Fort Collins Utilities Water Supply Vulnerability Study Draft Report

Prepared for: Fort Collins Utilities **in coordination with** Northern Water
Prepared by: Stantec in Association with RTI International

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Fort Collins Water Supply Vulnerability Study

Final Report

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Fort Collins Utilities
In coordination with Northern Water

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Executive Summary

Introduction

The City of Fort Collins is located 65 miles north of Denver in Larimer County, between the Rocky Mountains foothills and the Eastern Plains of Colorado. Fort Collins Utilities (FCU) currently serves about 75% of Fort Collins' residents and businesses. The FCU service area boundary for water, which does not coincide with Fort Collins city limits, is landlocked by neighboring water districts. Current estimates for the FCU service area show an increase in population to about 178,000 by 2065. Fort Collins is home to Colorado State University and a few large commercial enterprises.

The Fort Collins Water Supply Vulnerability Study (WSVS) was performed to investigate the ability of the FCU water supply system to meet future demands under current policy criteria and level of service goals when subjected to alternative hydrologies and various risks and uncertainties. The WSVS compiled alternative hydrologies, demands, and infrastructure risks and uncertainties into risk scenarios, resulting in a broad range of potential future conditions. The performance of the Fort Collins system under these risk scenarios was evaluated to inform under what future conditions the FCU water rights portfolio, raw water infrastructure and water supply policy and planning efforts are most vulnerable.

This project was performed by Stantec Consulting Services, Inc. under a contract with the City of Fort Collins. RTI International was a subconsultant to Stantec for hydrologic analyses and demand tool development.

Water Resources System Model

The WSVS involved risk-based water resources planning analyses that required a robust modeling platform to simulate the performance of FCU's raw water system under a wide range of possible future conditions. The modeling system used for the WSVS consists of three separate models: the Colorado-Big Thompson Quota Model (CBTQ), the Poudre Basin Network Model (PBN) and the Fort Collins System Model (FCSys).

- The CBTQ Model was developed by Northern Water to estimate annual quotas of C-BT and Windy Gap water for its allottees based on hydrology and current operations.
- The PBN Model is a MODSIM model that simulates water supply infrastructure and operations by municipal, industrial, and agricultural entities in the Poudre River basin and the lower South Platte River basin below the Poudre River confluence near Greeley. It was originally developed by Resource Consultants in 1985 for the Fort Collins Drought Study, but has been enhanced by Fort Collins, Northern Water and Greeley over the years to serve a number of purposes.
- The FCSys is a MODSIM model developed by FCU that simulates the FCU water supply system under various water demand, water rights, infrastructure and operational scenarios. The FCSys simulates city water deliveries, deliveries to large contractual users (LCU), return flow obligations

from the use of converted agricultural water rights and various other operations of the FCU water supply system.

These models were run in sequence through a Data Management System as shown in **Figure ES-1.** The system is semi-automated and includes the ability to export FCSys output as PBN inputs and vice versa.

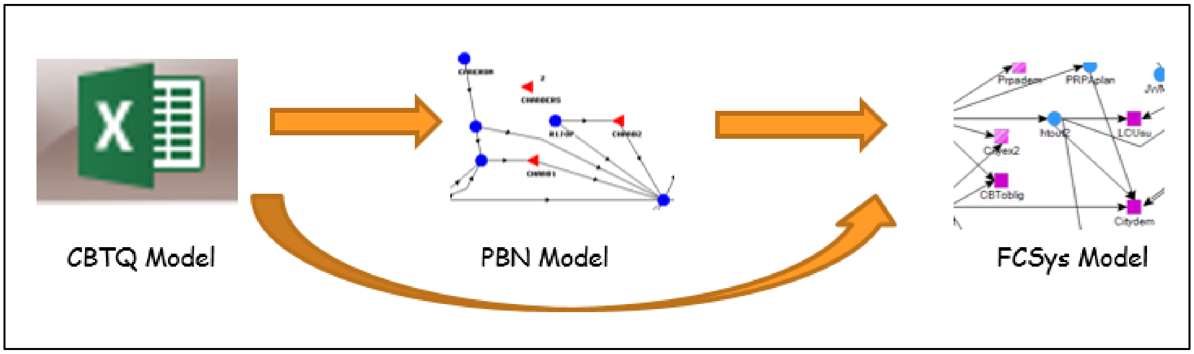


Figure ES-1 FCU Modeling System Overview

Fort Collins and other agencies have used previous versions of the PBN and FCSys models for past water resources planning and decision-making. The WSVS modeling system was not developed to re-evaluate any previous planning studies and it does not simulate flows in streams that could be affected by water development projects in the Poudre River basin. This modeling system was developed to identify and prioritize future risks for which FCU should be planning.

The WSVS used the FCU modeling system to evaluate FCU water supply system performance. “System performance” is defined as the ability to meet customer demands and satisfy adopted water supply planning policy criteria. For FCU, the Water Supply and Demand Management Policy (WSDMP) establishes an objective of:

- meeting demands calculated using a per capita use factor of 150 gallons per capita per day,
- through the 1-in-50-year drought,
- with no shortages or water restrictions,
- while maintaining a minimum of 20 percent of annual demand in reservoir storage at all times (storage reserve factor).

As part of the WSVS, the performance of the FCU water supply system was quantified using measurable parameters (metrics) with target values based on the criteria defined in the WSDMP (level of service goals). The performance metrics and level of service goals were identified and calculated as part of the modeling system outputs. Risk-based water supply planning commonly considers three categories of performance metrics: reliability metrics (i.e., measures of how often certain conditions occur), resilience metrics (i.e., how long certain conditions occur) and vulnerability metrics (i.e., how severe certain conditions area). Many specific reliability, resilience and vulnerability performance metrics were identified to help quantify the impacts of risks and uncertainties to the FCU water supply system. As the WSVS progressed, FCU staff found that the following four performance metrics were most useful for identifying the impactful risks.

- Average annual total demand shortage in years when shortages occur
- Reliability (i.e., frequency) of maintaining 20% of annual demand in storage (storage reserve factor)
- Percentage of time in any level of water use restrictions based on the current planning policy criteria
- Reliability of meeting indoor demand

Hydrology

Synthetic sets of potential future hydrologic model inputs that include natural variability and large-scale shifts in precipitation and temperature trends due to potential climate change were generated for use in the Fort Collins Modeling System.

Figure ES-2 provides an overview of the process used to generate hydrologic datasets for the WSVS. Application of this process resulted in 20 sets of 100 sequences of natural hydrologic variability (referred to as a "trace"), with each set representing a particular future climate condition. Future climates were described by the offset of temperature and precipitation from historical conditions. Based on review of previous climate change studies for the Front Range region, the temperature offset ranged from 0 to plus 8 degrees F compared to average annual 1981 to 2010 observed temperature, and the precipitation offset ranged from -10% to +15% of average annual 1981 to 2010 observed precipitation.

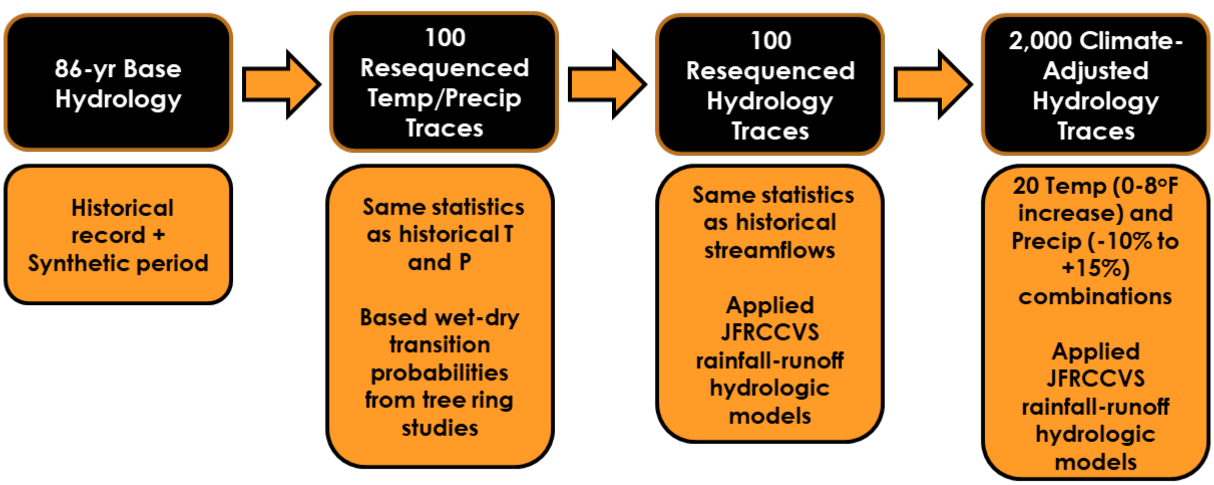


Figure ES-2 Overview of Hydrologic Analysis Process

Note: JVRCCVS = Joint Front Range Climate Change Vulnerability Study

Temperature and precipitation changes in the range adopted for the WSVS were found to have significant effects on streamflow contributing to FCU water supply. The hottest/driest climate condition (T=+8, P=-10%) reduced the Poudre River at the Canyon Mouth mean annual streamflow by an average of 30% for the 100 hydrologic traces, compared to the non-climate adjusted traces. The coolest/wettest climate condition (T=0, P=+15%) increased the Poudre River mean annual streamflow by an average of 39% for the 100 hydrologic traces, compared to the non-climate adjusted traces. This is shown in **Figure ES-3**.

In the past, FCU has used a 6-year critical period within the 86-year model simulation period to determine the 1-in-50-year drought for water supply planning. Hydrologic inflows were based on synthetic runoff data. This 6-year critical period for the Poudre River at the Canyon Mouth has an average annual runoff of 196,090 acre-feet per year (AFY). The 100 hydrologic traces in the WSVS hydrologic dataset for the unaltered historical climate conditions (T=0, P=0%) have an average 6-year critical period flow at this location of 191,343 AFY, which is a 2% reduction. The hottest/driest climate condition (T=+8, P=-10%) produces an average 6-year critical period annual streamflow that is 31% less than the critical period streamflow currently used for planning. The coolest/wettest climate condition (T=0, P=+15%) produces an average 6-year critical period annual streamflow that is 38% more than the critical period streamflow currently used for planning. This is important when interpreting the vulnerability study results relative to current water supply policy criteria that are based on the 6 year long, 1-in-50-year drought in the synthetic runoff data. When considering the full set of 100 hydrologies times 20 climate scenarios generated for the WSVS, there are traces which capture more severe and more frequent critical periods than the historical 6-year critical period used in previous water supply planning to represent the 1-in-50 year drought. Additionally, there are traces in the WSVS that do not see critical periods as severe as the historical.

		Delta P				
Basin	Delta T	-10%	-5%	0%	7%	15%
Cache La Poudre at Canyon Mouth	8 F	70% 189,516	79% 214,864	88% 241,156	103% 279,926	120% 326,717
	5 F	72% 197,600	82% 224,065	92% 251,456	107% 291,295	125% 339,726
	2 F	75% 204,550	86% 233,415	97% 263,366	113% 307,497	132% 361,271
	0 F	77% 209,967	88% 240,600	100% 272,680	118% 320,455	139% 378,560
Lake Granby	8 F	70% 190,797	80% 215,992	89% 241,377	102% 276,540	117% 316,072
	5 F	74% 200,493	84% 226,635	93% 252,835	107% 288,931	121% 328,746
	2 F	78% 210,964	88% 237,245	97% 263,351	111% 299,719	126% 340,232
	0 F	81% 218,725	90% 244,938	100% 270,981	113% 306,969	128% 347,893

Figure ES-3 Average Annual Flow Volume for Hydrologic Traces for All Climate Conditions

Note: Each cell shows the mean of the average annual flows for the 100 traces with the corresponding T/P combination expressed in AFY and as a percentage of the average annual flow for the T=0, P=0 combination.

