOAA, manages weather and climate data throughout the United States. NOAA publishes a series of reports summarizing extreme precipitation statistics for the United States, which include models of intensity, duration and frequency (IDF) curves that are used in flood planning. NOAA periodically updates those reports to reflect new observational data as those data become available. Collectively, these extreme precipitation reports are referred to as Atlas 14, and they provide a comprehensive dataset that is relied on by states and municipalities throughout the country. The Atlas 14 report for the midwestern region, which includes Colorado, was most recently updated in 2013 (Perica et al., 2013). This version of Atlas 14 includes a detailed statistical analysis of all station data to evaluate whether there are trends in annual maximum precipitation over the period of record.

Based on two different statistical tests, Perica et al. (2013) found positive trends in the annual maximum precipitation data for only 11-14% of the stations across the entire midwestern region. Many of the stations evaluated for the state of Colorado had records over 100 years in length. While it should be noted that this report was produced prior to the 2013 Colorado floods, the majority of stations along the northern Front Range showed no statistically significant trend in annual maximum 1-hour or 24-hour precipitation: Perica et al. (2013) identified positive trends in 1-hour precipitation maxima at a total of seven stations, and positive trends in 24-hour precipitation maxima at a total of four stations (Figure 1). Thus, there does not generally appear to be a long-term increasing trend in annual maximum rainfall for Colorado that could be linked to recent anthropogenic climate change.

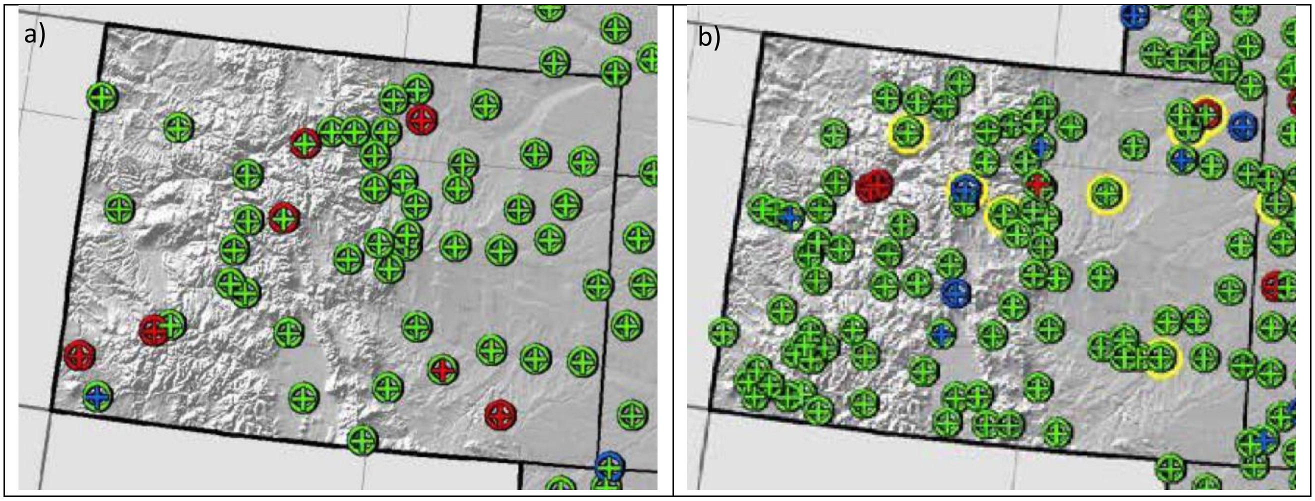


Figure 1. Results of trend analysis for a) 1-hour and b) 24-hour precipitation extremes in Colorado. Red symbols show stations with an increasing trend in extremes based on one of two statistical tests; blue symbols show stations with a decreasing trend; and yellow symbols show stations with a change in variability (source: Perica et al., 2013)

On a regional level, NOAA's statistical analysis also indicated that the historical data do not support the application of a climate-change trend to observed precipitation extremes:

> Results from the regional trend analysis also indicated that the null hypothesis, that there are no trends in AMS, [annual maximum timeseries] could not be rejected at the 5% significance level for any of the four climate regions for the 1-hour and 1-day durations.
>
> Because tests at both the 1-hour and 1-day durations indicated no statistically significant trends in the data, the assumption of stationary AMS was accepted for this project area and no adjustment to AMS data was recommended. (Perica et al., 2013)

Based on the statistical analyses included in the NOAA Atlas 14 update, NOAA therefore did not find justification for incorporating a climate change trend into the analysis of extreme precipitation for the state of Colorado.

