Planning for Variability & Uncertainty: Climate Change and the UDFCD Urban Drainage System

By Dr. Andrew Earles[1], P.E., D.WRE; Ken Mackenzie[2], P.E.; David Bennetts[3], P.E.; and Julia Traylor[1], EIT.

Executive Summary

Climate change is a topic that we hear about almost daily in the news, and it is a topic that has been the subject of extensive Federal research for more than two decades. With the potential for climate change to affect temperature, rainfall, runoff, evapotranspiration and other hydrologic variables, it is reasonable to ask how these changes may affect the urban drainage system. Increasingly, this question has been posed to Urban Drainage and Flood Control District (UDFCD). To address this question, UDFCD and Wright Water Engineers, Inc. (WWE) have prepared this technical paper to review climate change projections for Colorado and the Front Range, to identify potential vulnerabilities of the urban drainage system and to inventory and assess UDFCD policies, criteria and programs that provide resiliency for future climate and hydrologic variability.

While global and regional climate models are generally consistent in projections of future increases in average temperatures, hydrologic effects of climate change are far less certain and range from decreases to increases in annual and seasonal precipitation. The natural variability of hydrology and the short period of record of available data make it very difficult to detect trends (if any) in long-term precipitation due to changes in climate. In addition, urban flood events and infrastructure design are usually governed by short-duration rainfall events rather than season or annual averages. At this point in time, there are insufficient data to reliably forecast changes in intensity-duration-frequency estimates used to define design storms, especially for less-frequently occurring events that are of most concern for flooding.

While future changes in peak flows and flooding are highly uncertain and impossible to predict on an event basis, changes in seasonal or annual temperatures, precipitation and stream flow have the potential to impact stream corridors because these systems are heavily reliant on vegetation being the first and often times the primary layer of armoring to resist erosive forces of flows. If the vegetation becomes stressed or dies off, it no longer has the structural integrity needed to help stabilize the system. Additionally, as noted in the UDFCD Good Neighbor Policy adopted in February, 2011 the Natural and Beneficial Functions (NBF) of streams and floodplains includes: trail corridors, parks, recreation, wildlife habitat, flood storage and groundwater recharge and serve as amenities to adjacent neighborhoods and

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[1] Vice President of Water Resources and Water Resources Project Engineer, Wright Water Engineers, Inc.
[2] Manager of Master Planning Program, UDFCD.
[3] Manager of Design, Construction, and Maintenance Programs, UDFCD.

entire communities. These NBF rely on diverse and healthy vegetation, which may be affected by climate change (drought or flood).

Given the high level of uncertainty in hydrologic projections and natural variability in hydrologic processes, it is not possible to say that precipitation, runoff, flooding or other variables will increase or decrease in the future. However, based on climate model projections, it is likely the variability will increase, resulting in both wetter-than-normal and drought years. Therefore, evaluating implications of increased and decreased precipitation is prudent.

Fortunately, UDFCD has practiced conservative engineering design through programs, policies and criteria since the early 1970s. Policies, criteria and practices have been refined through adaptive management over a period of more than 40 years to better address natural variability in hydrology, changes in regulations, new or revised technical practices, etc. Adaptive management and approaches are used in all of UDFCD's major program areas and provide important institutional flexibility that is critical for adapting to changes in climate in the future. Based on WWE's evaluation, these programs, policies and criteria provide a high degree of resilience to the effects of climate change in terms of both flooding and drought.

UDFCD programs, policies and criteria that provide resilience include:

- Master Planning Program – The Master Planning Program is responsible for criteria in the Urban Storm Drainage Criteria Manual and planning for outfall systems and major drainageways. The Master Planning Program is also responsible for development of stormwater quality management criteria and conducts research on the effectiveness of stormwater quality control practices. The Urban Storm Drainage Criteria Manual, originally created in 1969, includes policies and criteria that result in conservatively designed drainage and flood control infrastructure, providing a high degree of resilience for the range of potential future hydrologic scenarios projected by climate change experts. In addition, the Master Planning Program periodically updates criteria and policies for drainage, flood control and stormwater quality based on the evolution of the practice, and this adaptive management approach is well-suited for managing the effects of climate change on the urban drainage system in the future.
- Design, Construction, and Maintenance Program – The Design, Construction, and Maintenance (DCM) Programs purpose statement supports the larger mission and vision of UDFCD, which is to reduce flood risks by promoting healthy streams. This is implemented through mitigation projects and annual stream management work. DCM uses a Project Partners approach to delivering projects which brings together a team of experts at the onset of a project to work collaboratively to achieve identified goals. As with the Master Planning Program, the DCM Program continues to hone adaptive management practices to ensure program and specific project goals are met. With the recognition of the importance of stream health in the overall stability and NBF of streams, DCM has made understanding stream health as it pertains to floodplain management a program priority.

Based on projections from climate experts, one of the most likely scenarios for the future is greater stress on vegetation due to increased temperatures and greater hydrologic variability, which has the potential to affect stream health. DCM collects data and monitors vegetation along streams to identify and then assess stressors on vegetation. DCM works with a team of experts to make adjustments and respond to the changing environment. This has been a part of UDFCD's long-standing adaptive management approach.

- Floodplain Management Program – The Floodplain Management Program prepares flood hazard delineations and acts as a Cooperating Technical Partner for the Federal Emergency Management Agency related to permitting within the UDFCD boundaries. The UDFCD Floodplain Preservation Policy and the UDFCD Good Neighbor Policy place a great deal of importance on floodplain preservation and natural and beneficial uses of floodplains. Based on projections from climate experts, changes in the magnitude of the major (100-year) flood are uncertain. This is a function of the natural variability in rainfall-runoff, a limited period of record and other factors. 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. These conservative design practices along with UDFCD's policies to discourage development in flood prone areas provide resilience for current and future projected variability in hydrology.
- Information Services and Flood Warning Program – As demonstrated following the September 2013 Flood and other recent events, UDFCD operates a state-of-the-art flood warning system. Data collected through this program include precipitation and stream flow, and these sources of data may prove useful in the future for evaluating changes in rainfall-runoff. The Information Services and Flood Warning Program provides an additional degree of resiliency related to rainfall, runoff and flooding and is important for protection of public health, safety and welfare when large flood events do occur.

In summary, although increases in average temperatures and increased variability in hydrology are widely projected by climate change experts, the effects of these changes in the urban drainage system cannot be forecast with a high degree of certainty. Existing programs, policies and criteria of UDFCD have been developed over a period of more than 40 years with an understanding and respect for the natural variability of hydrology. As a result, the urban drainage systems in many parts of the metropolitan Denver area where improvements have been constructed in accordance with 100-year design standards already have a high degree of resilience to potential future hydrologic changes associated with climate. In addition, UDFCD programs have a long history of adaptive management, and this approach will serve UDFCD well in addressing future changes in climate whether these changes include increases or decreases in precipitation and runoff or both.

Introduction

Climate change is a topic that has been at the forefront of federal and state research for more than two decades and is a topic that is frequently covered by the media. Increases (or decreases) in temperature, precipitation, runoff and other environmental conditions have the potential to significantly affect communities across the country and around the world. Because temperature is a fundamental driver of the hydrologic cycle that influences processes including precipitation, evapotranspiration, snowmelt and others, changes in climate affect the distribution of water in solid, liquid and vapor phases.

UDFCD was established by the Colorado legislature in 1969, for the purpose of assisting local governments in the Denver metropolitan area with multi-jurisdictional drainage and flood control problems. The UDFCD covers an area of 1,608 square miles and includes Denver, parts of the 7 surrounding counties, and all or parts of 32 incorporated cities and towns. There are about 1,600 miles of "major drainageways" which drain watersheds of at least 1,000 acres. The population of UDFCD is approximately 2.8 million people.

Because hydrology is fundamental to the work conducted by UDFCD, variability in precipitation and the probabilistic nature of flood events are topics that UDFCD has addressed for more than 40 years. Increasingly, UDFCD has received inquiries from its citizens and communities on UDFCD's plans to adapt to climate change and effects of climate change on flooding, drainage criteria and the overall urban drainage system. Effective performance of the urban drainage system is essential for protection of public health, safety and welfare, so understanding and planning for potential changes in climate and the effects on the urban drainage system is important to UDFCD.