Water Demands

Future water demands for general residential and commercial customers in the FCU service area were estimated using a new Demand Estimation Tool developed for this project. The Demand Estimation Tool consists of individual linear regression models, each developed for the following groups of water customers: single family and duplex, multifamily, commercial small, commercial medium, and commercial large customers. It was developed using processed historical customer-level water use data from 2001-2016.

Three demand scenarios were developed by FCU for use in the WSVS: City Plan 2, City Plan 3 and City Plan 3 plus 20%. The first two demand scenarios are based on the most likely proposed future development scenarios for 2070 developed as part of the Fort Collins City Plan update. The median average annual water demand in 2070 under City Plan 2 assumptions, including the effects of climate change, is 37,700 AFY. The more aggressive growth assumptions in the City Plan 3 scenario result in a median total water demand of 39,200 AFY, for an increase of 4% compared to City Plan 2. The City Plan 3 Plus 20% scenario increased both the general residential and commercial portion of the total demand and a portion of the Large Contractual User demand by 20%. This resulted in a median total water demand of about 45,200 AFY. **Figure ES-4** compares the total annual demands for these three scenarios. The average annual demand for 2065 developed from previous FCU planning studies is 40,629 AFY; this is referred to as the “baseline demand” in this study.

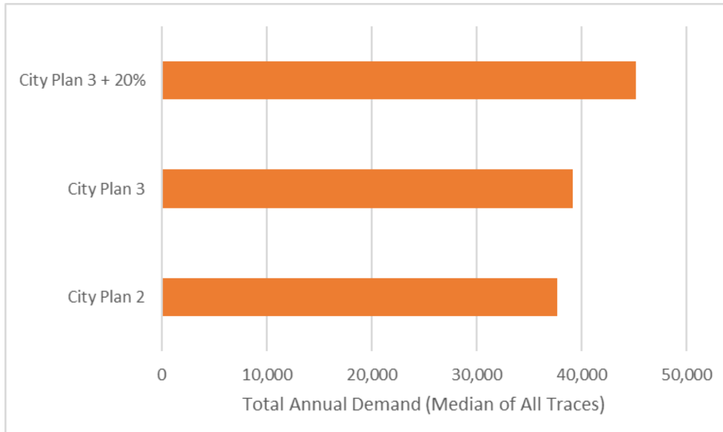


Figure ES- 4 Total Annual Demand in 2070 Including Climate Change (Median of All 2,000 Traces for Each Development Scenario)

Note: Average Baseline demand = 40,629 AFY

Risks and Uncertainties

The purpose of the WSVS is to identify the vulnerability of the FCU water supply system to a range of risks or threats that could occur in the future and factors that cannot be accurately forecasted. Risks and uncertainties that could affect the future performance of the FCU water supply system were brainstormed in workshops held at Fort Collins Utilities and Northern Water. Identified risks and uncertainties were organized in the following categories that span the various aspects of the FCU water supply system.

- ***Climate and Hydrology*** risks relate to weather variability and other hydrologic factors, both short- and long-term, that can impact the potential yields from a watershed.
- ***Watershed*** risks relate to physical watershed conditions that can impact the yields available to FCU.

- ***Operational and Infrastructure*** risks relate to how FCU delivers physically and legally available water to its treatment facilities.
- ***Administrative and Legal*** risks relate to conditions, regulations, or policies that could impact the legal allocation or availability of water supplies.
- ***Demand*** risks relate to changes in required volume, timing, and quality of water that will need to be delivered to water treatment facilities to meet customer needs.

Some risks are long-term, or chronic, and would persist indefinitely and affect all future years. Other risks are short-term, or acute, and would only occur for a short period of time (e.g., several months or a few years). Although long-term and short-term risks could have very different impacts on the FCU raw water system performance, both types of risks were assessed together in the WSVS.

The identified risks were rated as part of the prioritization process. Individual risks were rated by assigning a 1 to 5 score for both likelihood (possibility of the risk or uncertainty occurring) and impact (consequences to the FCU/C-BT water supply system if the risk or uncertainty were to occur). The composite score was calculated by multiplying the likelihood score by the impact score and was then used to prioritize risks. The prioritized risks and uncertainties were organized into five major threat groups that span the various risk categories. These threat groups are: climate change, demands, critical outages, enhanced environmental stressors and shared infrastructure (i.e. risks or uncertainties due to lack of infrastructure ownership by FCU). The risks and uncertainties selected for analysis in the WSVS are shown in **Table ES-1.**

Table ES-1. List of Key Risks and Uncertainties Prioritized for Simulation

ID	Risk or Uncertainty Name	Threat Group	Description
O1	Outage - 24 Pipeline	CO	Short term outage due to flooding, landslides, wildfire, etc.
O2	Outage - 27 Pipeline	CO	Short term outage due to flooding, landslides, wildfire, etc.
O3	Algal Blooms	EES	Algal blooms in storage reservoirs and rivers increases water quality issues and potential treatment problems.
C1	Longer duration droughts	CC	Multi-year and/or more severe droughts occur in the future that are not captured in the observed record.
A1	New Regulations	EES	New regulations (either federal or state) impact availability of yields from existing water rights.
W1	Wildfires	EES	Wildfires occur, causing a variety of impacts on water quality, runoff and threats to infrastructure.
C3	Change in precipitation type - Hydrology	CC	More precipitation falls as rain instead of snow during the Fall and Spring.
C4	Changes in frequency/ magnitude of precip events - Hydrology	CC	Precipitation events, particularly summer rainstorms, become less frequent and more intense.
C2	Changes in runoff timing	CC	Early higher runoff and lower late-season baseflow reduces yield from volumetric decrees that list specific diversion dates.
W2	Forest Health Degradation	EES	Forested area health decreases due to beetle kill, pollution, warming climate, etc.

ID	Risk or Uncertainty Name	Threat Group	Description
A4	Changing state administration	CC	Policies around state water administration change, impacting yields from water rights
D3	Development Uncertainty	D	The composition of development in service area (e.g. density, type, outdoor area) is different that past.
A2	Increased Basin Demands	D	Higher demands across the entire Poudre River basin (due to climate change/population growth) impact use of water rights.
O5	Outage - Horsetooth Reservoir Intake	CO	Short term outage of reservoir outlet and intake to WTP; higher risk due to lack of redundancy.
O4	Outage - Michigan Ditch	CO	Short term outage due to flooding, landslides, wildfire, etc.
D2	Water Use Changes	D	Decrease in per capita use continues and how water is used (e.g. indoor vs. outdoor) changes.
D1	Service area growth and Regionalization	D	Ft. Collins expands its service area or enters into agreements to provide water to regional entities.
A9	Elimination or Interruption of Reuse Plan	SI	Platte River Power Authority decommissions Rawhide Energy Station, effectively eliminating the need for the Reuse Plan. In multi-year droughts, water from the Reuse Plan is reduced or unavailable.
D8	Change in precipitation type - Demands	CC	More precipitation falls as rain instead of snow during the Fall and Spring.
D9	Changes in frequency/ magnitude of precip events - Demands	CC	Precipitation events become less frequent and more intense.
A3	Changes to Northern Water C-BT Operations	SI	Allocation of C-BT water through setting of the quota and ways in which C-BT water can be managed, changes in the future.
W3	Development in Watersheds	EES	Land development in watersheds (recreation, residential, O&G, mining) increases risk of water quality contamination.
D6	Hotter summer changes irrigation	D	A warmer climate increases the length of the irrigation season and hotter days increase demand during the summer.
O6	Outage - Chambers Reservoir	CO	Short term outage due to flooding, landslides, wildfire, etc.
O8	Outage - Joe Wright Reservoir	CO	Short term outage due to flooding, landslides, wildfire, etc
O11	Outage - Pleasant Valley Pipeline	CO	Short term outage due to flooding, landslides, wildfire, etc.

Note: Threat Group ID definitions: CC = Climate Change, D = Demands, CO = Critical Outages, EES = Enhanced Environmental Stressors, SI = Shared Infrastructure

Risk Scenarios

Risk scenarios were developed by FCU to represent combinations of future conditions for which a vulnerability analysis was desired. Scenarios are comprised of single or multiple risks and are designed to allow FCU to understand how its water resources system would behave under a range of future stressful conditions.

In general, a WSVS scenario consists of three parts:

- A climate condition, defined as one of the 20 temperature and precipitation combinations, which determines 100 hydrologic traces representing climate variability around that climate condition.
- A demand condition, defined as one of the two City Plan demand scenarios or the baseline planning demand.
- A system risk condition, defined as a combination of one or more of the risks and uncertainties.

The process for creating WSVS scenarios is shown in **Figure ES-5**.

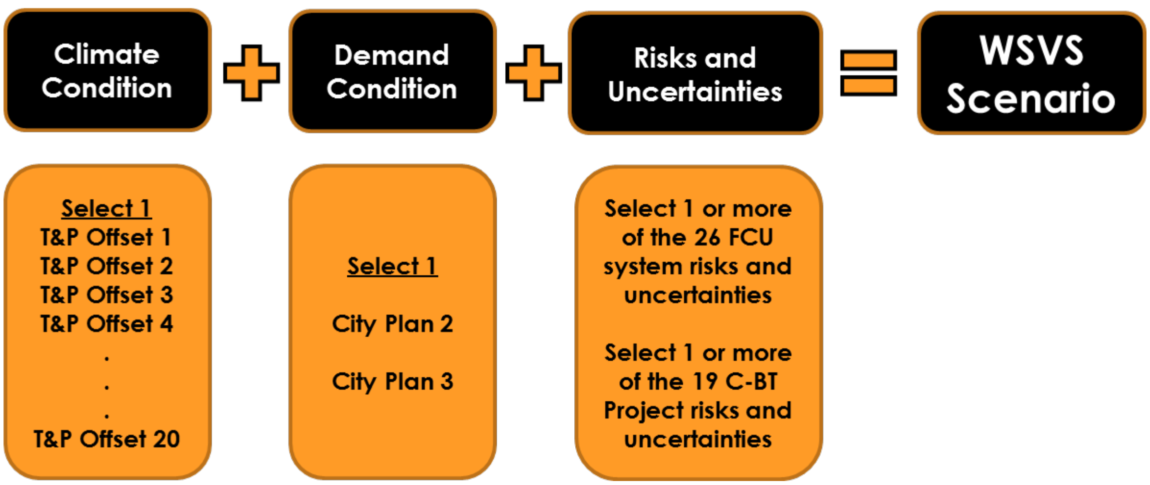


Figure ES-5. Process of Creating WSVS Scenarios

FCU Staff, in coordination with Northern Water, identified 13 scenarios for simulation, including baseline conditions. The 12 non-baseline scenarios were selected to represent a range of future conditions believed to be possible and potentially impactful to the FCU water resources system. They represent both long-term or chronic conditions (i.e., those that occur over the entire simulation period) and short-term or acute conditions (i.e., those that occur for only a short period of time). These risk scenarios are described briefly below.

- Baseline – Future conditions, including current water rights and anticipated acquisitions, current water supply infrastructure, Halligan Reservoir enlargement and a demand of 40,629 AFY.
- Climate Change Impacts – 20 future climate conditions with constant demand and no other risks.
- Loss of Storage – No Halligan Reservoir enlargement and no C-BT carryover storage in Horsetooth Reservoir.
- Increased Demands – Two City Plan based demand scenarios and one increased demand scenario beyond the City Plan development assumptions.

- No Halligan Enlargement – No enlargement of Halligan Reservoir as currently proposed.
- Poudre River System Acute Outage – Short-term outage of 24-inch and 27-inch delivery pipelines and Pleasant Valley Pipeline.
- C-BT System Environmental Impacts – Impacts on C-BT quota allocations due to environmental issues resulting from wildfires in the receiving East Slope watershed or restricted use of Horsetooth as a water source because of algal blooms.
- Poudre River System Environmental Impacts – Impacts due to algal blooms or environmental issues resulting from wildfires in source watersheds (e.g. increased sediment deposition) that would limit FCU's diversions from the Poudre River.
- C-BT System Acute Outage – Short-term loss of C-BT deliveries due to delivery infrastructure failures.
- C-BT System Long-Term Reduction - Captures possible effects of a wide range of conditions that could reduce C-BT deliveries and quotas over a period of 10 years.
- Horsetooth Reservoir Outage – Short-term outage of deliveries from Horsetooth Reservoir due to infrastructure failures.
- Reuse Plan Changes – Two options: Reuse Plan Change 1 represents 100% elimination of the Reuse Plan; Reuse Plan Change 2 represents 50% reduction in the Reuse Plan.