US Army Corps of Engineers (USACE)

As the federal agency tasked with managing much of the United States' flood control infrastructure, USACE has a great deal at stake to ensure that flood risks are properly characterized. USACE has developed a number of reports related to climate change over the past decade, ranging from general guidance to quantitative assessment tools.

USACE's 2014 Climate Change Adaptation Plan (USACE, 2014) summarizes a range of USACE service areas where climate change could affect their operations. The document does not provide any specific detail on how climate change could affect flood risk, except to summarize some of the academic literature on climate change and nonstationarity[1]. The 2015 update to the Climate Change Adaptation Plan (USACE, 2015) adds relevant priorities and guidelines issued after 2014. Those updated priorities and guidelines include a summary of Executive Order 13690, which proposed a new Federal Flood Risk Management Standard (FFRMS) for critical federal infrastructure.

[1] In hydrology, stationarity refers to the idea that the variability in parameters like annual peak flow is unchanging with time. In contrast, nonstationarity suggests that there is a trend in these parameters, such that the probability of an extreme flood could increase due to human-driven changes (i.e., today's 100-year flood could become a 50-year flood in the future)

In the past several years, USACE has issued more quantitative guidance for incorporating climate change into flood risk assessment. The majority of this work has focused on ways to include observed historical changes in hydrology, where they exist, into flood risk analysis. As an example, in 2017 USACE issued an Engineer Technical Letter (ETL) entitled *Guidance for Detection of Nonstationarities in Annual Maximum Discharges*(USACE, 2017). The motivation for the ETL is described as follows:

> USACE projects, programs, missions and operations have generally proven to be robust enough to accommodate the range of natural climate variability over their operational life. But in some places and for some impacts relevant to USACE operations, climate change and modifications to watersheds are undermining the fundamental design assumption of stationarity (the statistical characteristics of hydrologic time series data are constant through time). (USACE, 2017)

The ETL is accompanied by a nonstationarity detection tool (Friedman et al., 2018), which can analyze annual maximum streamflow records to evaluate whether nonstationarities exist. Combined, the ETL and the nonstationarity detection tool provide a means to evaluate whether *historical* streamflow records may have been modified by climate change. However, these documents do not provide specific recommendations for how engineering design should be altered to accommodate any nonstationarities if they are detected; nor do these documents provide guidance on how *future* hydrologic projections should be considered.

In 2018, USACE issued Engineering and Construction Bulletin 2018-14 (ECB 2018-14), which "provides guidance for incorporating climate change information in hydrologic analyses in accordance with the USACE overarching climate preparedness and resilience policy" (USACE, 2018). As with other USACE documents, however, the guidance is not intended to be prescriptive:

> At the time of issuance of this ECB, USACE policy does not require a quantitative assessment of how climate change might impact probable maximum flood (PMF) magnitudes for a particular study area (USACE, 2018).

Thus, while USACE has provided guidance on how to detect and quantify historical climate change signals in hydrologic records, this guidance does not appear to have developed to the point of providing specific recommendations for changes in engineering design.

Federal Emergency Management Agency (FEMA)

FEMA's mission is to help people both prepare for and recover from disasters, including floods. While the majority of FEMA's resources are devoted to disaster recovery, the agency also has a range of programs designed to mitigate risk prior to disasters. Incorporating climate change into analysis of risk is therefore relevant to FEMA's mission.