To facilitate planning for future climate change scenarios, UDFCD has prepared this paper, which addresses the following:

- Review of the latest projections from climate scientists related to temperature, precipitation, stream flow and other variables affecting the urban drainage system.
- Review of potential vulnerabilities of the urban drainage system and potential hydrologic changes including increases in precipitation and increased drought periods.
- Identification and review of UDFCD policies and criteria that provide resilience to hydrologic changes.
- Strategies for adapting to potential future changes including periods of greater precipitation as well as periods of extended drought.

It is critical that this paper is understood in the context of variability and uncertainty. For the purposes of this paper, variability refers to natural fluctuations in hydrologic parameters such as rainfall, soil characteristics, physical rainfall-runoff relationships and other factors. Uncertainty refers to how accurately we know the parameters that are used for design. Higher variability generally leads to a higher degree of uncertainty, especially in the case of hydrologic data, which typically are based on periods of record that are considerably shorter than the recurrence intervals of severe events.

Hydrology, by its very nature has a high degree of variability and uncertainty. Precipitation depths and runoff rates and volumes can vary by orders of magnitude from small events to large events. The data, parameters and procedures used to plan and design urban drainage systems also exhibit uncertainty and variability, including mean precipitation depths used to define design storms, runoff coefficients selected to transform rainfall to runoff, and computer models and engineering methods for routing flows and calculating water depths.

How Communities Are Adapting to Climate Change

The United States National Climate Assessment (USNCA) produced a report in 2014 assessing climate change impacts across the United States presently and in the future. It integrates findings of the U.S. Global Change Research Program with results of research and observations from across the U.S. and around the world, including reports from the U.S. National Research Council. This report addresses climate change related impacts and responses for various sectors and regions and aims to better inform public and private decision-making at all levels.

A universal adaptation solution to the challenges of adjusting to climate change impacts is nonexistent since solutions differ depending on local circumstance, scale and internal capacity. Consequently, state and local governments are required to develop individualized climate adaptation plans. In a survey of 298 local U.S. governments, 59% indicated they are in the midst of forming some sort of adaptation plan (USNCA 2014). Recently, the City and County of Denver published a Climate Adaptation Plan outlining both short-term and long-term adaptation activities for sectors of broad planning areas that will be affected by climate change impacts (Denver Environmental Health 2014). The Western Water Assessment, University of Colorado Boulder and Colorado State University have developed the *Colorado Climate Change Vulnerability Study* (Gordon and Ojima 2015). This study provides an assessment of vulnerabilities of major sectors of Colorado's economy to climate change including ecosystems, water, agriculture, energy, transportation, outdoor recreation and tourism, and public health. The study emphasizes the importance of adaptive management in preparing for potential effects of climate change.

Climate change adaptation planning activities will serve municipalities of varying sizes and in diverse geographical areas. While adaptation to climate change goes far beyond water resources, stormwater management and green infrastructure are important components of many adaptation strategies. Examples across the country, in areas with varying vulnerabilities, include:

- Satellite Beach, Florida and Groton, Connecticut have partnered with local estuary programs to assess vulnerability to rising sea levels and incorporate sea level rise projections and policies into the city's comprehensive growth management plan.
- Portland, Oregon updated its city code to require on-site stormwater management for new development and re-development.

- The City of Lewes, Delaware uses a stakeholder-driven process to understand how climate adaptation activities could be integrated into hazard mitigation planning.
- Five municipalities in San Diego Bay, California partnered with more than 30 organizations to develop the San Diego Bay Sea Level Rise Adaptation Strategy, to identify key vulnerabilities for the Bay and adaptation actions that can be implemented by individual agencies and regional collaboration.
- Through a number of development projects, Chicago, Illinois added 55 acres of permeable surfaces since 2008 and has completed or planned more than four million square feet of green roofs.
- King County, Washington created the King County Flood Control District in 2007 to address impacts from flooding through activities such as acquiring repetitive loss properties, maintaining and repairing levees and revetments, and improving countywide flood warnings.
- New York City is updating its Federal Emergency Management Agency (FEMA) Flood Insurance Rate Maps (FIRMs) based on more precise elevation data. The new maps will assist stakeholders in better understanding current flood risks as well as allow the city to plan for climate change more effectively.
- In 2006, the Philadelphia Water Department developed a green stormwater infrastructure, intended to convert more than a third of the city's impervious area to "Greened Acres" which includes green facilities, green streets, green open spaces, green homes, etc., along with stream corridor restoration and preservation.

As would be expected, many of these efforts focus on areas that are susceptible to coastal flooding, a risk that is not present in Colorado. Nonetheless, effects of climate change related to precipitation, snowmelt, drought and other factors have the potential to impact Colorado and other inland states, and many of the larger municipalities are in the process of developing adaptation strategies.

What Are the Climate Experts Telling Us?

The Intergovernmental Panel on Climate Change (IPCC) is the leading international body for the assessment of climate change. The United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) established the IPCC in 1988 "to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts (IPCC 2015)." The IPCC published a series of Assessment Reports (ARs), the 5th of which was published in 2013. The State of Colorado has also studied climate change in efforts led by the Colorado Water Conservation Board (CWCB 2014) and the Western Water Assessment of the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado Boulder. To prepare this paper we have relied on projections related to temperature, precipitation, drought, stream flow and wildfire susceptibility from these and other sources. The goal of this paper is not to evaluate whether these projections are reasonable or if they will occur. Instead the authors have accepted these projections as they are, and have evaluated the range of projections and determined how changes in climate could potentially affect the urban drainage system in the Front Range of Colorado.

Attachment A provides selected figures and text from the CWCB report and other references to supplement the discussion below.

Temperature

While the IPCC studies address temperature on global and regional scales, the best source of regional data and analysis currently available for Colorado is the CWCB's *Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation* (2014). The CWCB report summarizes Colorado-specific findings from regional peer-reviewed studies and draws on the work of Colorado experts in climate and hydrology. Figure 1 shows annual mean temperature variation from the 1950-1999 average for the period from 1930 to 2007. The dark line represents the 10-year moving average. Key findings from climate experts related to temperature include the following, which are quoted from the CWCB report:

- In Colorado, statewide annual average temperatures have increased by 2.0°F over the past 30 years and 2.5°F over the past 50 years. Warming trends have been observed over these periods in most parts of the state.
- According to the CWCB report, in general daily minimum temperatures in Colorado have warmed more than daily maximum temperatures during the past 30 years. Temperatures have increased in all seasons.
- All climate model projections indicate future warming in Colorado.[4] The statewide average annual temperatures are projected to warm by +2.5°F to +5°F by 2050 relative to a 1971–2000 baseline under a medium-low greenhouse gas emissions scenario. Under a high emissions scenario, the projected warming is larger at mid-century (+3.5°F to +6.5°F), and much larger later in the century as the two scenarios diverge.

[4] Climate modeling includes Global Climate Models (GCMs) and regional models. The current generation of models is known as CMIP5 and the previous generation was CMIP3. The CWCB report evaluated results from CMIP3 and CMIP5. CMIP3 included 22 models with 120 model simulations (projections) carried out at 16 modeling centers, and CMIP5 includes 55 models with 250 simulations (projections) that were computed at 30 modeling centers. Simulations evaluate different greenhouse gas emissions scenarios (CWCB 2014).