Vulnerability Assessment

The impacts of these various risk scenarios on the FCU water supply system were quantified using the system performance metrics tied to the current water supply planning policy criteria. Vulnerabilities were investigated in a systematic methodology based on the following steps.

1. Determine the current system's performance for the baseline demand with no climate or infrastructure risks.
2. Investigate how potential short-term climate variability and broader climate change could affect the performance of the baseline system.
3. Assess the impacts of increased demands, generated by the new Demand Estimation Tool in combination with the climate-adjusted hydrologies.
4. Evaluate the superposition of the risk scenarios with the climate-adjusted hydrologies and each City Plan based demand scenario.
5. Identify the risk scenarios with the greatest potential to adversely affect the FCU system performance.

The process for evaluating risks in the WSVS is shown in **Figure ES- 6** below.

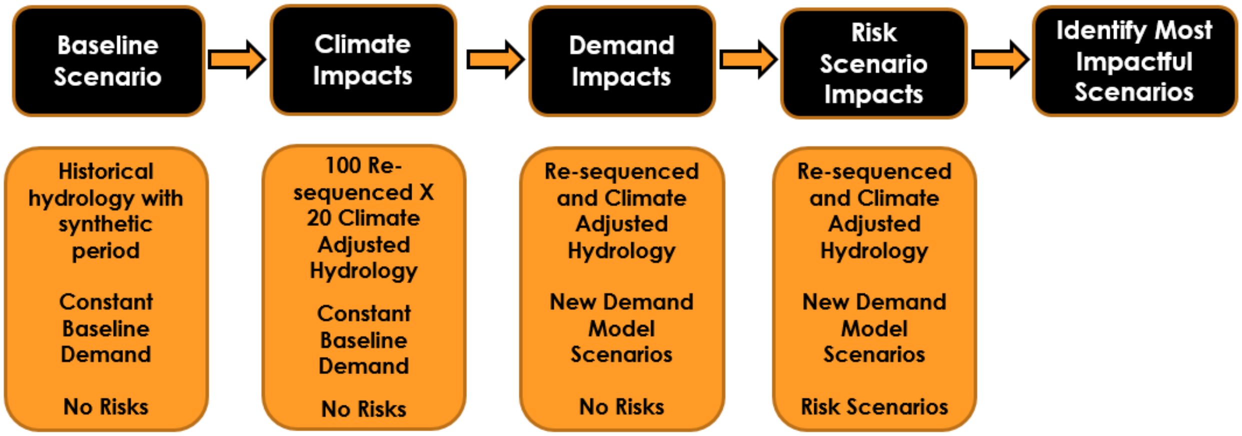


Figure ES- 6 Method for Risk Evaluation

Results showed that FCU's water system and water rights portfolio is well adapted to current climate conditions. The existing system, which includes the Halligan Reservoir enlargement, meets all demands, including Reuse Plan demands, with 99.1% reliability. Indoor demands are met 99.8% of the time. The results also showed that the system maintained the policy guideline of a 20% storage reserve factor in 97.1% of the total simulated months. Note that none of the WSVS simulations include the effects of water use restrictions.

However, system performance declines as the climate gets hotter and drier. The effect of climate on the reliability of meeting an annual demand of 40,629 AFY is shown in **Figure ES-7**. This figure shows the average percent of months in which the target baseline demand was met across the 100, 86-year traces for each of the 20 climate conditions. Comparing these reliability results to the current water supply policy of 100% reliability, under almost all climate futures, including no change in climate, the FCU system is unable to meet this level of service goal. Uncertain future hydrology is the biggest threat to FCU's future water supply, as it is heavily influenced by changing climate. Even the risk scenarios with the worst performance under current climate conditions were shown to perform better than a scenario with no system risks and an increase in temperature and decrease in precipitation.

Percent of Months Meeting Demands

Temperature Change (Degree F)	Precipitation Change -10%	-5%	0%	7%	15%
8 F	62.9%	81.5%	94.0%	99.4%	100.0%
5 F	70.7%	87.1%	96.7%	99.8%	100.0%
2 F	77.0%	91.5%	98.3%	99.9%	100.0%
0 F	82.3%	94.7%	99.1%	100.0%	100.0%

Figure ES-7. Average Monthly Reliability of Meeting Total Demands for All Climate Conditions

Simulations of increased demands showed the FCU baseline system is only moderately vulnerable to the City Plan 2 and City Plan 3 scenarios and only for hotter/drier climates. However, the City Plan 3 + 20% condition has more significant effects and represents a greater threat to FCU system performance. **Figure ES-8** shows the effects of the demand scenarios on the average annual shortage metric. This metric calculates the average annual shortage across the years when shortages occur. The figure also shows the number of years when shortages occur for each scenario. The current water supply policy establishes a level of service goal of no shortages during the 1-in-50-year drought. With the exception of significantly wetter climates, all demand scenarios have a shortage, showing the FCU system is unable satisfy this level of service goal, even for traces where the critical drought period is less than the historic 1-in-50-year drought used in previous water supply planning.

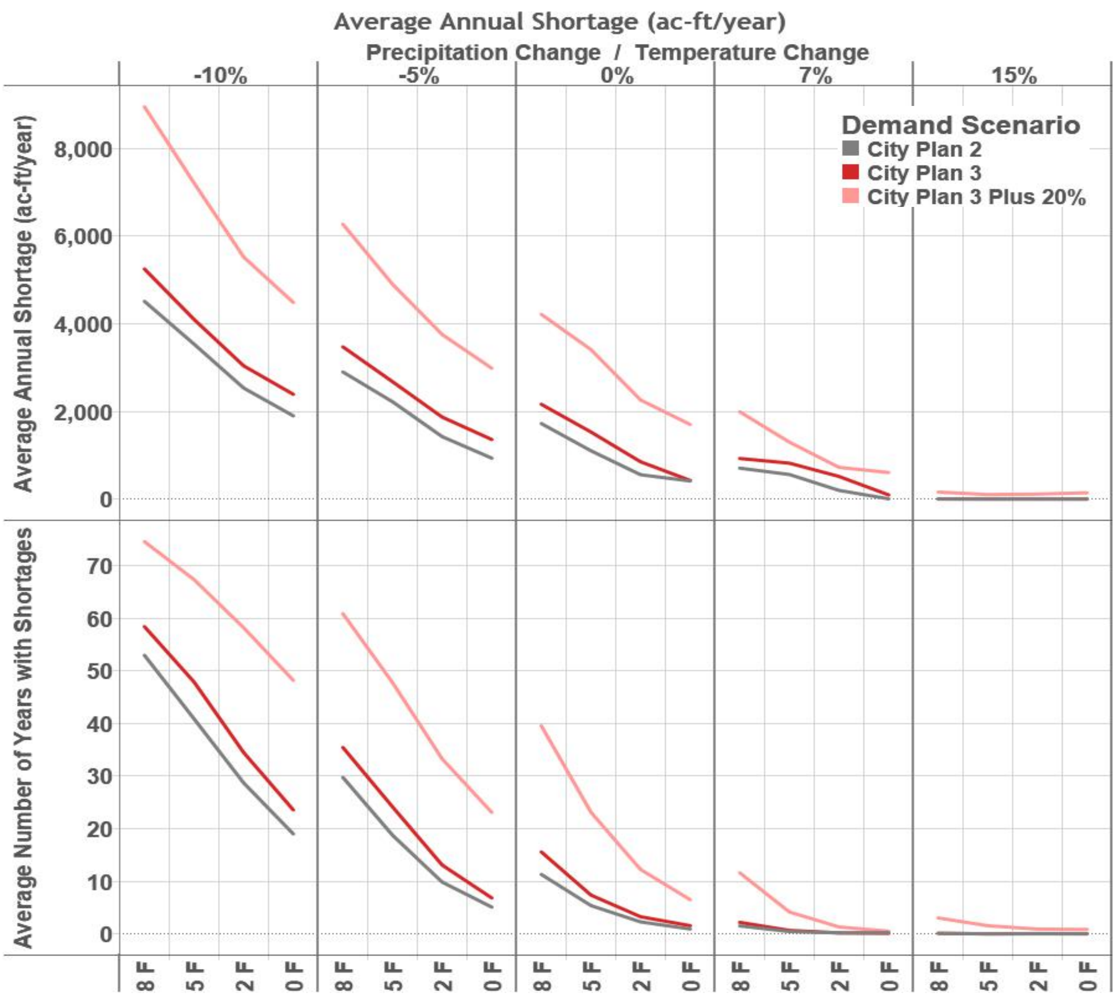


Figure ES-8 Average Annual Total Demand Shortage for Increasing Demand Scenarios and All Climate Conditions

Notes:

a) Poorer performance is indicated by greater shortage volume towards the top of the graph.
b) Current water supply planning policy goal is no shortages for the 1-in-50-year drought.

Besides climate change and increased demands, the risks found to have the largest impact on the Fort Collins system performance relative to the current water supply planning policy criteria are:

- loss of storage, including no Halligan Reservoir enlargement;
- Reuse Plan changes, including elimination or 50% reduction;
- increase in demands above the expected City Plan 3 levels;
- and a long-term reduction in C-BT quota due to constrained C-BT supply or other factors.

Over the four metrics analyzed in this report, those risks and risk scenarios show the poorest performance for current climate conditions and their performance is significantly reduced for the warmer and drier climates.

Figure ES-9 shows the storage reserve metric for all risk scenarios as a function of climate. The storage reserve metric measures the ability to maintain a minimum of 20% of total annual demand in reservoir storage. The water supply policy establishes a level of service of 100% for the storage reserve factor. Under any risk, the FCU system cannot satisfy this LOS goal at most climate futures however the Loss of Storage and No Halligan Enlargement risks have the most significant cumulative impact on maintaining 20% of total annual demand in storage.