In 2016, FEMA issued updates to its floodplain management regulations that were designed to incorporate climate change into flood risk assessment:

> In order to ensure resiliency, Federal agencies, when taking actions in and around floodplains, should include considerations of the effects of climate change, including sea level rise, more frequent and severe storms, and increasing river flood risks. (FEMA, 2016)

Similar to USACE, FEMA's 2016 updates were developed to align with the Federal Flood Risk Management Standard (FFRMS). The FFRMS applied to federally funded projects, and allowed agencies to establish floodplains using one of four approaches:

(1) Climate- Informed Science Approach (CISA): Utilizing the best-available, actionable hydrologic and hydraulic data and methods that integrate current and future changes in flooding based on climate science;

(2) Freeboard Value Approach (FVA): Freeboard (base flood elevation + X, where X is 3 feet for critical actions and 2 feet for other actions);

(3) 0.2 percent annual chance Flood Approach (0.2PFA): 0.2 percent annual chance flood (also known as the 500-year flood); or

(4) the elevation and flood hazard area that result from using any other method identified in an update to the FFRMS. (FEMA, 2016)

FEMA (2016) includes a flow chart to guide agencies' decisions regarding how floodplains should be defined, depending on whether the actions are federally funded projects, and whether they are considered critical actions (Figure 2). This flow chart was developed to help agencies evaluate whether to adjust their infrastructure plans to accommodate larger floods under future climate regimes. Under the FFRMS, the default for non-critical, non-federal actions was to use the 1% annual chance (100-year) floodplain to guide future planning.

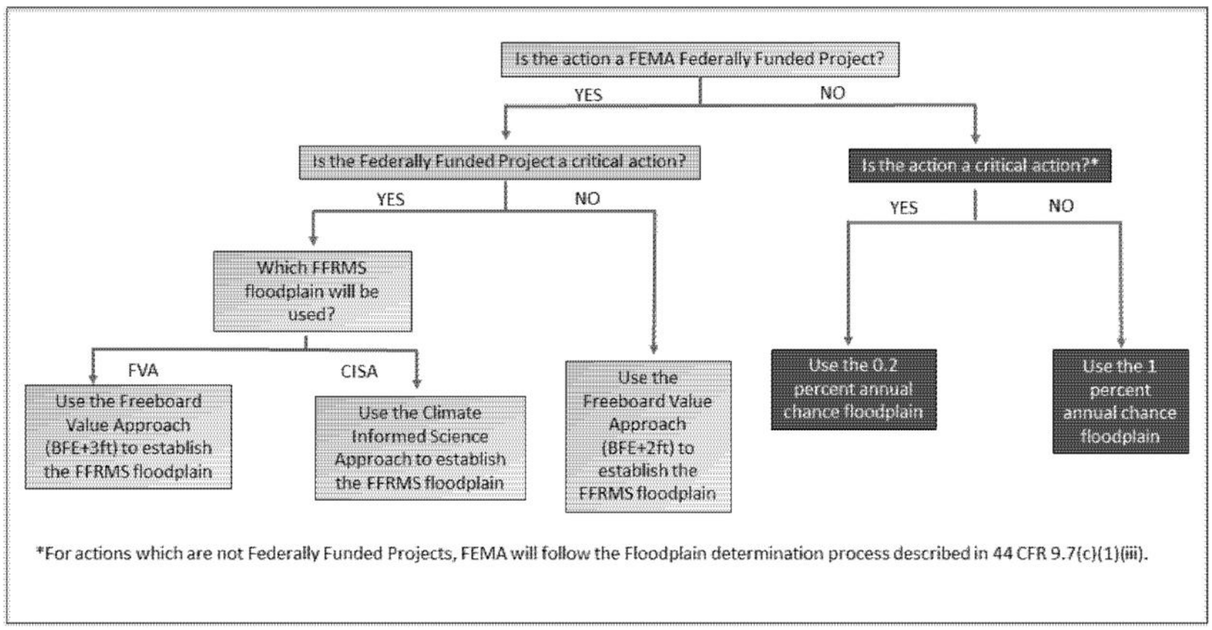


Figure 2. Flow chart for implementation of the Federal Flood Risk Management Standard

Under the FFRMS, the definition of a "critical action" was based on advice included in Executive Order 11988, which provided early guidance on floodplain management. That advice defined a critical action as "any activity for which even a slight chance of flooding is too great…and reflects a concern that the impacts of floods on human safety, health, and welfare for many activities could not be minimized unless a higher degree of protection than the base flood was provided."(Interagency Task Force on Floodplain Management, n.d.). Based on this definition, "critical actions" include construction of facilities that would add dimensions to a flood disaster (such as storage of toxic or water-reactive materials); or facilities that could increase potential for loss of life in a flood disaster (such as hospitals, schools, or nursing homes). For those types of facilities, the flow chart accompanying the FFRMS leads to the highest level of conservatism in constructing those facilities in and near floodplains – either using the 0.2 percent annual chance floodplain for non-federal actions or using the Freeboard Value or Climate-Informed Science approach for federal actions (see Figure 2).