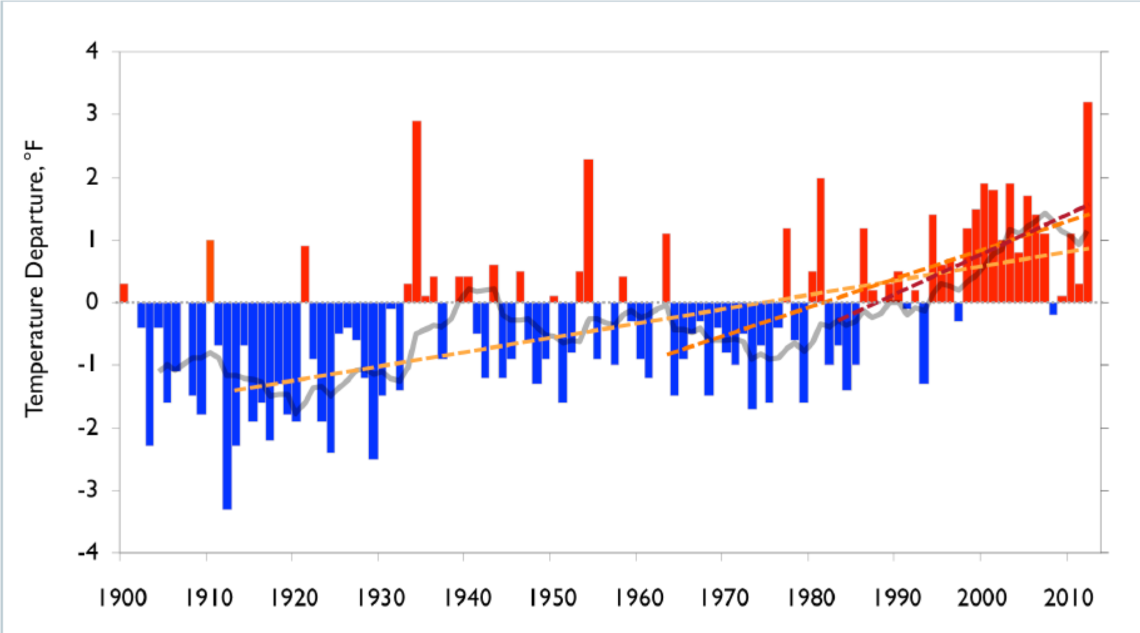
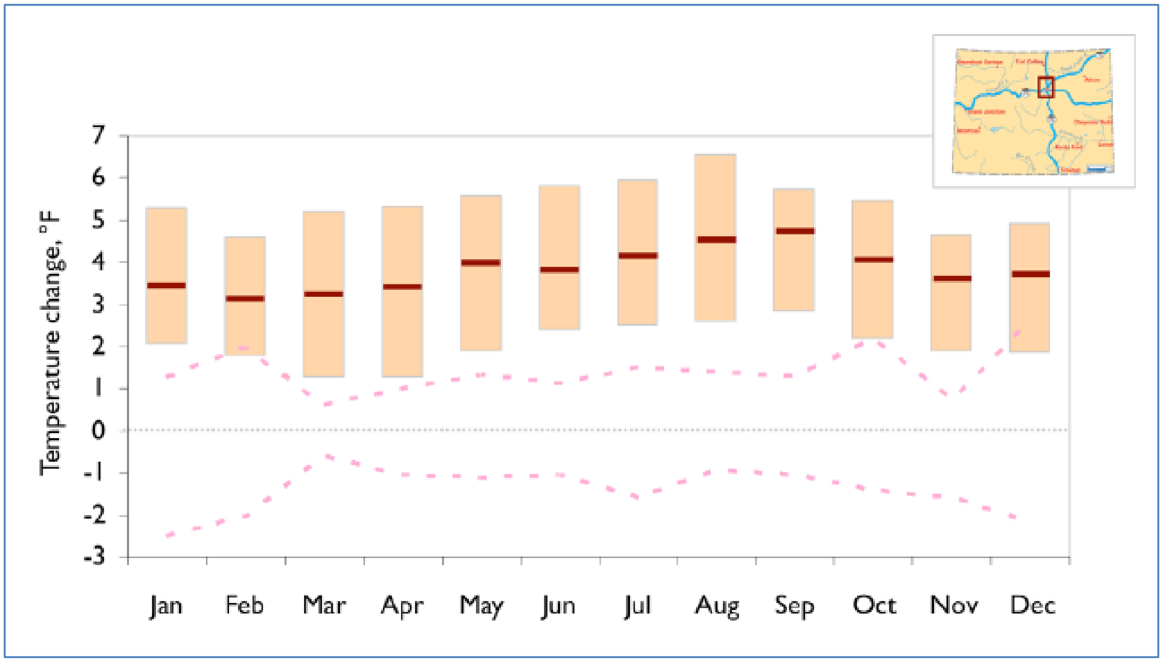


Figure 1. Colorado Statewide Annual Average Temperature, 1900–2012 (CWCB 2014) - Annual departures are shown relative to a 1971–2000 reference period. The light-orange, orange, and red lines are the 100-year, 50-year, and 30-year trends, respectively. All three warming trends are statistically significant. The gray line shows the 10-year running average. The record shows a cool period from 1900 to 1930, a warm period in the 1930s and again in the 1950s, a cool period in the late 1960s and 1970s, and consistently warm temperatures since the mid-1990s.
(Data source: NOAA NCDC; http://www.ncdc.noaa.gov/cag/)

- Figure 2 illustrates seasonal/monthly trends projected under a low-moderate emissions scenario for the Denver Metropolitan sub-regional model. The dark red lines in Figure 2 show the median projection for each month; the orange bars show the range from the 10th percentile to the 90th percentile of the individual model projections. The pink dashed lines show the envelope of observed multi-decadal variability in monthly temperature, derived from the running 30-year averages of a long-term (>100-year) station record within that sub-region. By mid-century, projected temperatures are outside of the bounds of historical variability at local scales and monthly timescales.
- Summer temperatures are projected to warm slightly more than winter temperatures. Typical summer temperatures by 2050 are projected [under a medium-low emissions scenario] to be similar to the hottest summers that have occurred in past 100 years.
- Mid-21st century summer temperatures on the Eastern Plains of Colorado are projected to shift westward and upslope, bringing into the Front Range temperature regimes that today occur near the Kansas border.

Increases in mean temperatures, as described above, would be expected to affect hydrologic and meteorological processes relevant to the urban drainage system including evapotranspiration, precipitation, stream flow, soil moisture, groundwater, drought and others. However, these are complex and interrelated processes influenced by many factors in addition to temperature. Therefore, projections related to future hydrology have a much higher degree of uncertainty.



Range from the 10th percentile to the 90th percentile of the individual model projections
Median projection for each month
Envelope of observed multi-decadal variability in monthly temperature

Figure 2. Projected Monthly Temperature Change for Denver Metro Sub-region under Low-moderate Emissions Scenario for 2035–2064

(Source: Figure 5-9 CWCB 2014 from BCSD5 statistically downscaled CMIP5 projections, Reclamation 2013

http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/)

Precipitation

As the September 2013 Colorado flooding reminded us all, extreme precipitation events have occurred in the past and will occur again in the future. The event was remarkable in many aspects including return period estimates for 24-hour and greater durations on the order of a "1000-year" event in some locations. While the rainfall totals were staggering to the general public, they were foreseeable and expected at some point in time by engineers who understand the probabilistic nature of rainfall. Indeed, in many publications of the American Society of Civil Engineers and other professional societies going back 50 years and longer, the need to anticipate extremely large rainfall and flood events was clearly stated.

The natural variability of precipitation and the short period of record of available data make it very difficult to detect trends (if any) in long-term precipitation due to changes in climate. In addition, urban drainage systems are usually most heavily taxed by short-duration rainfall events rather than seasonal or annual averages. At this point in time, there are insufficient data to reliably forecast changes in intensity-duration-frequency estimates, especially for less-frequently occurring events that are of greatest concern for flooding.[5]

Key findings from climate experts related to precipitation include the following, which are quoted from the CWCB report:

- No long-term trends in average annual precipitation have been detected across Colorado, even considering the relatively dry period since 2000.
- No long-term statewide trends in heavy precipitation events have been detected. The evidence suggests that there has been no statewide trend in the magnitude of flood events in Colorado.
- Climate model projections show less agreement regarding future precipitation change for Colorado. The individual model projections of change by 2050 in statewide annual precipitation [under a medium-low emissions scenario] range from -5% to +6%. Projections [under a high emissions scenario] show a similar range of future change (-3% to +8%).
- Nearly all of the projections indicate increasing winter precipitation by 2050. There is weaker consensus among the projections regarding precipitation in the other seasons.