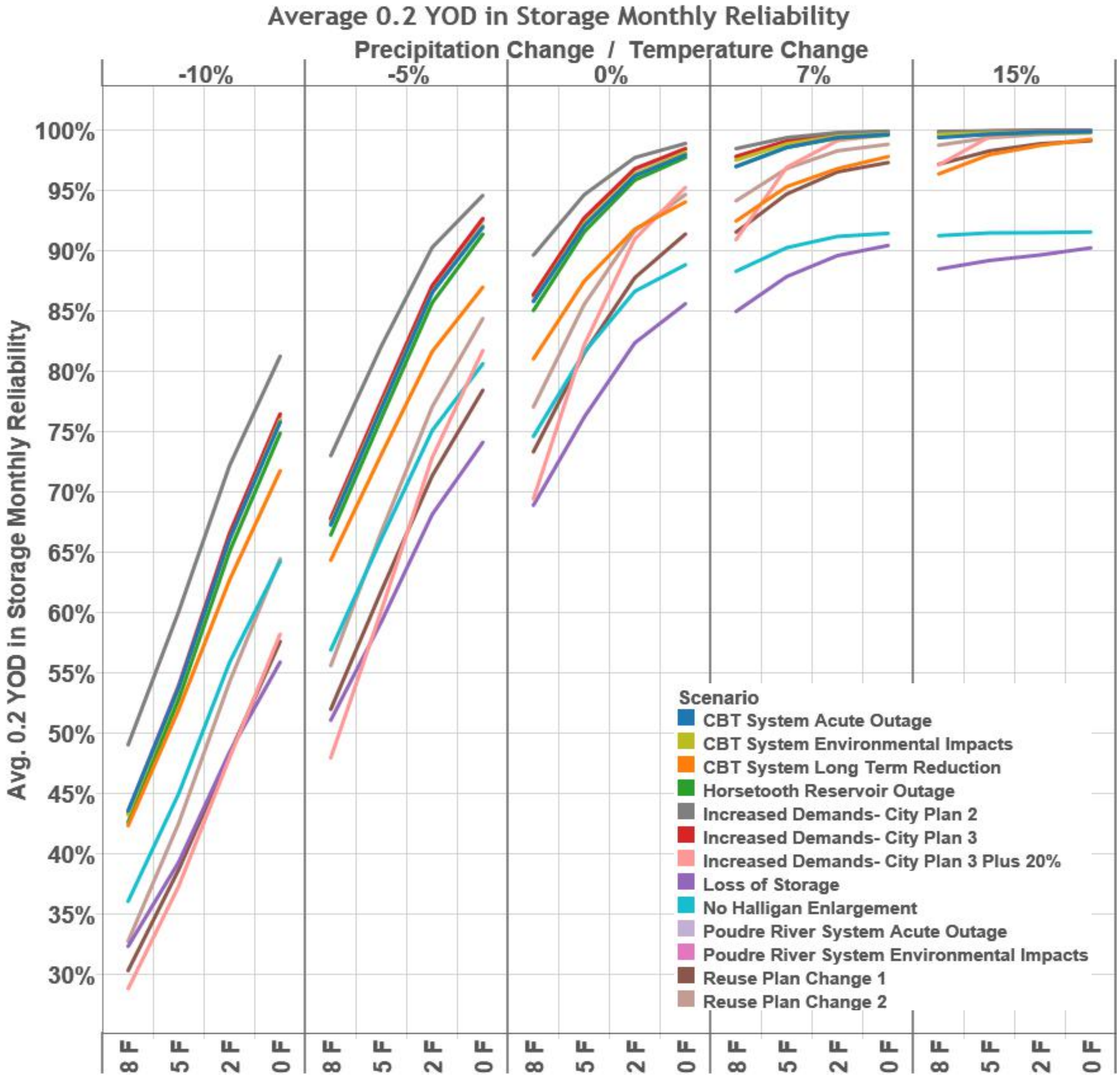


Figure ES-9 Storage Reserve Metric for All Risk Scenarios and All Climate Conditions

Notes:

a) Poorer performance is indicated by lower reliability towards the bottom of the graph.

b) Current FCU policy establishes a goal of 100% for the storage reserve factor during the 1-in-50-year drought.

The risk scenario simulations demonstrated the fundamental difference between long-term or chronic risks and short-term or acute risks. All the most impactful risks based on the metrics used in the WSVS are long-term risks. This is biased by the metrics themselves which, with the exception of the annual demand storage metric, are always calculated over the entire 86-year simulation period. Thus, long-term risks that adversely affect system performance over the entire simulation period or for many years within the simulation period affect metric values more than short-term risks that occur for only a few months or years. Short-term risks such as an outage of the Poudre River pipelines or C-BT facilities can have extreme impacts on system performance for a short period but are masked by climate shifts that cause significant long-term impacts to performance. The effects of long-term risks are not as easily masked by the shifts in climate, as their impacts are also significant over several years or the entire simulation.

Figure ES- 10 highlights the storage reserve metric for the five short-term risks simulated for the WSVS. This figure shows that most of the short-term risk scenarios have very similar performance when measured by the WSVS metrics. Additional investigation may be warranted to develop different metrics that are useful in comparing performance of short-term risks to each other. Many of these short-term risks received relatively high composite scores (likelihood multiplied by impact) at the risk identification workshops, meaning they are of high concern to FCU staff and should be further assessed.

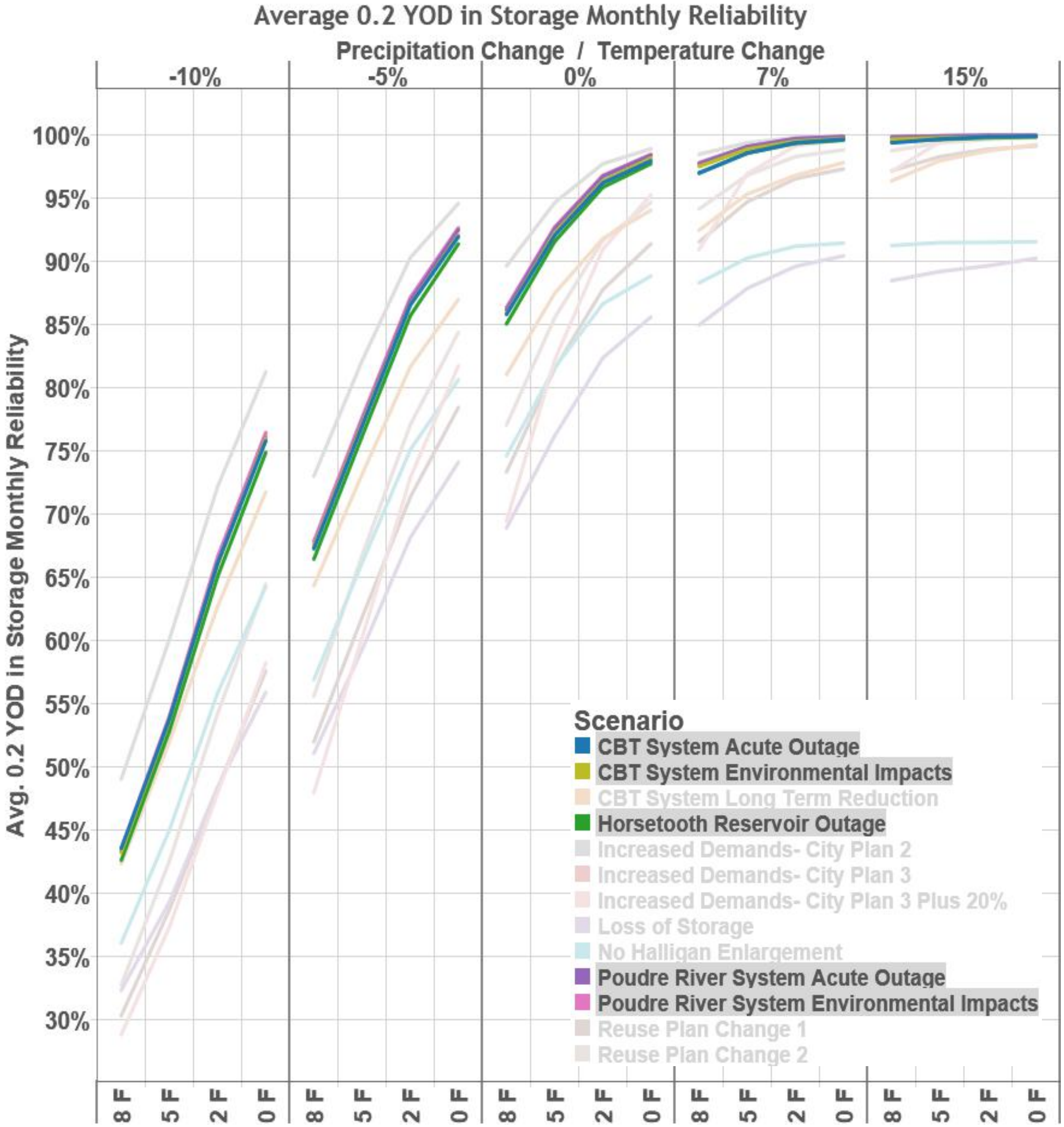


Figure ES- 10 Reliability of Retaining 20% Storage Reserve for Short Term Risks Compared to Long Term Risks

Conclusions

FCU plans to use the results and conclusions of the WSVS as the foundation for updating its Water Supply and Demand Management Policy and its long-range water resources strategy. The following findings from the WSVS may be important as FCU contemplates the coming planning process.

- Climate change is the most important vulnerability faced by the FCU system. Future climate conditions may be more impactful to FCU's ability to meet its water supply planning policy criteria than the occurrence of any particular infrastructure outage or environmental condition simulated by the WSVS risk scenarios. However, climate change is the most difficult risk to track. Long-term trends are difficult to measure and are obscured by the natural variability in wet and dry years. Participating in or keeping informed of state and federal climate change studies will help FCU understand the trajectory of climate change in the region.

- Water demands higher than those forecast in the City Plan 3 scenario represent a significant vulnerability to the current FCU system. This points out the importance of FCU maintaining its water conservation program, and working with City Planning Department to closely monitor population and development density trends to see how they are tracking with City Plan assumptions. An increase in 2070 demands by 20% significantly increases shortages and incidence of failures to meet current water supply policy requiring 20% of average annual demand in storage through a 1-in-50-year drought.

- The risk scenarios found to have the largest impact on the FCU system performance across the range of performance metrics are listed below.

    - Loss of storage, including no Halligan Reservoir enlargement; the FCU system is storage-limited, therefore loss of any existing or proposed storage capacity has significant adverse effects.

    - Reuse Plan changes, including elimination or 50% reduction in the amount of water incorporated in the Plan; the Reuse Plan is a water supply agreement with other Northern Colorado entities that results in additional water supplies for FCU in most years. Losing all or part of the supplies generated from this agreement has compounding effects on FCU water supply.

    - A long-term reduction in C-BT quotas due to C-BT supply or delivery infrastructure issues; C-BT supply is a critical part of FCU's water supply portfolio and reduction in that source over several years significantly impacts FCU's ability to meet its water supply planning policies.

- For most risk scenarios, shortages for climate conditions that are wetter than the current climate would occur most often in late summer and early fall. For warmer and drier climate conditions, shortages would occur throughout the year except in the peak runoff months of May and June. This shows the challenge of maintaining a resilient water resources system in the face of a warmer and drier climate with the limited amount of storage in the FCU raw water system.

- Without the proposed Halligan Reservoir enlargement of 8,125 AF, FCU system performance would be significantly impacted and current water supply planning policy criteria could not be met under most future climate and demand conditions.
- The WSVS highlights the importance of storage in the FCU system and the significant vulnerability posed by the inability to implement the proposed Halligan Reservoir enlargement or a similar storage project as a strategy to mitigate effects of climate change and other risks.
- The WSVS validates that FCU is highly reliant on the C-BT system and is particularly susceptible to extended periods of low quotas and loss of the carryover storage program. FCU should monitor conditions that could trigger either of those risks.
- Results of the WSVS are biased toward long-term risks, but a number of short-term risks were identified that could severely impact FCU operations for a few weeks or months. These conditions will require further study and may involve a different management strategy in the future water supply plan.
- The WSVS analysis was performed without simulating the effects of demand management measures that FCU could adopt under the City's current Water Supply Shortage Response Plan. Investigating benefits of the current shortage response policy should be a key aspect of the water supply plan update.
- FCU now has a water supply modeling tool that can be used to conduct more detailed analyses of the WSVS risk scenarios or explore a broader range of uncertainties or operating conditions if desired. It can also be used to measure and compare the effectiveness of alternative water supply system improvements.

Abbreviations

AFY	acre-feet per year
Ag	Agricultural
C-BT	Colorado-Big Thompson Project
CBTQ	Colorado-Big Thompson Quota Model
CTP	Common Technical Platform
DMS	Data Management System
DWRF	Drake Water Reclamation Facility
EIS	Environmental Impact Study
ELCO	East Larimer County Water District
FCLWD	Fort Collins-Loveland Water District
FCSys	Fort Collins System Model
FCU	Fort Collins Utilities
GCM	Global Climate Model
GMA	Growth Management Area
JFRCCVS	Joint Front Range Climate Change Vulnerability Study
JOP	Joint Operations Plan
LCU	Large contractual users
LOS	Level of Service
NEPA	National Environmental Policy Act
Northern Water	Northern Colorado Water Conservancy District
PBN	Poudre Basin Network Model
PRPA	Platte River Power Authority
SQL	Structured Query Language
SSD	South Side Ditches
TAC	Technical Advisory Committee
WSSC	Water Supply and Storage Company
WSDMP	Water Supply and Demand Management Policy
WSVS	Water Supply Vulnerability Study

1.0 INTRODUCTION

1.1 PROJECT OBJECTIVES

The objective of the Fort Collins Water Supply Vulnerability Study (WSVS) is to investigate the ability of the Fort Collins water supply system to meet future demands under current policy criteria and level of service goals when subjected to various risks and uncertainties. The WSVS explores and prioritizes the impacts of a wide variety of risks and uncertainties, including:

- hydrologic changes resulting from a warming climate;
- risks of water supply disruptions, such as infrastructure failures;
- wildfires, water quality and other environmental factors; and
- changes in water demands resulting from shifts in population, development density and water use patterns.