In 2017, Executive Order 13807 was established to streamline environmental review and permitting processes for infrastructure projects. Although the major goal of EO 13807 was to reduce permitting times for environmental reviews, this order also revoked the FFRMS. As a result, this flood management standard providing guidance for siting of projects within floodplains was removed from federal agency guidelines.

US Bureau of Reclamation (USBR)

The US Bureau of Reclamation is the largest water wholesaler in the United States. As the second largest producer of hydroelectric power in the country, USBR also manages dams throughout the western United States. As a result, USBR has an interest both in securing water supply and in protecting its infrastructure against extreme flood events. USBR's research on climate change has focused on both of these goals.

In 2011, USBR and the USACE jointly released a publication entitled "Addressing Climate Change in Long-Term Water Resources Planning and Management" (Brekke, 2011). In it, the agency lays out approaches for considering climate change in planning, as well as major gaps that remain before these data can be made actionable. Among the gaps included in that report was a "method for estimating extreme meteorological event possibilities, deterministically or probabilistically, in a changing climate" (Brekke, 2011, p. 46). Another gap identified by USBR was "guidance on how to make decisions given the uncertainties introduced by consideration of climate projection information" (Brekke, 2011, p. 69). Thus in 2011, USBR recognized the difficulty in both quantifying future extremes and making climate change information actionable for decision-making.

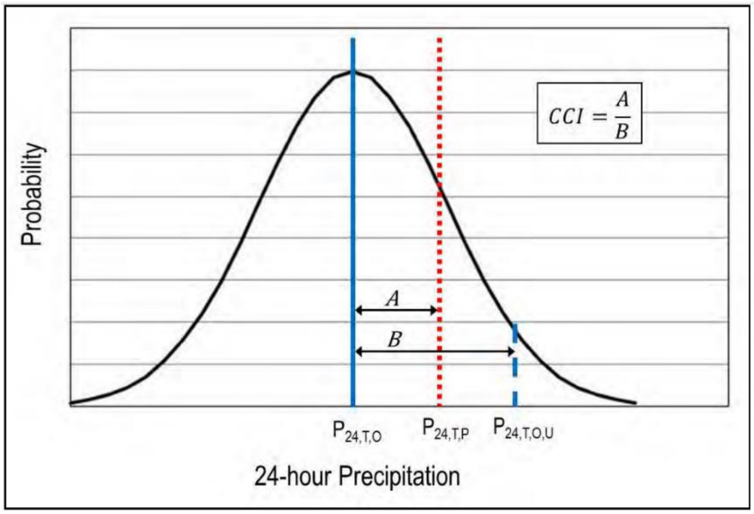
More recently, USBR published its Climate Adaptation Strategy, in 2016. The primary focus of this document is on water supply and reservoir management across the Western United States. The report also provides a general overview of anticipated changes in flooding, but this overview is focused on changes in the timing of spring runoff and implications for water storage and management. It is not as focused on how changes in extreme rainfall could affect specific infrastructure or assets.

US Department of Transportation (USDOT)

USDOT supports the maintenance of roads, bridges and other transportation infrastructure across the United States. An increase in the frequency and severity of floods and other extreme events could therefore tax limited resources available to the agency. Over the past several years, DOT has developed a vulnerability assessment framework, provided funding to states for climate change impact studies, and prepared multiple reports on how to incorporate climate change into transportation planning.

In 2014, USDOT published a policy directive entitled "Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events" (USDOT, 2014), which highlighted DOT's commitment to identifying climate-related risks to transportation systems. This directive did not provide any prescriptive guidance, but it did underscore the need within DOT to consider climate change and extreme events for its operations.