Reflecting the high degree of variability in precipitation, some models project increases of 2 inches during rainy months and others show decreases of 1.5 inches by 2050 compared to historic data (iCliCS 2014). Figure 3 illustrates seasonal/monthly trends projected under a low-moderate emissions scenario for the Denver Metropolitan sub-regional model. Total precipitation is estimated to change very little in the summer; however, there will likely be an increase in the frequency of summer thunderstorms and convective storm activity due to increased evaporation from higher temperatures (USEPA 1997 and Ojima & Lackett 2002). Precipitation in the spring and fall is estimated to increase by approximately 10 percent, while winter precipitation increases may be greater (USEPA 1997). While projections for precipitation amounts and intensities are highly uncertain, there is less uncertainty in projections of temperature increases. In combination there is a higher degree of confidence in more of winter precipitation falling as liquid rather than snow, which has implications for winter runoff.

The dark red lines in Figure 3 show the median projection for each month; the blue bars show the range from the 10th percentile to the 90th percentile of the individual model projections. The purple dashed lines show the envelope of observed multi-decadal variability in monthly precipitation, derived from the running 30-year

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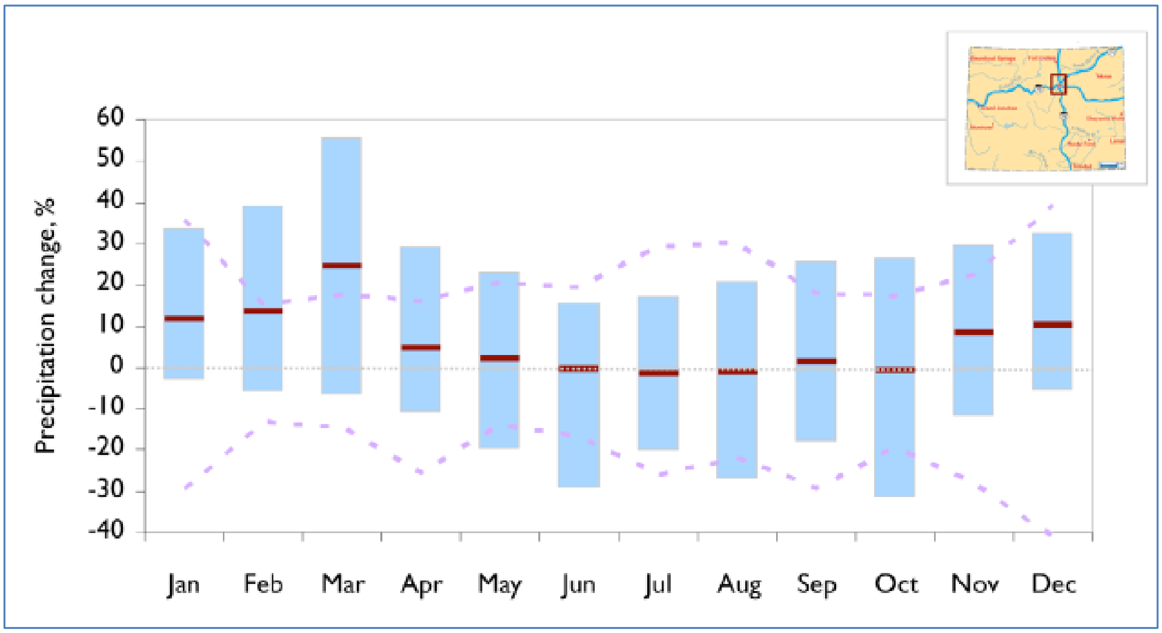
[5] Recent updates to Colorado precipitation mapping as a part of NOAA Atlas 14 actually show modest decreases in 1-hour point precipitation values for a range of return periods. When statistical confidence limits of the NOAA Atlas 14 data are compared with the preceding NOAA Atlas 2 mapping, the new published mean values are not different from the NOAA Atlas 2 values with statistical confidence. Therefore, UDFCD continues to use the precipitation data published in Volume 1 of the Urban Storm Drainage Criteria Manual as the basis for design-storm rainfall within UDFCD.

averages of a long-term (>100-year) station record within that sub-region. By mid-century, most projections for precipitation are within the bounds of historical variability. High emissions scenarios generally demonstrate the same types of variability and uncertainty as shown in Figure 3 for a low-moderate emissions scenario.

While the magnitude of increases or decreases in precipitation has a high degree of uncertainty, most climate models agree that there will be a higher degree of variability, so planning for periods of increased precipitation and periods of extended drought is appropriate for the urban drainage system.



Range from the 10th percentile to the 90th percentile of the individual model projections
Median projection for each month
Envelope of observed multi-decadal variability in monthly temperature

Figure 3. Projected Monthly Precipitation Change for Denver Metro Sub-region under Low-moderate Emissions Scenario for 2035–2064

(Source: Figure 5-10 CWCB 2014 from BCSD5 statistically downscaled CMIP5 projections, Reclamation 2013

http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/)

Stream flow

Stream flow is of great interest to water supply and ecological health, and the CWCB report addresses snowpack, timing of runoff, storage and related topics. Within UDFCD, streams including the South Platte River, Bear Creek, Clear Creek, Boulder Creek, Ralston Creek and others with mountainous headwaters are directly affected by snowmelt, runoff and storage. While snowmelt/runoff is not normally the primary mechanism for major flooding for most urban streams, water availability is a factor in the health, character and function of all streams in the urban drainage system.

Key findings from climate experts related to stream flow include the following, which are quoted from the CWCB report:

- Snowpack, as measured by April 1 snow-water equivalent (SWE), has been mainly below-average since 2000 in all of Colorado's river basins, but no long-term (30-year, 50-year) declining trends have been detected. As with precipitation data, natural variability of snowpack and runoff makes detection of trends difficult given the relatively limited available period of record for analysis[6].
- The timing of snowmelt and peak runoff has shifted earlier in the spring by 1–4 weeks across Colorado's river basins over the past 30 years, due to the combination of lower SWE since 2000, the warming trend in spring temperatures, and enhanced solar absorption from dust-on-snow.
- The peak of the spring runoff is projected to shift 1–3 weeks earlier by the mid-21st century due to warming. Late-summer flows are projected to decrease as the peak shifts earlier. Changes in the timing of runoff are more certain than changes in the amount of runoff.
- In the first projections of future Colorado hydrology based on the latest climate model output, most …projections are more evenly split between future increases and decreases in stream flow by 2050 for the Colorado Headwaters, Gunnison, Arkansas, and South Platte basins. However, other hydrology projections show drier outcomes for Colorado, and the overall body of published research indicates a tendency towards future decreases in annual stream flow for all of Colorado's river basins.

For the South Platte River basin, projections show a high range of variability (roughly -20% to +10% or more) for future April 1 SWE. Projections differ for northern and southern portions of the South Platte River Basin; although, overall trends for the South Platte River basin generally follow statewide trends listed above. While this degree of variability has significant implications for water supply, the changes in stream flow that are projected would have minimal effects on flood control and conveyance functions of the urban drainage system in the Front Range. However, stream flow and water availability have the potential to affect vegetation (type, density and health), riparian habitat, aquatic life, aesthetics, recreational opportunities and water quality, along with regulatory water quality issues such as NDPES permit requirements.

[6] In statistical analysis it is critical to understand the effect of the population size (e.g. number of points in the data set) on the confidence in results. For relatively small data sets, detection of trends, statistically significant differences, etc. can be dictated as much by the size of the population as by the true presence or absence of a trend/difference. This is especially true when the difference or trend is relatively small or gradual.