The WSVS combines alternative hydrologies, demands, and infrastructure vulnerabilities into plausible scenarios, resulting in a broad range of potential future conditions. Knowledge of these potential futures and the impacts of possible risks and uncertainties on the ability to meet the criteria specified in Fort Collins' current water supply planning policy will allow Fort Collins to determine if its water rights portfolio, raw water infrastructure, and water supply policy and planning efforts are adequate to meet changing water demands into the future.

Results of the WSVS will be used by Fort Collins in the future to investigate potential water resources system improvements and operating policies as part of a planned update to its Water Supply and Demand Management Policy (City of Fort Collins, 2012).

1.2 PROJECT BACKGROUND

1.2.1 Fort Collins Utilities

The City of Fort Collins is located 65 miles north of Denver in Larimer County, between the Rocky Mountains foothills and the Eastern Plains of Colorado. Horsetooth Reservoir borders Fort Collins to the west, the Cache la Poudre River winds its way through north Fort Collins before reaching the South Platte River, east of Greeley and several small gravel pit reservoirs and agricultural reservoirs are located in and around the city.

Fort Collins Utilities (FCU) currently serves about 75% of Fort Collins' residents and businesses. The FCU service area boundary for water, which does not coincide with Fort Collins city limits, is landlocked by neighboring water districts. FCU anticipates little new development and mostly re-development of existing properties within the service area boundary. Fort Collins-Loveland Water District (FCLWD) and East Larimer County Water District (ELCO) provide water to some areas within the city limits and will serve much of the new development in the Fort Collins Growth Management Area ("GMA", or future City limits).

Figure 1-1 shows the spatial extent of the City Limits with respect to the FCU service area, GMA and surrounding water districts.

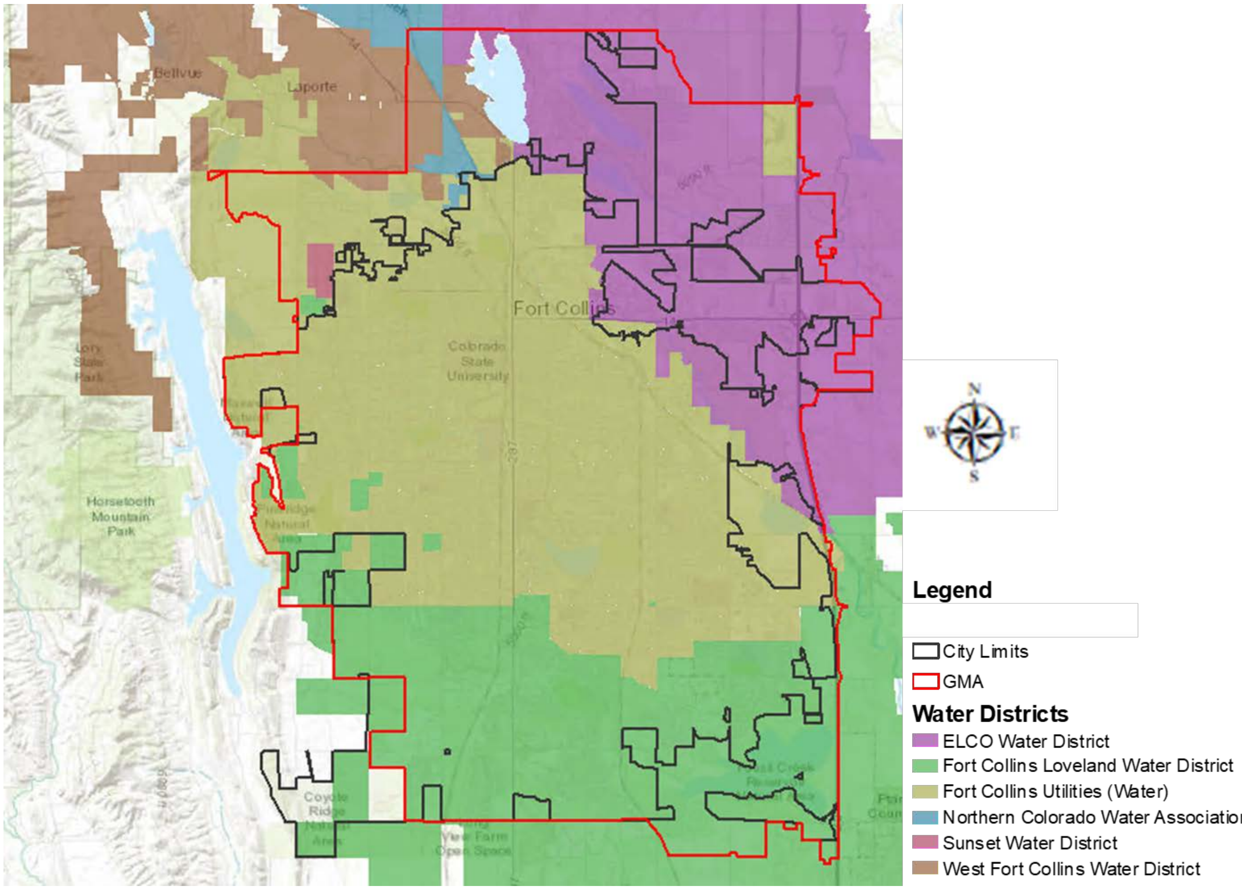


Figure 1-1 Spatial Extent of Fort Collins Utilities Service Area, City Limits and Surrounding Water Districts

FCU supplies an average of about 24,000 acre-feet per year (AFY) of treated water and about 1,100 AFY of raw water to both residential and commercial users with a service area population of approximately 134,300. Additionally, FCU currently has about 3,400 AFY of Colorado-Big Thompson Project obligations, including to City facilities and various Homeowners Associations, as well as agreements with surrounding water districts, municipalities and other entities. Current estimates for the FCU service area show an increase in population to about 178,000 by 2065. Fort Collins is home to Colorado State University and a few large commercial enterprises.

1.2.2 Fort Collins Utilities' Water Supply Sources

FCU's water supply sources come from the Poudre River Basin, the North Platte River Basin (with a transmountain diversion into the Poudre River Basin) and the Colorado-Big Thompson (C-BT) Project, including Horsetooth Reservoir and the Windy Gap Project. FCU's supplies include direct flow rights, converted agricultural rights, C-BT units, supplies from the Michigan Ditch, and storage in Joe Wright

Reservoir and Rigden Reservoir. Key facilities related to delivering water from these sources include two diversion points on the Poudre River, pipelines delivering Poudre River water, Joe Wright Reservoir, the Michigan Ditch, as well as facilities utilized to deliver C-BT and Windy Gap Project water. **Figure 1-2** shows the water supply system for FCU. FCU currently owns limited water supply storage outside of Joe Wright Reservoir. The reservoir, located near Cameron Pass along Colorado State Highway 14, has an active capacity of approximately 7,100 acre-feet. Joe Wright Reservoir is mainly utilized to satisfy current operational and exchange agreements, leaving limited availability for year over year or long-term drought storage. FCU has access to limited carryover storage as part of its ownership in the C-BT system. This storage is not managed by FCU and carries additional costs to utilize. FCU finalized construction and began operation of Rigden Reservoir in 2015. Rigden Reservoir, with an active capacity of 1,900 acre-feet, is located below the FCU wastewater treatment facilities and is not directly tied to treated water operations. Rigden Reservoir is mainly utilized as an operational reservoir to help meet return-flow obligations.

FCU's water supply portfolio contains enough sources to meet demands in most years. However, yields of many of its sources are greatly diminished in dry years, and yields are typically much greater in wet years (some in excess of FCU demands, particularly during the months of high Poudre River flows in May and June). Previous modeling efforts have shown the effect of reliably meeting demands by increasing ownership of water rights is relatively small compared to the effect of increasing system storage capacity due to the uncertainty of the timing of Poudre River flows with respect to the timing of demands.

FCU is currently in the midst of the National Environmental Policy Act (NEPA) permitting process for the enlargement of Halligan Reservoir, an existing reservoir on the North Fork of the Poudre River. The current capacity of Halligan Reservoir is owned and operated by the North Poudre Irrigation Company and cannot be utilized by FCU for water supply storage. Raising the dam will increase Halligan Reservoir's capacity from approximately 6,400 acre-feet to about 14,500 acre-feet and at the same time provide an opportunity to rehabilitate the over 100-year old dam. FCU has various existing water rights to fill the enlarged portion of the reservoir and enlargement would provide an additional 8,100 acre-feet of storage for FCU's use. Previous planning and analyses by FCU staff have determined that enlarging Halligan is a very cost-effective solution to increasing the use of their water rights.

On an annual average basis, FCU receives approximately half of its water supply from the Poudre River and half from the C-BT and/or Windy Gap Projects, which deliver water to Horsetooth Reservoir. FCU works closely with the Northern Colorado Water Conservancy District (Northern Water), which administers the C-BT and Windy Gap Projects, to utilize water supplies out of Horsetooth Reservoir.

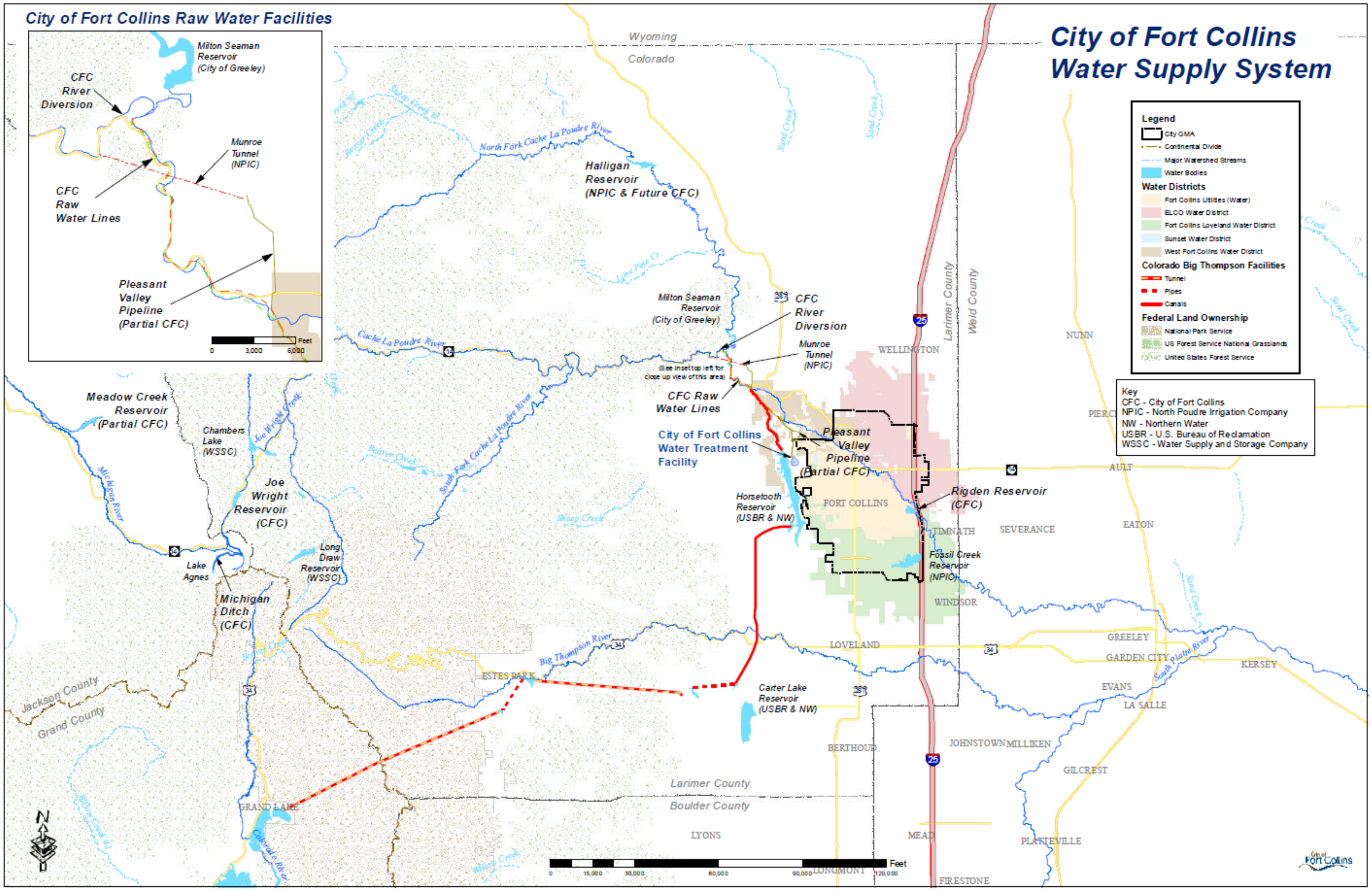


Figure 1-2 City of Fort Collins Water Supply System

1.3 SCOPE OF WORK

The WSVS Scope of Work consisted of the following main tasks.