DOT's 2016 report *Highways in the River Environment – Floodplains, Extreme Events, Risk, and Resilience* (also referred to as HEC-17) "provides guidance and methods for assessing the vulnerability of transportation facilities to extreme events and climate change in riverine environments" (USDOT, 2016). Similar to USACE's guidance documents, much of HEC-17 describes tools to detect nonstationarities in hydrologic records and methods to adjust for those nonstationarities. The document provides links to tools that DOT has developed to analyze climate model outputs.



All of these tools are placed into context through a proposed analysis framework, in which a "Climate Change Index" (CCI) is proposed as a way to evaluate whether climate change should be incorporated into project design. The CCI is a ratio of the projected change in design flows due to climate change vs the uncertainty in the design flows using historical data alone. Under this framework, explicit incorporation of climate change into engineering design is recommended only when the CCI is larger than approximately 0.8 (USDOT, 2016); in other words, climate change should be incorporated into design only when the climate change signal is large and clear.

Figure 3. Calculation of the CCI, per USDOT: In this example, the value of "A" is the difference in the design precipitation event under baseline vs future climate, and the value of "B" is the uncertainty in the baseline design storm estimate. DOT (2016) recommends incorporating climate change into design only when the climate change signal A is large relative to the uncertainty in the design storm. (Source: USDOT, 2016 Figure 7.4)

Summary of Federal Guidance

Each of the federal agencies with flood control, water management, or disaster preparedness in its mission acknowledges that climate change is likely to affect flood risk in the future. Some, like USGS, NOAA and USACE, have developed statistical methods, guidelines and tools for quantifying historical changes in precipitation and flood magnitudes. Others, like FEMA, have considered broad guidance like the Federal Flood Risk Management Standard, (EO 13690), which included guidelines for construction of new facilities in floodplains to make those facilities more resilient to potential changes in flood risk. USDOT provides a framework for using climate change information to evaluate when future projections should be considered more quantitatively. However, most of the federal agency documents we evaluated do not provide quantitative guidance on how to incorporate future changes in flood risk into engineering design.

Based on this review, virtually every federal agency tasked with managing water infrastructure or flood risk acknowledges that climate change is likely to affect flood risk in some way. However, there do not yet appear to be any prescriptive federal guidelines or policies describing how local planning agencies should incorporate climate change into engineering design for flood risk management.

State Guidance Regarding Climate Change and Flood Risk

There are a number of state agencies in Colorado who are tasked with managing water resources or protecting Colorado's citizens and assets from natural hazards. This section summarizes some of these agencies and specific guidance they have issued.

Colorado Water Conservation Board (CWCB)

In 2014, CWCB partnered with the Western Water Assessment and others to develop "Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation"(Lukas et al., 2014). According to this synthesis report, "the evidence suggests that there has been no statewide trend in the magnitude of flood events in Colorado." However, Lukas et al. (2014) also cite analyses noting that extreme (1-in-20-year) daily precipitation events in Colorado are projected to increase by 5-10% by mid-century. Ultimately, Lukas et al. (2014) conclude that "the range of projected changes for a given hydroclimate variable…is most appropriately used as a general guide to expected tendencies, not as a probability distribution that provides precise quantification of future risk." Thus, the recommendations in Lukas et al. (2014) do not provide quantitative guidance on how to modify any engineering structures to incorporate climate change.

More recently, CWCB was a lead agency involved in a climate change risk assessment referred to as the Future Avoided Cost Explorer: Colorado Hazards (FACE:Hazards)(CWCB, 2020). The main objective of the FACE:Hazards project was to quantify and monetize the economic impacts of climate change as a communication tool to help Colorado's citizens, municipalities, and legislators better understand their climate-related vulnerabilities. However, the tool also includes a sampling of general resilience strategies for flooding, along with examples from communities on how those strategies have been implemented in the past. Those strategies include regulating development in high-risk zones, integrating flooding into existing plans, adopting smart flood hazard reduction practices, adopting nature-based solutions to watershed health, and improving community warning and evacuation plans, among others. The majority of these resilience strategies are general, and were not meant to provide any prescriptive guidance.