Drought and Wildfire

Drought and wildfires are projected to increase in Colorado and along the Front Range as temperatures increase. Key findings from climate experts related to drought and wildfire include the following, which are quoted from the CWCB report:

- The Palmer Drought Severity Index (PDSI) shows a trend towards more severe soil-moisture drought conditions in Colorado over the past 30 years, reflecting the combination of the below-average precipitation since 2000 and the warming trend.
- Tree-ring records and other paleoclimate indicators for Colorado show multiple droughts prior to 1900 that were more severe and sustained than any in the observed record.
- Most climate projections indicate that heat waves, droughts and wildfires will increase in frequency and severity in Colorado by the mid-21st century due to the projected warming. Wildfire projections have a high level of uncertainty because the cycle of building up fuel, effects of insects on forest health, dry periods, temperature, and other factors are all related.

As drought affects water availability, potential effects on urban drainage systems go hand-in-hand with those identified for stream flow. Wildfires pose different challenges including dramatic increases in runoff, debris flows and sediment transport. In areas near the urban-wild land interface, including many parts of the western metropolitan area, this affects the urban drainage system in terms of flooding and damage to property and infrastructure from debris and sediment. In recent years, wildfires in the South Platte River and Boulder Creek watersheds, among others, have highlighted the significant impacts that wildfires have on rainfall-runoff, sediment transport, mud and debris flows and flooding.

Potential Vulnerabilities of Urban Drainage System to Climate Change

For Colorado, the more certain climate trends and reliable projections are those associated with mean temperatures. As shown in Figure 2 by the orange bars which show the range from the 10th percentile to the 90th percentile of the individual model projections, even these projections vary by 3°F or more depending on the model scenario. Projections related to hydrology are far less certain and range from decreases to increases in precipitation. While quantification of increases or decreases in precipitation varies based on the model scenarios, most models indicate increased variability in the future. In Colorado, we already live in a climate with large daily and seasonal temperature fluctuations, large and small rainfall-runoff events, flash floods and other variability. Nonetheless, changes in temperatures, precipitation, drought and stream flow have the potential to affect the urban drainage system. The following sections identify major components of the urban drainage system and potential effects of changes projected by climate experts. Table 1 summarizes elements of the urban drainage system and potential vulnerabilities. Please note that the following sections identify changes in components of the urban drainage system that could or may occur due to climate change projections. Effects on the urban drainage system have not been comprehensively studied. There are many complex variables in addition to climate, temperature and precipitation that affect urban drainage systems that will influence what actually happens in the future.

Minor Drainage System

The minor drainage system includes streets, inlets, storm drains and other infrastructure that is typically designed to manage runoff from events with return periods in the 2- to 10-year range. Warmer temperatures may affect the minor system by increasing stress on vegetation due to drought periods and/or heat waves. Furthermore, the minor system may experience more frequent flows in the summer months, additional runoff in the non-summer months, and a shift in timing and frequency in spring runoff. Some projections indicate a shift in the frequency of minor events in the 2- to 50-year return period range (e.g. current 10-year event of same magnitude as future 5-year event, current 50-year event of same magnitude as future 25-year event); however these projections do not extend to major flood events (iCliCS 2014). This is an emerging area of research, and there are currently few peer-reviewed, published studies. The ability to detect trends in the magnitude or frequency of rainfall – runoff events over time is limited by the period of record for many streams and rain gages. If such a shift occurs, street flooding would be expected to become more common as minor system capacity is exceeded more frequently. Increases in winter precipitation also may lead to more frequent nuisance drainage problems in winter and spring.

Streets, inlets and storm drains

With projections of increased convective storm activity, streets, inlets and storm drains would be expected to experience more frequent runoff in the summer which could lead to storm drain system capacity exceedances and an increased frequency in street flooding. Additionally, more precipitation in winter months could lead to problems with icing.

On-site Detention and Water Quality Ponds

With warming temperatures, detention and water quality ponds would experience heat stress on vegetation, as well as greater evaporation and evapotranspiration from ponds with permanent water surfaces or wetland ponds. Other potential system stresses include more frequent summer runoff events and reduced inter-event time. Consequently, increased maintenance may be required.

LID and Green Infrastructure

Temperature has many different effects on the kinetics of biological, chemical and physical processes in green infrastructure controls. Temperature increases would likely modify the plant "palette" for many green infrastructure practices. Furthermore, runoff temperature moderation effects and non-stormwater urban heat island benefits are likely to become increasingly important if temperatures increase. Increased runoff frequency and extended dry periods and/or heat waves have the potential to affect vegetation and maintenance.