1. Project Management – Manage scope, schedule and budget and coordinate the project with FCU staff and Northern Water
2. Background and Literature Review – Obtain background information on FCU water supply system and water resources and review applicable literature on climate change and other factors affecting FCU's' water supply reliability
3. Future Water Demand Considerations – Create and apply a Demand Estimation Tool to forecast future water demand, incorporating climate change, population growth and changing land use patterns.
4. Identify Water Supply and Demand Vulnerabilities – Brainstorm and prioritize risks and vulnerabilities that could affect water resources system performance.
5. Develop Potential Yield Changes – Estimate the effect of climate change on hydrology and water rights yield.
6. Scenario Analysis and Framework Development – Create future scenarios comprised of one or more types of risk or uncertainty and assess the performance of the existing water resources system under those scenarios.

1.4 PROJECT AUTHORIZATION

This project was performed by Stantec Consulting Services, Inc. under a contract with the City of Fort Collins. RTI International was a subconsultant to Stantec for hydrologic analyses and demand tool development.

1.5 PROJECT COORDINATION

This project was coordinated closely with FCU staff throughout the project through a series of seven formal workshops, weekly project updates and numerous informal meetings and conference calls.

Northern Water was a partner in the WSVS, providing supplemental funding as well as information and expertise related to its systems. Northern Water staff were included in workshops and project meetings as appropriate.

FCU assembled a Technical Advisory Committee (TAC) consisting of citizens and experts from its Water Resources Board, Colorado State University, and a member representing the surrounding water districts. TAC members were invited to project workshops and received project updates at selected milestones. TAC members included:

- Chris Goemans, Ph.D

- Neil Grigg, Ph.D
- Phyliss Hortman
- Steve Malers
- Richard Raines

2.0 WATER RESOURCES SYSTEM MODEL

The WSVS involved risk-based water resources planning analyses that required a robust modeling platform to simulate the performance of FCU's raw water system under a wide range of possible future conditions. This section provides a high-level description of the modeling system used to support the WSVS analysis.

The basis of the WSVS modeling system is the water resource modeling platform developed by FCU and other regional water providers in the Poudre River Basin including Northern Water. New modeling tools and improvements to certain model constructs were developed as part of the WSVS project. Most new model development for FCU was performed under Stantec and RTI contracts separate from, but coordinated with, the WSVS study.

2.1 MODELING SYSTEM OVERVIEW

The modeling system used for the WSVS consists of three separate models: the Colorado-Big Thompson Quota Model (CBTQ), the Poudre Basin Network Model (PBN) and the Fort Collins System Model (FCSys). These are run in sequence through a Data Management System (DMS), as shown in **Figure 2-1**. The system is semi-automated and includes the ability to export FCSys output as PBN inputs and vice versa. The models operate on a monthly time-step and each model run simulates a single set of future conditions (water resources system operations and annual demand) for 86 years of variable hydrology.

The three models are described below.

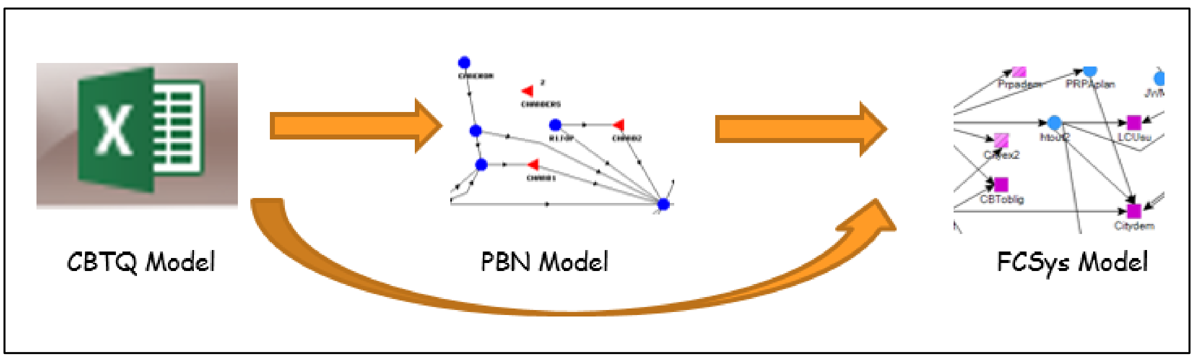


Figure 2-1 FCU Modeling System Overview

2.1.1 CBTQ Model

Northern Water issues allotment contracts for the allocation of Colorado-Big Thompson Project water supplies to water users such as FCU. The allotment contracts call for annual water allocations, known as quotas, to be set by the Northern Water Board based on hydrologic conditions and the needs of its allottees for supplemental water. Because a significant portion of FCU water supply comes from the C-BT Project, WSVS analyses required an estimate of future C-BT quotas for the conditions being simulated.

The CBTQ Model was developed by Northern Water to estimate annual quotas of C-BT water for its constituents based on hydrology and current operations. The primary function of this model is to determine the C-BT agricultural (Ag) deliveries to the Poudre River for use in the Poudre Basin Network Model (PBN) described below. The CBTQ model is a spreadsheet model and includes native flows of pertinent rivers and creeks on the East Slope and the West Slope that contribute to the C-BT project. Other model inputs include precipitation at the Fort Collins station, starting reservoir storage volumes, initial C-BT M&I ownership and demand, C-BT Ag demand, carryover, influence of the Windy Gap Project and influence of East Slope wildfires. Outputs include annual C-BT quotas, Windy Gap Firming Deliveries and other agricultural ditch deliveries to be imported into the PBN Model. From the C-BT quota, the Fort Collins C-BT allocation can be generated as an input to the FCSys model.

2.1.2 PBN Model

The Poudre Basin Network (PBN) Model is a MODSIM model that simulates water supply infrastructure and operations by municipal, industrial and agricultural entities in the Poudre River basin and the lower South Platte River basin below the Poudre River confluence near Greeley. It was originally developed by Resource Consultants in 1985 for the Fort Collins Drought Study (Resource Consultants, 1985) but has been enhanced by Fort Collins, Northern Water and Greeley over the years to serve a number of purposes. The PBN includes all major water rights within the basin and exchanges operated under their given priority. It also has several special constructs to model system operations such as the routing of transbasin water, return flows and ground water.

The main purpose of the PBN is to quantify yields of agricultural and municipal water rights in the Poudre and South Platte basins. For municipal water providers, the PBN quantifies the potential yield from their water rights for use in their individual system models (such as the Fort Collins System Model described below) for a more refined estimation of current and future water system operations and water use.

Extensive documentation of the PBN model can be found in the Common Technical Platform (CTP) Modeling Report used for the Northern Integrated Supply Project (NISP) environmental impact studies (CDM Smith, 2013). The CTP is also used in the upcoming Halligan Water Supply Project environmental impact studies. Input data selections for the PBN model were the same as the future conditions used for the NISP and Halligan projects environmental permitting analyses.

2.1.3 FCSys Model

The Fort Collins System Model (FCSys) is a MODSIM model developed by FCU that simulates the FCU water supply system under various water demand, water rights, infrastructure and operational scenarios. Output from the PBN model informs the FCSys direct flow water right yields and storage water rights owned by FCU. The FCSys simulates city water deliveries, deliveries to large contractual users (LCU), releases from Joe Wright Reservoir to meet minimum flow requirements under the Joint Operations Plan (JOP) and return flow obligations from the use of converted agricultural water rights. The model also includes several potential future system components, including additional storage and inflow points for conditional water rights yields.

The FCSys simulates the yield from FCU's shares in several agricultural ditches. These shares are subject to specific terms and conditions, laid out in the change of use decrees. For shares that have not yet been converted to municipal use, certain assumptions have been made regarding future limitations on their use.

As part of the WSVS model upgrades, several improvements were made to the FCSys to more accurately simulate current raw water operations and to remove dependencies of the Excel preprocessing spreadsheet to streamline the automatic simulation of scenarios. Key improvements are described below.

- Simulate the operation of two change of use decrees for the South Side Ditches (SSD), which include New Mercer Canal, Larimer No. 2 Canal and Arthur Ditch, which requires the model to constrain diversions such that they do not exceed the 1-year, 10-year and 30-year running average volumetric limits specified in the decree. The model was revised to include a new side construct and custom code to iterate on the river exchanges such that the water available to meet demand does not exceed the diversion constraints or the exchange potential in the river. The new model also simulates the associated return flow obligations triggered using that water, which is dynamically calculated at run time.
- The FCSys simulates operation of FCU's Reuse Plan. The Reuse Plan is a series of water trades between FCU, Platte River Power Authority (PRPA) and the Water Supply and Storage Company (WSSC). The purpose of the Reuse Plan is to provide 4,200 AFY of reusable (wholly consumable) water produced at the Drake Water Reclamation Facility (DWRF) to the PRPA Rawhide Energy Station. The first use of 6,339 AFY of reusable water, delivered to single-use water customers, results in 4,200 AF of reusable effluent at DWRF that can be piped to the PRPA power plant to fulfill the terms of the Reuse Plan. The upgraded model implements a dynamic representation of the Reuse Plan reducing the water available to meet the City demand if any of the water sources (or combination of sources) fails to have enough water to operate the full Reuse Plan. This implementation allows the model to dynamically simulate water supply operations with a reduced Reuse Plan, making sure that the flexibility to operate the plan is reflected in meeting the requirements and the effects of different water use are carried over to the following years.
- The upgraded model enables simulation of meeting an 800 acre-feet PRPA water demand that is part of the Reuse Plan. This demand can be supplied from storage in Halligan Reservoir, Joe Wright Reservoir, Rigden Reservoir and the SSD return flows. The upgraded model simulates the SGP Reservoir node with a capacity of 1,600 acre-feet. The implementation of this demand links its operation with the Reuse Plan operation, reducing the demand if the full Reuse Plan is not able to be operated.
- The upgraded model implements a new logic for blending water from the Poudre River and Horsetooth Reservoir for water quality purposes at the water treatment plant. The blending logic

controls diversions from the Poudre River to achieve a typical or desired operational mixing ratio between those two sources. This operation supplies the city with a mix of Horsetooth Reservoir and Poudre River supply that is feasible and cost efficient for the City to treat at the current treatment plant while meeting the desired water quality. The logic relaxes the blending constraint in water stress periods when there is not enough water in either of the sources to supply the full demand, i.e., the logic uses the available water in water stress situations to avoid causing additional water shortages.

2.1.4 Data Management System

The modeling framework used for the WSVS consists of a new Data Management System (DMS). As shown in **Figure 2-2**, the DMS structure has three major components: the Structure Query Language (SQL) server database (in which model inputs such as hydrology, demand and system risks and output metrics are stored), the simulation model system and the DMS program (code) itself. User defined model settings are entered into the DMS which extracts the desired model inputs and scenario information from the database and translates them into raw input files for the CBTQ, PBN and FCSys models. The models are then run with these settings, in sequence, and the DMS calculates and extracts the output metrics. The results stored in the database can be accessed by external visualization software such as Tableau for further analysis.