Colorado Department of Natural Resources - Dam Safety Program

The Colorado Department of Natural Resources houses the Dam Safety Program, which is charged with ensuring that dams are operated safely and that plans and specifications for future dams follow best practices for modern dam safety. In accordance with this mission, Dam Safety produced the "CO-NM Regional Extreme Precipitation Study" (CO NM REPS; Mahoney et al., 2018) to evaluate how climate change can be incorporated into estimates of the probable maximum precipitation (PMP). This evaluation was developed to help stakeholders in Colorado and New Mexico make informed risk management decisions around dam safety.

The CO-NM REPS report includes a summary of the science regarding climate change projections for temperature and precipitation, as well as federal agency guidance relevant to understanding climate change risks. It concludes with a set of recommendations for how climate science should be incorporated into future planning for infrastructure design:

> While anthropogenic climate change may have other, less certain, effects on storm characteristics, observations and model simulations suggest that the basic thermodynamic effect—the increase in precipitable water (PW) with warming temperatures—is likely to take precedence over the other effects, at least at regional to global scales. At local scales, other effects may become more prominent than the PW increase […] Accordingly, our recommendation is that the implementation of PMP or other metrics of risk from extreme precipitation in infrastructure design and regulation by the states of Colorado and New Mexico account for this fundamental, thermodynamically driven PW change, either qualitatively or quantitatively. (Mahoney et al., 2018)

Mahoney et al. (2018) proceed to provide three different "families" of approaches for how climate change can be considered in decision-making in Colorado:

1) A qualitative approach, in which more conservative options are chosen for flood risk analysis when there are choices in design (i.e., rules for calculating risk for each dam classification would be applied to the next lower classification);

2) A quantitative approach, in which the PMP is adjusted upward by a factor that corresponds to the increase in precipitable water; and

3) A quantitative, risk-informed framework that formally incorporates non-stationary climate into flood risk, for example via climate-adjusted intensity-duration-frequency curves for precipitation.

Based on the set of recommendations contained in Mahoney et al. (2018), the Dam Safety program issued new rules for future dam construction that are most analogous to bullet #2 above. This new rule was developed to incorporate climate change into the calculation of the inflow design flood (IDF) for spillway design. Specifically, the regulation is as follows:

> All rainfall depth estimates calculated by means acceptable to the State Engineer shall be multiplied by a factor of 1.07 prior to calculating runoff to account for expected increases in temperature and associated increases in atmospheric moisture availability over the 50-year period 2020 to 2070 (Colorado DNR, 2020)

With the adoption of these rules in January 2020, the State of Colorado now has formal guidance for incorporating climate change into the inflow design calculations for new dams or modifications to existing dams. This guidance is based on the general principle that a warming atmosphere can hold more moisture, thereby increasing the potential for larger precipitation extremes.

Summary of State Guidance

Both CWCB and the Colorado Dam Safety Program have acknowledged the role of climate change in extreme precipitation and flood risk. CWCB's guidance is generally qualitative, whereas the Dam Safety Program has issued a formal rule that incorporates a percentage change in extreme rainfall into inflow design flood estimation.

Based on this review, the State of Colorado, through the Dam Safety Program, has endorsed a formal rule for incorporating climate change into inflow design calculations for new dam construction. This rule requires that any rainfall depth estimates used for calculating the inflow design flood must be multiplied by a factor of 1.07 to account for future climate change over the middle of the 21st century.

Local Guidance Regarding Climate Change and Flood Risk

At a more local level, entities including Boulder County, the City of Boulder, and the Mile High Flood Control District have acknowledged the importance of climate change in local flood risk planning. While none of these entities have developed formal rules such as those from the Dam Safety program, each of them provides further context for incorporating climate change into flood risk studies.

Boulder County

The Boulder County Climate Change Preparedness Plan (CCPP; Vogel et al., 2012) includes an overview of how climate change has affected Boulder County in the recent past, and how those changes might manifest in the future. The CCPP underscores the difficulty in quantifying trends in extreme precipitation at any given location, and notes that "no trends in the historical record of extreme climate events have been definitively detected in Boulder County." Nonetheless, the CCPP acknowledges that "heavy and extreme precipitation (e.g., the magnitude of the 100-year event) have the potential to increase in a warmer climate" (Vogel et al., 2012). An analysis of regional climate model outputs in the CCPP showed that most models project increases in heavy winter precipitation events, even as summer rainfall extremes were generally projected to decrease.