Components of Urban Drainage System	Climate Change Forecasts						
	Temperature		Precipitation			Streamflow	
	Mean temperature increase (most in late-summer/fall) *2.5°F (2025), 4°F (2050), 7°F (2100)*	*Summer heat waves, more intense drought periods, increased potential for wildfires*	*More frequent summer thunderstorms/convective activity*	*More precipitation in winter, fall and spring (10%, on order of 2.0 additional inches of precipitation in rainy months)*	*Shift in stormwater runoff frequency (iCliCS): 10-yr --> 5-yr; 25-yr --> 10-yr; 50-yr --> 20-30-yr; 100-yr --> unchanged to 50-yr*	*Large declines in snowpack below 8200 feet*	*Earlier runoff and lower streamflow in late-summer/fall*
Minor System	Minor system temperature effects are primarily related to stress on vegetation from drought periods and/or heat waves.		More frequent flows in minor system in summer months. Minor system may receive additional runoff in non-summer months, a shift in timing and frequency. Street flooding may become more common as minor system capacity is exceeded more frequently.			No significant direct impacts, but decreased water availability may lead to water rights challenges to green infrastructure practices that increase evapotranspiration.	
Streets, inlets and storm drains	•No significant direct temperature impacts.		•More frequent summer runoff. •More precipitation in winter months could lead to more problems with icing. •Storm drain system capacity exceeded more frequently. Increased frequency of street flooding. •Maintenance needs may increase due to increased frequency of runoff.				
On site detention ponds	•Heat stress on vegetation, greater evaporation/ET from ponds with permanent water surface or wetland ponds.		•More frequent summer runoff. •Reduced inter-event time. •Increased winter runoff. •Increased maintenance may be required.				
On site water quality ponds							
LID and Green Infrastructure	•Temperature increases may modify plant "palette" for many green infrastructure practices. •Runoff temperature moderation effects and non-stormwater urban heat island benefits are likely to become increasingly important. •Temperature has many different effects on the kinetics of biological, chemical and physical processes in green infrastructure controls.		•Increased frequency of inundation may affect some types of vegetation. •Increased maintenance frequency should be anticipated for increased runoff frequency and pollutant loading. •Winter runoff and associated pollutants may affect vegetation.				
Major System	Effects of temperature are related to stress on vegetation, greater evapotranspiration, effects of lower streamflows and drought on aquatic ecosystems.		More frequent runoff from smaller storms, increased potential for channel erosion. Major storm predictions in a study of the Boulder Creek watershed by iCliCS range from no change from current 100-year peak flows to a shift of the 100-year frequency to a 50-year frequency. Increased maintenance requirements.			Primary effects include decreased baseflows, more intermittent waterways and greater water quality impacts from urban runoff due to lower streamflows.	
Channels/Streams--Hydrology	•Earlier runoff, lower streamflow in summer/fall, decreased baseflows, dry stream conditions.		•More frequent stormwater flows in channels may increase erosion potential. •Seasonal precipitation and runoff patterns likely to lead to lower flows and/or dry channels in late summer/fall. •Potentially more "flashy" hydrology and small watershed flash flooding from convective storms. •More frequent flooding in areas with undersized major drainageways.			•Lower baseflows, earlier runoff for major urban streams.	
Channels/Streams--Water Quality	•Increased water temperature decreases dissolved oxygen and affects other water quality parameters. •Increased stream temperatures and lower flows will affect aquatic ecosystems.		•More frequent runoff/pollutant loading with increased runoff temperatures in summer, often in times of low streamflow. •More winter precipitation snow/ice/rain or mix often during times when streamflows are low.			•Lower flows and earlier runoff may increase water temperature. •More streams may be intermittent. •Stormwater runoff may have a more pronounced impact on stream water quality with lower flows.	
Floodplains	•Characteristics of vegetation may change with stresses of temperature and drought.		•More frequent flooding in areas with local drainage problems and undersized systems. •Floodplains that have been preserved with allowance for freeboard should still provide similar level of protection. •Frequency of out of bank flows may increase.			•No significant direct impacts, aside from water availability for vegetation.	
Wetlands	•Increased evapotranspiration--more water required. •Transition of some wetlands areas to transitional areas and some transitional areas to uplands.		•Potential changes in seasonality of hydrology and greater potential evapotranspiration.			•Decreased availability of water to sustain wetlands. •If water levels (surface or groundwater) decline, wetland vegetation may be displaced.	
Trails	•No significant direct temperature impacts.		•More frequent trail inundation. •Increased maintenance frequency.			•No significant direct impacts.	
Riparian Corridor Ecosystems	•Increased temperatures have potential to shift the make-up of aquatic ecosystems as water temperatures increase. •Types of vegetation successful along riparian corridors may also shift to plants that are tolerant of heat and drought (and flooding).		•Systems are likely to experience greater fluctuations between extreme drought and flooding with shift in flooding frequency and increased temperatures. •Declines in streamflows may make less water available to sustain ecosystem, especially in late summer and fall. •Increased winter runoff. •Increased maintenance requirements.			•Decreased water availability, along with increased temperatures may alter the character of vegetation along riparian corridors.	
Detention Storage Facilities	•Heat stress on vegetation. •Greater evaporation/ET from ponds with permanent water surface or wetland ponds. •Increasingly greater difficulties in water rights for BMPs that have permanent water features.		•More frequent operation at minor event stages as well as more frequent floods in the 10- to 50-year range. •Potentially more frequent operation at major event stage, but models are highly uncertain. •Increased maintenance requirements.			•Detention facilities that have permanent pools or wetlands may be more likely to dry out (or be converted by owners) if there is decreased water availability.	
Regional Water Quality Facilities			•More frequent summer runoff, reduced inter-event time. •Increased winter runoff. •Increased maintenance requirements.				
Watersheds	Primary impacts are related to stresses to vegetation that have the potential to lead to increased erosion and increased wildfire risk.		Increased frequency of runoff from more frequent storms, winter runoff and pollutant loading and potential for increased erosion in drought periods.			Impacts are primarily indirect.	
Vegetation/Erosion	•Increased wildfire risk has potential to create increasing number of debris flow and flooding problems in areas near urban/wildland interface. •Changes in vegetation (native and urban) due to higher evapotranspiration, greater water conservation, etc. may increase erosion potential of developed and undeveloped watersheds.		•Lack of precipitation in late-summer and early fall, coupled with warmer temperatures may stress some types of vegetation. •Increased erosion from more frequent intense rainfall in areas with poor quality vegetative cover may increase the sediment load to the urban drainage system.			•Indirect impact of lower streamflows may be increased water conservation, decreases in irrigated areas, etc. that could affect runoff and erosion characteristics in watersheds.	
Runoff	•Increased runoff temperatures from storm events •Less spring runoff occurring earlier in season.		•Increased frequency of runoff from small events, increase in frequency of flows exceeding minor system capacity. •Increased winter runoff.				
Pollutant loading	•Potential increases in erosion from decreased vegetative cover; temperature effects of runoff on streams.		•More frequent runoff/pollutant loading in summer with increased runoff temperatures, often in times of low streamflow. •More winter precipitation and runoff, often during times when streamflows are low.				
Maintenance Operations	Increased temperature may stress some types of vegetation in the existing system. Increased watershed erosion would lead to increases in maintenance system-wide.		More frequent maintenance may be required both because of more frequent runoff/flooding and because of stresses on vegetation from increased temperatures.			Lower streamflows may stress some types of vegetation in major drainageways and other urban drainage facilities. Diligent maintenance will be required to identify areas where vegetation is in distress and/or has died and to find an alternative type of cover better suited to climatic variability.	
Flood Warning	Increased wildfire risk may lead to need for additional monitoring/warning systems in foothills.		Increased potential for flash flooding (5- to 50-year storms), increased wildfire risk, increased interest in monitoring precipitation and runoff in light of climate change all highlight the importance and likely need for future expansion of the UDFCD flood warning system.			No significant direct impacts.	

Major Drainage System

The major drainage system refers to drainage infrastructure including channels, regional detention and water quality facilities, and stream corridors that are designed to manage the major (100-year) event. Effects on the major drainage system from increased temperatures would be expected to include stress on vegetation, greater potential evaporation and evapotranspiration, lower stream flow, and more frequent periods of precipitation as well as drought. Increased frequency in runoff from smaller storms would increase the potential for channel erosion and would increase the frequency of stormwater flows in the major drainage system. Primary stream flow effects in urban drainage systems may include decreased base flows, more intermittent waterways, and greater water quality impacts from urban runoff due to lower stream flows.

Channels/Streams – Hydrology

Channel and stream hydrology may be affected by earlier runoff, lower stream flow in summer and fall, decreased base flows, and dry stream conditions related to warmer temperatures. Additionally, more frequent stormwater flows in channels have the potential to increase erosion. Seasonal precipitation and runoff patterns are expected to lead to lower flows and/or dry channels in some cases in late summer and fall. Also, increased variability in precipitation may lead to more "flashy" hydrology and small watershed flash flooding from convective storms and more frequent flooding in areas with undersized major drainageways.

Channels/Streams – Water Quality

Water quality may be affected by more frequent runoff and pollutant loading with increased runoff temperatures in summer, often in times of low stream flow. Increases in water temperature decrease dissolved oxygen in the water column, affecting aquatic ecosystems. If more streams were to become intermittent, stormwater runoff would have more pronounced impact on stream water quality, especially during low flow or no-flow periods.

Floodplains

Floodplain vegetation characteristics may change with stresses of temperature and drought. Increases in precipitation predicted by some models would have the potential to cause more frequent flooding in areas with local drainage problems and undersized systems, and the frequency of out of bank flows would likely increase. Current projections do not indicate a trend of increasing or decreasing flooding for large (e.g. 100-year and greater) events, and 100-year floodplain limits would not be expected to change. In cases where floodplains that have been preserved and/or drainageways have been engineered with an adequate allowance for freeboard, the level of protection provided and flood risk would not be expected to change significantly based on projections from climate experts.

Wetlands

Climate change has the potential to affect wetlands primarily due to seasonality of precipitation and increased temperatures. Increased evapotranspiration would require additional water to maintain wetlands. If surface or groundwater levels decline, wetland vegetation will not be able to be sustained and wetlands may be displaced. Consequently, the transition of some wetland areas to transitional areas and some transitional areas to uplands may occur.

Trails

Increases in precipitation may result in more frequent trail inundation, especially at crossings, resulting in a greater need for maintenance attention.

Riparian and Aquatic Ecosystems

The make-up of riparian and aquatic ecosystems has potential to shift with increases in temperatures. For example, types of vegetation successful along riparian corridors may shift if there is greater variability in temperature, precipitation, runoff, stream flow and drought. Declines in stream flows would make less water available to sustain an ecosystem, especially in late summer and fall. Additionally, water quality may be affected by increased pollutant loading from winter runoff, which would affect aquatic life.

Regional Water Quality and Detention Storage Facilities

Climate change may affect permanent water surfaces or wetland ponds through greater evaporation and evapotranspiration. Consequently, detention facilities may be more likely to dry out or be converted by owners if there is decreased water availability. There may be increasing difficulties in water rights for BMPs that have permanent water features. Based on some projections of increased minor storm magnitude, detention storage facilities could potentially require more frequent operation at minor event stages, and potentially more frequent operation at the major event stage, although models are highly uncertain. Regional water quality facilities could experience more frequent summer runoff, reduced inter-event time, and increased pollutant loading in winter months. For each facility type, increased maintenance would be expected.