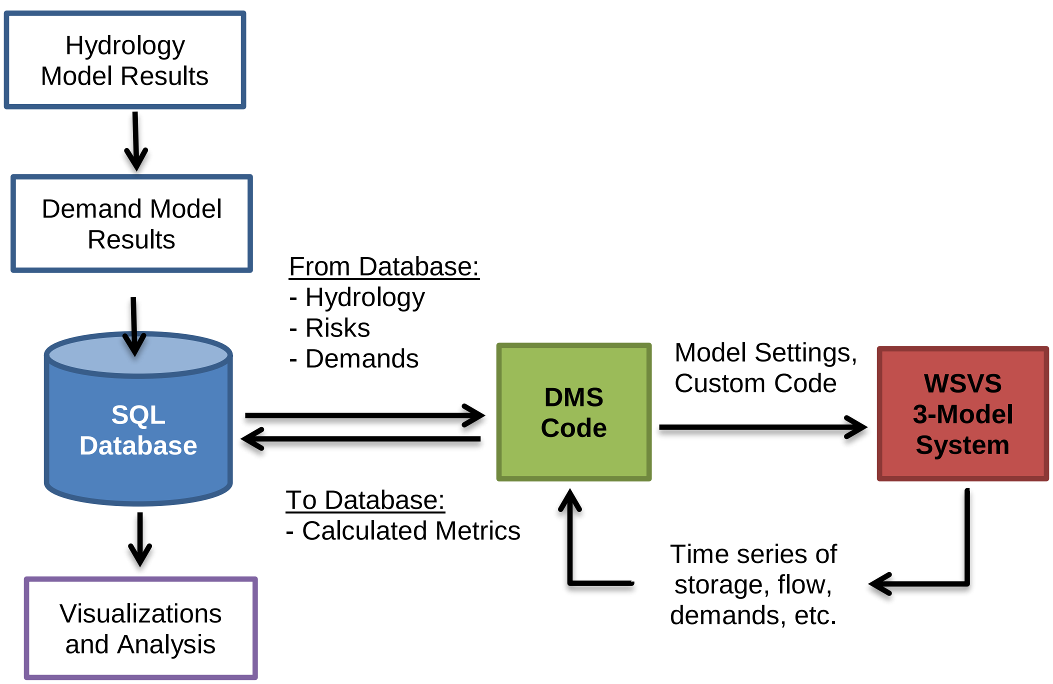


Figure 2-2 WSVS Data Management System

2.1.5 Comparison of WSVS Modeling System to Previous Models

Fort Collins has used previous versions of the PBN and FCSys models for past water resources planning and decision-making. Other agencies such as Northern Water and Greeley have used previous versions of the PBN model for their planning. For example, the Halligan Water Supply Project Environmental Impact Study (EIS) and the Northern Integrated Supply Project EIS used previous versions of the PBN and FCU's system models in a Common Technical Platform (CTP) to size the respective water supply projects and EIS alternatives and assess their hydrologic impacts in the Poudre River Basin. For the WSVS, analyses including an enlarged Halligan Reservoir were all based on the size of the enlargement developed from the CTP and used in the EIS studies.

The Halligan Project EIS modeling and the WSVS modeling are distinct modeling efforts that have been conducted for separate purposes. The WSVS modeling system was not developed to re-evaluate the proposed sizing of the Halligan Water Supply Project, and it does not simulate flows in streams that could be affected by water development projects in the Poudre River basin. Rather, the modeling system modifications made as part of the WSVS were necessary to give FCU the ability to assess future risks to the performance of its water resources system. Previous versions of the modeling system were not capable of simulating risks to the system such as climate variability, environmental risks and infrastructure outages, or of running and tracking many different scenarios simultaneously. In addition, the previous modeling system was not set up to calculate measures of system performance such as reliability and resilience that FCU wants to use in future water supply planning studies. These modeling system improvements were required as part of the WSVS to identify and prioritize future risks for which FCU should be planning with or without the proposed enlargement of Halligan Reservoir.

2.2 METRICS AND LEVEL OF SERVICE GOALS

This section summarizes the development of metrics and level of service goals that were necessary to measure and assess the performance of the FCU water resources system under simulated risks and uncertainties. More detail is provided in the Level of Service Goals and Metrics Technical Memorandum (Stantec, 2018a), included in Appendix A.

The WSVS used the FCU modeling system to evaluate FCU water supply system performance. "System performance" is defined as the ability to meet customer demands and satisfy adopted water supply planning policy criteria. For FCU, the current policy establishes an objective of:

- meeting demands calculated using a per capita use factor of 150 gallons per capita per day,
- through the 1-in-50-year drought,
- with no shortages or water restrictions,
- while maintaining a minimum of 20 percent of annual demand in reservoir storage at all times (storage reserve factor).

As part of the WSVS, the performance of the FCU water supply system was quantified using measurable parameters (metrics) with target values based on the water supply policy criteria (level of service goals). The performance metrics and level of service goals were identified and calculated as part of the modeling system outputs.

Performance metrics and level of service goals, needed to quantify satisfactory and unsatisfactory water supply system performance, are further defined as follows.

> **Performance Metrics** are specific measures characterizing the key features of a water supply system that are definable, measurable, representative and unique. Performance metrics are traditionally presented using the terms reliability, resilience and vulnerability (RRV) but can also be calculated using statistical measures such as the mean, median, maximum, or minimum. The formal definitions of reliability, resilience and vulnerability are:
>
> - *Reliability* is the probability that the water supply system feature is in a satisfactory state, answering the question "how often".
> - *Resilience* is the probability that a time period when the water supply system feature is in an unsatisfactory state is followed by a time period when the water supply system feature is in the satisfactory state, answering the question "how long".
> - *Vulnerability* is the severity or magnitude of the unsatisfactory state for the water supply system feature, answering the question "how severe".
>
> Other examples of performance metrics could be maintaining a minimum volume of water in storage in July, years without customer restrictions, or a target for use of C-BT supplies.
>
> **Level of Service (LOS)** goals are thresholds used to separate key performance metrics into satisfactory and unsatisfactory states. Examples of level of service goals could be triggering customer watering restrictions 5% of the time or maintaining a volume of water equivalent to 1 year of demand in storage in April in 90% of years.

Performance metrics were identified during a workshop conducted with FCU staff and were tied to the current water supply planning policy criteria. **Table 2-1** lists the identified performance metrics for the FCU water supply system that were used for the WSVS.

Table 2-1 Identified Performance Metrics

	ID	Performance Metric	Description
Meeting Customer	**1**	Minimum Met Annual Demand	The minimum annual demand met in acre-ft/year across a simulation
	2	Meeting Indoor Demands	The RRV[3] of meeting indoor demands across a simulation
	3	Meeting Reduced Demands	The RRV[3] of meeting demands after they have been reduced by restrictions

	ID	Performance Metric	Description
	4	Annual Response Level 1 Restrictions[1]	The R&R[2] of when customers are in Response Level 1 restrictions across a simulation
	5	Annual Response Level 2 Restrictions[1]	The R&R[2] of when customers are in Response Level 2 restrictions across a simulation
	6	Annual Response Level 3 Restrictions[1]	The R&R[2] of when customers are in Response Level 3 restrictions across a simulation
	7	Annual Response Level 4 Restrictions[1]	The R&R[2] of when customers are in Response Level 4 restrictions across a simulation
Maintaining Supply in Storage	**8**	0.1-Year of Demand in System Storage	The RRV[3] of maintaining 0.1-Year of Demand in Storage at all times during a simulation
	9	0.2-Year of Demand in System Storage	The RRV[3] of maintaining 0.2-Year of Demand in Storage at all times during a simulation
	10	0.3-Year of Demand in System Storage	The RRV[3] of maintaining 0.3-Year of Demand in Storage at all times during a simulation
	11	0.4 Year of Demand in System Storage	The RRV[3] of maintaining 0.4-Year of Demand in Storage at all times during a simulation
	12	0.5 Year of Demand in System Storage	The RRV[3] of maintaining 0.5-Year of Demand in Storage at all times during a simulation
	13	0.6 Year of Demand in System Storage	The RRV[3] of maintaining 0.6-Year of Demand in Storage at all times during a simulation
	14	0.7 Year of Demand in System Storage	The RRV[3] of maintaining 0.7-Year of Demand in Storage at all times during a simulation
	15	0.8 Year of Demand in System Storage	The RRV[3] of maintaining 0.8-Year of Demand in Storage at all times during a simulation
	16	0.9 Year of Demand in System Storage	The RRV[3] of maintaining 0.9-Year of Demand in Storage at all times during a simulation
	17	1.0 Year of Demand in System Storage	The RRV[3] of maintaining 1.0-Year of Demand in Storage at all times during a simulation
	18	Minimum Storage – Year of Demand	Minimum Year of Demand storage volume during a simulation
	19	Minimum Storage – acre-feet	Minimum acre-foot storage volume during a simulation
Operational	**20**	Lost Water Due to Water Quality Requirement	Statistical quantifications (average, max, count) of annual volume of water lost due to water quality blending requirements
	21	Lost Water Due to Insufficient Storage	Statistical quantifications (average, max, count) of annual volume of useable water lost due to insufficient storage capacity
	22	Meeting Reusable Demands	The RRV[3] of meeting reusable demands

Notes:
1) As defined in the Water Supply Shortage Response Plan (City of Fort Collins, 2014)
2) R&R is Reliability and Resilience
3) RRV is Reliability, Resilience and Vulnerability

The performance metrics were evaluated to determine which are applicable as level of service goals and what the thresholds for level of service are. Seven performance metrics were included as level of service goals, which are shown in **Table 2-2**. Level of service goals were selected to align with FCU's water supply planning policy criteria.

The selected level service goals are primarily customer-facing, such that futures that significantly impact customers based on the current water supply policy will be considered unsatisfactory. These are defined briefly below.

- Any future for which indoor demands are not always met (100% reliability) will be unsatisfactory.
- The current water supply policy sets a goal of meeting all demands during the 1-in-50 year drought without water restrictions. However, based on recent experience, FCU accepts future conditions in which any type of water restriction is declared as often as every 1 in 10 years (90% reliability) with more impactful water restrictions occurring less frequently.
- To comply with the current water supply policy, at least 20% of annual demand must be maintained in storage at all times for a future to be considered satisfactory. This is referred to as the Storage Reserve Factor.
- Finally, all reusable demands must be met 100% of the time.

Table 2-2 Selected Level of Service Goals

ID	Performance Metric	Level of Service Goal	Justification
2	Meeting Indoor Demands	100% Reliability	Greatest customer impact
4	Annual Response Level 1 Restrictions[1]	1 in 10 Years (90% Reliability)	Perceived customer risk tolerance
5	Annual Response Level 2 Restrictions[1]	1 in 25 Years (96% Reliability)	Perceived customer risk tolerance
6	Annual Response Level 3 Restrictions[1]	1 in 100 Years (99% Reliability)	Perceived customer risk tolerance
7	Annual Response Level 4 Restrictions[1]	1 in 500 Years (99.8% Reliability)	Perceived customer risk tolerance
9	0.2-Year of Demand in System Storage	100% Reliability	Governing policy
20	Meeting Reusable Demands	100% Reliability	Reuse Plan Agreement

[1]As defined in the Water Supply Shortage Response Plan (City of Fort Collins, 2014)

These LOS goals were used in the WSVS to separate futures for which water supply system performance is satisfactory from those for which it is unsatisfactory. However, these LOS goals are a policy decision, and one potential water resources strategy is to change the LOS goals or thresholds to take on more risk. For example, FCU could lower the storage requirement from 0.2 to 0.1 years of demand in storage with 100% reliability, thereby improving performance (relative to the relaxed objective) but increasing the risk that sufficient water would not be available during an emergency. This question will be addressed as part of a future study to update the FCU Water Supply and Demand Management Policy.