Given these uncertainties, the Boulder County CCPP noted that "further analysis is required to estimate the degree of conservatism in design standards that minimizes regrets. That is, are the present costs associated with a design standard that proves to be overly conservative less than the present value of future costs due to failure of a design standard that proves to be insufficiently conservative?" While the CCPP does not answer this question for any specific design standards, it does note that "any study should recognize the need for ongoing re-assessment of design standards as our state of knowledge about climate improves" (Vogel et al., 2012).

City of Boulder

The City of Boulder Multihazard Mitigation Plan update (MMP; AMEC, 2018) notes that "globally, precipitation extremes and their hydrological impacts (e.g., the magnitude of 100-year floods) are expected to get larger because in most places, higher temperatures will result in increased atmospheric water vapor available to form precipitation." Given this general finding, it suggests that "the 100-year flood of today might become a more frequent event in the future (i.e., a 50-year event), meaning that current design levels and regulatory practices might be less adequate in the future" (AMEC, 2018).

The summary of mitigation actions in the Boulder MMP update includes reference to Boulder's "Critical Facilities Floodplain Ordinance," which was completed in 2014. This ordinance is focused only on critical facilities and lodging, but expands regulations for structures in 100-year floodplains to structures in 500-year floodplains as well (City Council, 2014). The MMP also summarizes future and ongoing actions that the City of Boulder is undertaking to improve flood resilience. However, these actions do not generally include specific modifications to engineering design standards.

Mile High Flood Control District

The Mile High Flood Control District (formerly Urban Drainage and Flood Control) is a local resource to proactively protect against the impacts of flooding on people and property. In 2019, MHFCD published a study entitled "Planning for Variability and Uncertainty: Climate Change and the UDFCD Urban Drainage System" (Earles et al., 2011). In it, the authors acknowledge the uncertainties in future hydrologic projections of climate change, noting that "it is not possible to say that precipitation, runoff, flooding or other variables will increase or decrease in the future" (Earles et al., 2011). However, they note that "UDFCD criteria related to hydrologic and hydraulic modeling and freeboard provide a margin of safety in design above and beyond the 100-year flood event and therefore, provide resilience to accommodate floods that are larger than the 100-year event in many areas." Thus, MHFCD suggests that the freeboard and factor of safety concepts that are already incorporated into engineering design are likely to be sufficient to accommodate for future climate changes in Colorado.

Summary of Local Guidance

Local governments and agencies around Boulder have evaluated the role of climate change in flood risk. The majority of this work has been qualitative, but recommendations align with the more quantitative guidance from the Dam Safety Program.

Based on this review, the local agencies tasked with flood control and management have each acknowledged climate change in their guidance documents. The City of Boulder's floodplain ordinance expands the regulations applicable to 100-year floodplains into the 500-year floodplain for critical facilities, in line with the qualitative guidelines established in the FFRMS. The City of Boulder's MMP also highlights the atmospheric water vapor driver for potential increases in flooding, in line with the State recommendations from the NM-CO REPS report.

Summary

We reviewed guidance from academic literature and from local, state and federal agencies regarding how climate change could affect flood risk, and how these changes should be incorporated into infrastructure design. Our main findings are as follows:

- As global temperatures warm, the atmosphere can hold more water vapor. On average, this increase amounts to approximately 7% more water in the atmosphere per degree C of warming. Accordingly, the potential for extreme rainfall is generally expected to increase with continued global warming.
- A survey of federal agency guidelines and documents shows that the agencies tasked with managing water resources or flood risk acknowledge that climate change should be considered in their long-range planning; however, there is little to no prescriptive guidance on how to modify engineering designs to account for climate-induced changes in flood risk.
- State and local agencies in Colorado have also generally acknowledged the potential impact of climate change on flood risk, including guidelines for floodplain development.
- The State of Colorado's dam safety guidelines require that for new dam designs, inflow design floods must be adjusted upwards by 7% to account for the increased moisture holding capacity of a warming atmosphere by mid-century.

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