Watersheds

Primary impacts of climate change on watersheds that affect the urban drainage system are related to stresses on vegetation that have the potential to lead to increased erosion and wildfire risk. Other potential effects include increased frequency of runoff due to more frequent storms, greater amounts of winter runoff and pollutant loading, and higher potential for increased erosion in drought periods. Changes in vegetation, both native and urban, due to higher evapotranspiration, greater water conservation, etc. may increase erosion potential of developed and undeveloped watersheds. Lack of precipitation in late summer and early fall, coupled with warmer temperatures would stress some types of vegetation. Increased erosion from more frequent, intense rainfall in areas with poor quality vegetative cover would increase the sediment load to the urban drainage system resulting in greater maintenance needs. Indirect impacts of lower stream flows may include increased water conservation, decreases in irrigated areas, etc. that could affect runoff and erosion characteristics in watersheds. Increased wildfire risk has potential to create more debris flows and flooding problems in areas near an urban-wild land interface.

Runoff

Climate change may lead to warmer runoff temperatures during storm events (rainfall-runoff) and less spring runoff (snowmelt-runoff) occurring earlier in the season. Moreover, there may be increased frequency of runoff from small events and an increase in frequency of flows exceeding minor system capacity. Additionally, water quality could potentially be affected due to increased winter runoff and associated pollutant loads.

Pollutant loading

With increasing temperatures, sediment loading could potentially increase with more erosion from less vegetative cover, although this is a complex issue in urban areas related to landscaping, irrigation and water conservation practices. For many pollutants, build-up and wash-off in urban areas depends on atmospheric deposition, which is a significant source in the Denver Metropolitan area (Urbonas & Doerfer 2003). Given the uncertainty associated with climate projections, especially those related to precipitation, which drives mobilization of pollutants accumulated from atmospheric deposition, it is not possible to reliably project changes in the magnitude of pollutant loading. However, with seasonal changes in distribution of precipitation projected under many scenarios, the timing of pollutant loading during the year may change.

Many projections indicate that rising temperatures may lead to more frequent runoff and pollutant loading in the summer, traditionally times of lower stream flow. Increasingly, the temperature of runoff is being regulated as a "pollutant," and increases in air temperature and surface temperatures would translate into increased runoff temperatures and stream temperatures.

Stream Management

Each of these aforementioned implications of climate change has the potential to change stream management needs. Increased temperature and lower stream flows may stress some types of vegetation in major drainageways and other urban drainage facilities. Additional management may be required to identify areas where vegetation is in distress and/or has died in order to find an alternative type of cover better suited to climatic variability. Furthermore, increased watershed erosion, more frequent runoff, and flooding would likely lead to increased stream management requirements system-wide.

Flood Warning

Increased wildfire risk, potential for flash flooding (2- to 50-year storms), and an interest in monitoring precipitation and runoff in light of climate change all highlight the importance and likely need for future expansion of the UDFCD flood monitoring and warning system.

Regulatory Compliance

Changes in hydrology and climate also have the potential to affect environmental regulations because factors including rainfall-runoff, stream flow, temperature and others have the potential to affect in stream water quality and ecology. Uncertainty is too great to forecast regulatory changes that could result from climate change; however changes that affect hydrology and pollutant loading have the potential to affect water quality and may have regulatory implications.

UDFCD Programs, Policies and Criteria with Resiliency to Effects of Climate Change

UDFCD has planned and designed urban drainage systems throughout its jurisdiction since 1969 using policies and criteria that account for the variable nature of rainfall and runoff and apply conservative assumptions that account for uncertainty in parameters and engineering methods. When implemented these policies and criteria have served communities in UDFCD's jurisdiction well, as demonstrated in the September 2013 Flood and documented in *A September to Remember* (UDFCD and WWE 2014). The following sections outline UDFCD programs, policies and criteria that provide resilience to changes in climate and varying associated effects on the urban drainage system.

Increases in temperature and variability of precipitation leading to phenomena such as more frequent storm events, increased or decreased magnitude of frequent events, shifts in timing of seasonal moisture, drought and others would affect the urban drainage system. As demonstrated below, UDFCD's policies and criteria already provide a very high degree of resilience to the potential changes discussed above. UDFCD has long practiced adaptive management for policies and criteria as the state-of-the-practice has evolved in water resources engineering, and this same strategy of adaptive management will allow UDFCD to adapt to changes due to climate change in the future, as needed.

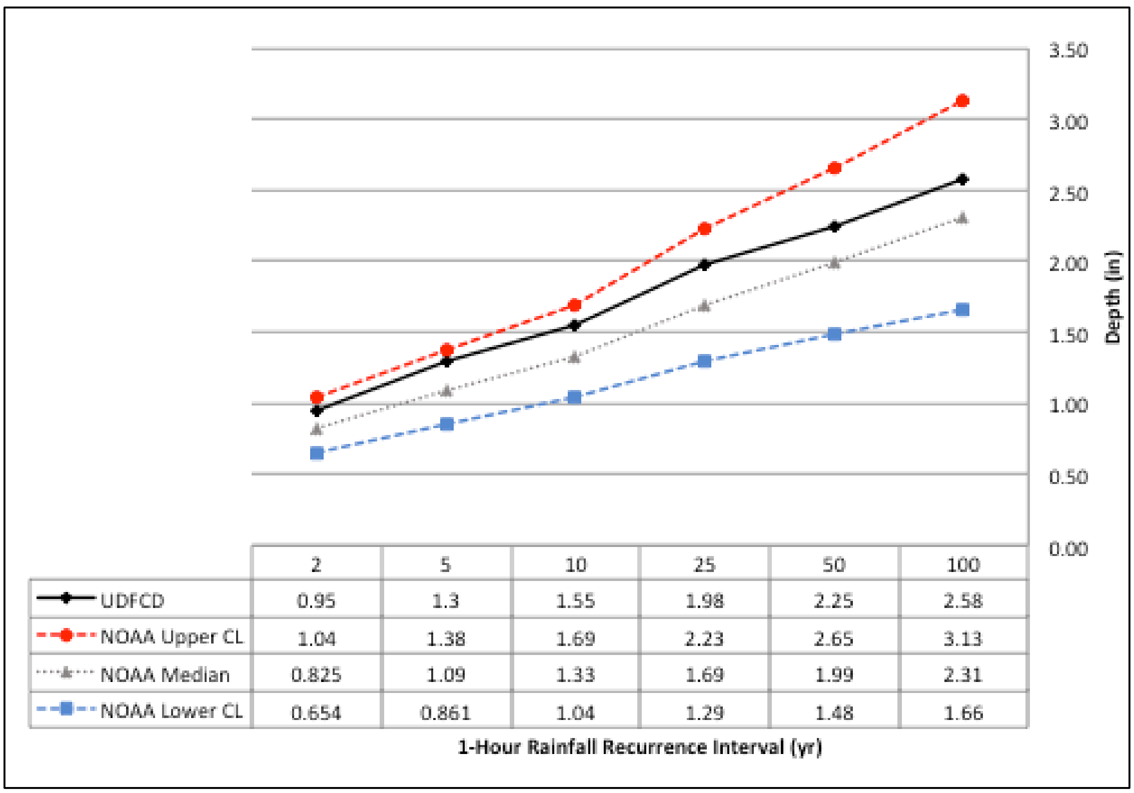
Floodplain Preservation

- Floodplain preservation policy (Policy 2.11)--Preservation of floodplains is a UDFCD policy to manage flood hazards, preserve habitat and open space, create a more livable environment, and protect the public health, safety, and welfare.
- UDFCD "Good Neighbor Policy" to preserve and enhance natural and beneficial functions of floodplains.
- UDFCD floodplain management approach helps provide knowledge of flood risk and improved protection for flood-prone areas through DCM projects, and criteria for new development seek to avoid creation of new flood hazards.

Rainfall

- 90% confidence of +/- 30 % for design rainfall depths (See Figure 4).
- Continued use of NOAA Atlas 2 with higher rainfall values rather than the updated NOAA Atlas 14. (UDFCD Position on the *NOAA Atlas 14 Precipitation-Frequency Atlas, Volume 8*).

- Spatial design storm assumptions (full watersheds contributing). Depth Area Reduction Factor (DARF) assumptions, which reduce rainfall totals used for design for larger watersheds, have recently been developed based on research in Colorado Springs; however, UDFCD adopted a more conservative approach (using average of Colorado Springs values and NWS values) and modified the DARFs only for minor storm events (2-, 5- and 10-year events) for areas greater than 2 square miles.
- Temporal rainfall distribution is based on conservative assumptions. For the 100-year, 2-hour distribution approximately 85% of the total precipitation occurs in the first hour, with 25% in a 5-minute period. This highly intense rainfall period is "built in" to longer duration storm distributions used for larger watersheds.
- Combination of conservative temporal and spatial storm assumptions leads to higher estimates of runoff peaks and volumes, especially in larger watersheds.



	2	5	10	25	50	100
UDFCD	0.95	1.3	1.55	1.98	2.25	2.58
NOAA Upper CL	1.04	1.38	1.69	2.23	2.65	3.13
NOAA Median	0.825	1.09	1.33	1.69	1.99	2.31
NOAA Lower CL	0.654	0.861	1.04	1.29	1.48	1.66

Figure 4. One-hour Point Depths from NOAA Atlas 14 with 90% Confidence Limits Compared to UDFCD One-hour Point Depths

Runoff

- Runoff is based on fully developed basin conditions (future imperviousness/land use).
- Sub-basin discretization in master plans is at a level (typ. 130 acres) that a

rapid rainfall-runoff response is calculated. Smaller sub-basins tend to produce higher peak flow rates, especially in areas that are just developing. UDFCD has studied this issue, and sub-basins in the size range used in master plans tend to produce conservatively high peak flow estimates. Runoff volume is insensitive to sub-basin size.

- EPA SWMM kinematic wave modeling is conservative because of simplifications. Does not account for:
    - Backwater effects resulting in inadvertent flood storage
    - Entrance/exit losses
    - Flow reversal
    - Pressurized flow – Max flow cannot be more than full normal flow
    - Floodplain storage and channel attenuation.
- Inadvertent storage and flow diversions (railroad/highway embankments, non-flood control reservoirs that are not filled to capacity, irrigation ditch crossings, etc.) are not accounted for unless there are written "adequate assurances."
- Recommended depression storage parameters are low to mid-range of typical published values.
- Historically it has not been common to include effects of disconnected impervious surfaces in modeling.
- Conservatively derived clogging factors are applied for inlets.
- Storm drains often have excess capacity beyond design flows due to selecting next-largest pipe size to what is calculated. Therefore, storm drains can often handle an incremental additional amount of runoff beyond their design capacity.
- Conservative nature of rainfall-runoff modeling in the region is demonstrated by comparisons of peak flows from stream gage flow-frequency analysis (for locations with a suitable period of record) and modeled peak flow rates. WWE is not aware of any streams in the metro area where the observed data suggest that modeled peak flows for the major event are too low.
- Floodplain modeling:
    - Subcritical flow modeling – Hydraulic modeling is conducted using a subcritical flow assumption. Therefore, even when hydraulic conditions indicate a lower, supercritical depth, the models are set to default to critical depth. When supercritical flow conditions are expected, it is also standard practice to check for the sequent depth (subcritical) to assure that if a hydraulic jump occurs, it will be contained in the channel or structure.
    - Steady flow assumptions – Floodplain modeling in the Denver metropolitan area typically assumes steady flow (i.e., the calculated peak flow rate is assumed as a steady, continuous flow for purposes of defining the floodplain and floodway). In reality, a hydrograph will have a rising limb, a peak and a falling limb, and the peak flow rates will persist only for a short period of time. For time varying flow such as this, temporary and inadvertent storage can play a significant role.

However, using a steady flow assumption, temporary and inadvertent storage are not explicitly accounted for, leading to more conservative floodplain delineation and design.
   - CLOMR/LOMR review process – The Conditional Letter of Map Revision (CLOMR)/Letter of Map Revision (LOMR) review process provides a safeguard for proposed and actual modifications to floodplains within the UDFCD boundary. UDFCD reviews CLOMR and LOMR submittals and updates floodplain mapping accordingly. The review process is intended to assure that changes to mapped floodplains are thoroughly vetted to understand impacts to drainageways and nearby properties. UDFCD is a Cooperating Technical Partner of FEMA, and the local knowledge that UDFCD staff brings to the review process is an important asset for managing flood risk.
   - Non-levee embankment assumptions - Since Hurricane Katrina, it has been standard practice to ignore the effects of non-levee embankments in terms of flood protection. The typical analysis procedure is to evaluate the "wet side" of a non-levee embankment with the levee in place and to evaluate the "dry side" of the non-levee embankment with the berm/levee removed. This results in a conservatively high "wet side" water surface estimate and a conservative "dry side" estimate of the extent of the floodplain.
   - Conservative assumptions for ineffective flow and storage areas – Storage areas are accounted for in hydrologic and hydraulic models only when there are adequate assurances for perpetual operation and maintenance of the facility. In some cases, inadvertent storage areas have been accounted for as institutionalized storage areas when a local government provides adequate assurances that the storage will be provided in perpetuity. Many additional storage areas, including onsite detention and informal/inadvertent storage areas, are not accounted for in hydrologic and hydraulic modeling. This additional storage has beneficial effects in real flood events that are not accounted for in models that are used to define floodplains and floodways.

Detention

- Master plans do not assume storage unless detention facility has "adequate assurances" (3.2.7 Storage Chapter):
   - Serves a watershed that is larger than 130-acres, and
   - Provides a regional function, and
   - Is owned and maintained by a public agency, and
   - The public agency has committed itself to maintain the detention facility so that it continues to operate in perpetuity as designed and built.
- Detention Sizing for allowable unit release rate of 1 cfs/acre conservative for C/D soils, which are common along Front Range (Storage 3.2.1).

Freeboard

- 1 to 4 feet depending on jurisdiction and risk of debris specific to the channel for 100-yr storm for Bridge Design (Culverts and Bridges 7.3).
- Minimum of 2 feet for channel design (Open Channels 3.2).
- The elevation of the top of the embankment should be a minimum of 1 foot above the water surface elevation when the emergency spillway is conveying the maximum design or emergency flow (Storage 5.3).
- A retention pond with zero or very slow release should be sized to capture, as a minimum, 2.0 times the 24 hour, 100-year storm plus 1 foot of freeboard (Storage 6.7).
- Rundowns – design flow plus one foot freeboard (Hydraulic Structures 3.2.5).
- CWCB Critical Facilities Criteria and local ordinances for critical facilities.
- In many cases (especially newer development) the 500-year discharge is contained within the freeboard of the 100-year major drainage channels.

Flood Warning

- As demonstrated in the September 2013 Flood, UDFCD (and regional partners) operate a first class flood warning system.
- Rainfall and runoff data collected by UDFCD and others provides a vast resource of data for exploring trends in stream flows (low flow & flood flows) and precipitation.

Institutional

- Strong commitment to stream management and repair of urban drainage system.
- Regular updates to Urban Storm Drainage Criteria Manual as technology and practice evolve. This also allows for flexibility in adapting criteria as effects of climate change are observed in the urban drainage system.
- Research that UDFCD conducts on water quality, urban runoff management, revegetation, and stream management techniques establishes criteria that are based on science and engineering. By continuing research UDFCD can lead the way with adaptations to urban drainage practices as effects of climate change become more apparent.
- Public and technical community education & outreach—events such as the UDFCD Annual Conference, publications by UDFCD staff, UDFCD social media, publicly available floodplain mapping, etc. and others are effective tools. Climate change effects on the urban drainage system and flood risk would be a good topic for discussion in some of these forums.

Conclusions

In conclusion, although increases in average temperatures and increased variability in hydrology are widely projected by climate change experts, the effects of these changes in the urban drainage system cannot be forecast with a high degree of certainty. Existing programs, policies and criteria of UDFCD have been developed over a period of more than 40 years with an understanding and respect for the natural variability of hydrology. As a result, the urban drainage systems in many parts of the metropolitan Denver area where improvements have been constructed in accordance with 100-year design standards already have a high degree of resilience to potential future hydrologic changes associated with climate. In addition, UDFCD programs have a long history of adaptive management, and this approach will serve UDFCD well in addressing future changes in climate whether these changes include increases or decreases in precipitation and runoff or both.

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