3.0 HYDROLOGY

A primary input to the WSVS analysis was future inflows to the FCU water supply system. Because an objective of the WSVS was to investigate the impact of hydrologic uncertainty on the FCU system, estimating future inflows for water supply planning required a hydrologic analysis incorporating uncertainty in the timing and magnitude of future surface water supplies. Hydrologic uncertainty could be due to greater interannual variability than is present in the historical record or to long-term climate change.

This section summarizes the process used to develop 100 potential hydrologic sequences based on the same statistics as the historical hydrologic record but incorporating more variability and the adjustment of those sequences to incorporate potential future climate change. The process used to generate potential future hydrologies is described in two technical memoranda – Future Hydrologic Analysis Technical Memorandum (RTI, 2018) and Hydrologic Modeling Approach Technical Memorandum (RTI, 2018b) in Appendix D and in Appendix E.

3.1 HYDROLOGIC MODELING APPROACH

Synthetic sets of potential future hydrologic inputs that include variability and large-scale shifts in precipitation and temperature trends due to potential climate change were generated for use in the Fort Collins Modeling System. These datasets capture more natural variability and more climate effects than the historical observed streamflow record, and thus, represent sets of different potential conditions in the basin. **Figure 3-1** provides an overview of the process used to generate hydrologic datasets for the WSVS.

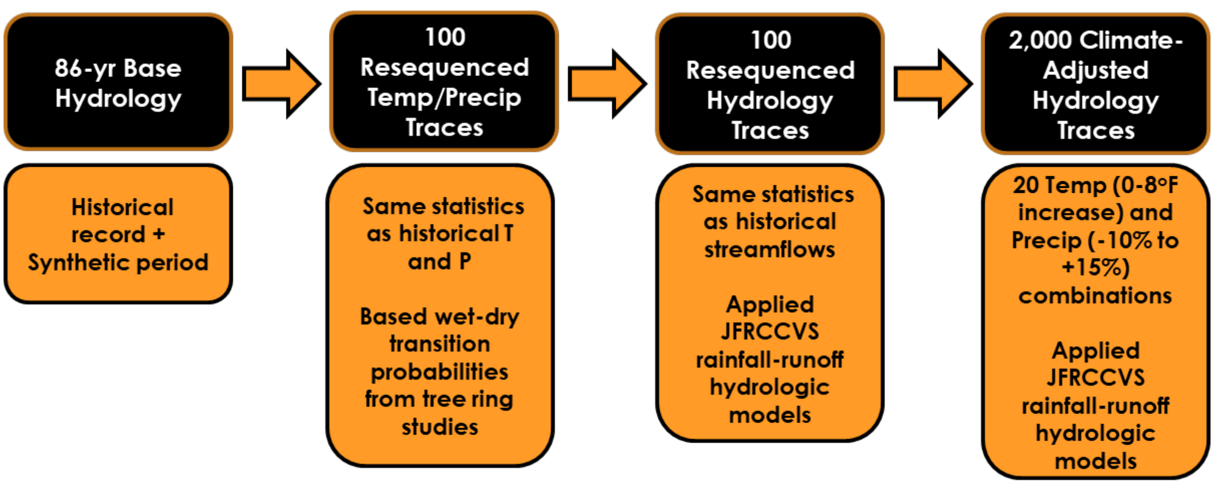


Figure 3-1 Overview of Hydrologic Analysis Process

Note: JVRCCVS = Joint Front Range Climate Change Vulnerability Study

To construct the WSVS hydrology datasets, 100 sets of 86-year long monthly precipitation and temperature data sequences were developed based on wet to dry year transition probabilities seen in an ensemble of reconstructed flows for the Cache la Poudre River at Canyon Mouth (Woodhouse, 2006). These traces of “weather” were then used to generate 100 streamflow traces using the Joint Front Range Climate Change Vulnerability Study (JFRCCVS) hydrologic models. These synthetic traces are similar to historical streamflow but with potentially longer dry periods or more variable transitions from wet to dry periods.

Next, each trace was climate adjusted based on 20 combinations of temperature and precipitation changes from historical conditions. The temperature and precipitation offsets were based on the range of future conditions forecast by commonly used Global Climate Models (GCMs). A range of published results for the CMIP 5 (Coupled Model Intercomparison Project Phase 5), 4.5 and 8.5 emission scenario GCM models in the Poudre River watershed are shown in **Figure 3-2**. In emission scenario 4.5, greenhouse gas emissions peak around 2040, then decline. In emission scenario 8.5, greenhouse gas emissions continue to rise throughout the 21st century.

The figure shows dots at pairs of simulated change in average temperature and precipitation from 1981-2010 to 2050-2074, for each GCM model and for each emission scenario, in relation to the selected temperature and precipitation changes selected for this study (i.e., shown by the triangles). In general, GCMs consistently show that future climate in the Poudre River watershed will be warmer, but they are not consistent in predictions about the direction of change in future precipitation. Similar findings apply to GCMs in the Upper Colorado River watershed that supplies the C-BT Project. The WSVS is concerned with hydrologic conditions that would stress the FCU water supply system, so 20 T/P combinations were selected ranging from 0 to 8 degrees Fahrenheit warmer and -10% to +15% wetter. The National Climate Change Viewer from USGS indicates precipitation changes from -6% to +31%, and temperature increases from 0.6 °C to 4.9°C for the Poudre basin across the different GCMs for the 2050-2074 period (Alder and Hostetler, 2013). If studies were to look further into the future, changes would likely continue to increase. While some GCMs indicate that precipitation may increase more than 15%, FCU does not expect larger precipitation increases to be a source of vulnerability. The result of the climate change review was selection of 2,000 (100 x 20) climate altered hydrologic sequences that could be used to test the impact of future climate on FCU system performance.

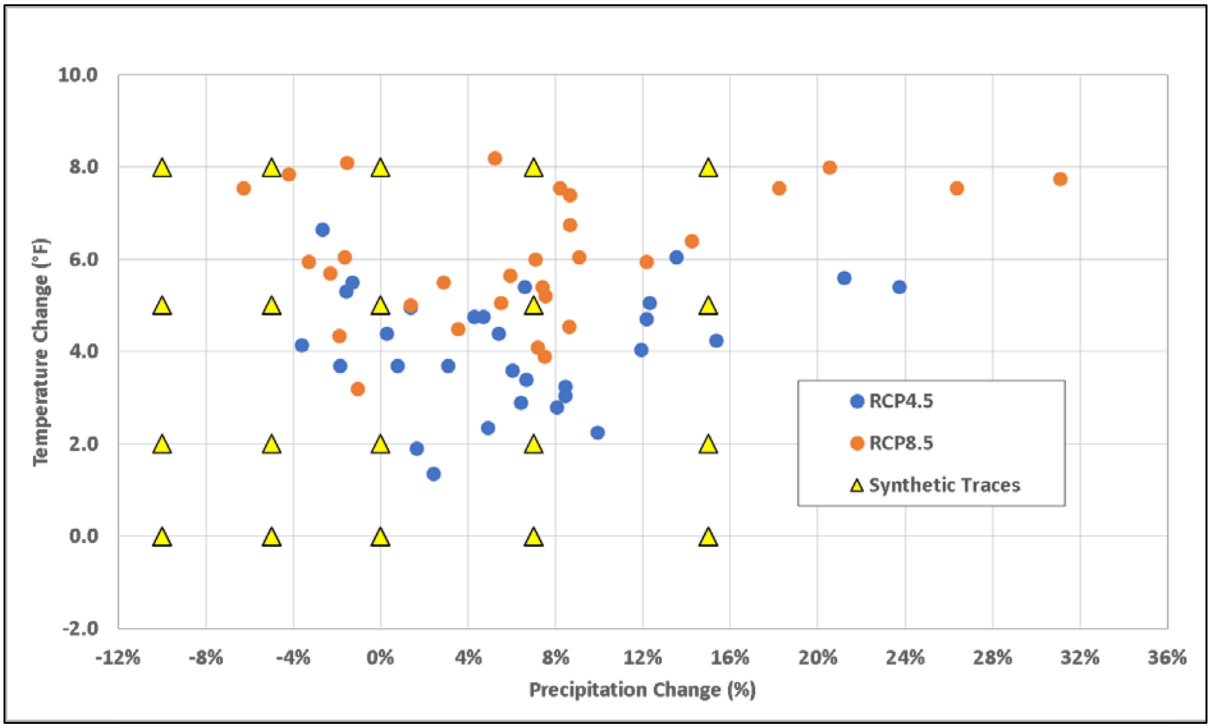


Figure 3-2 Temperature and Precipitation Combinations Used for Climate Change Hydrology Compared to Range of Selected GCMs

Note: GCM results represent the simulated increase in temperature and precipitation projected by the CMIP 5 models with emission scenarios 4.5 and 8.5. The increase in temperature and precipitation is calculated as the increase of the average simulated values for the period between 2050 and 2074 conditions, compared with the average for the period 1981-2010.

3.2 HYDROLOGIC RESULTS

The hydrology results described above capture more natural variability and more climate effects than the historical observed streamflow record; and thus, represent sets of different potential conditions in the basin. Reconstructed input data for the model were based on the sum of flows at the Cache la Poudre River at Canyon Mouth and the Colorado River at Granby Lake. **Figure 3-3** shows annual average flows for about 20 of the constructed flow traces without climate adjustments for the Cache La Poudre at Canyon Mouth and the Lake Granby gage locations. The blue line is the historically modeled flows from which the other traces were developed. As seen, there is significant year-to-year variability. The randomly chosen subset of constructed flows range from a minimum of around 50,700 AFY to a maximum of 687,800 AFY for the Cache La Poudre gage and from 79,600 AFY to 629,900 AFY for the Granby gage. The baseline trace for the Cache La Poudre gage has comparable overall annual averages between 50,700 AFY and 579,200 AFY and the baseline trace for the Granby gage has an overall average annual flow between 108,600 AFY and 514,000 AFY.

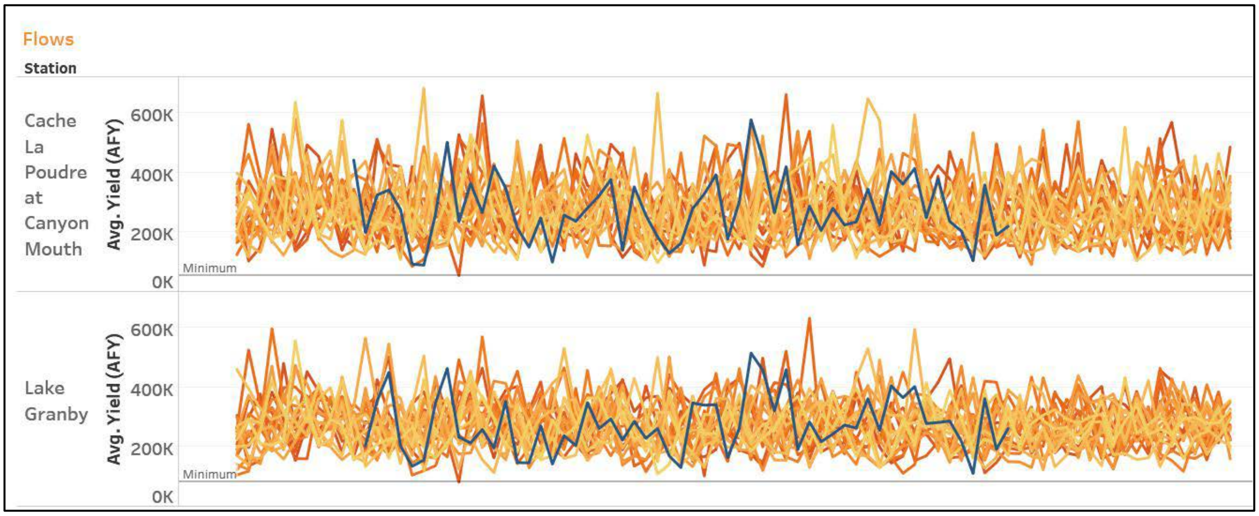


Figure 3-3 Average Annual Synthetic Flow Traces Without Climate Adjustment for the Cache la Poudre at Canyon Mouth and Lake Granby Gages

Naturalized streamflows for 11 inflow points in the PBN model that represent water availability were generated from these 2,000 new hydrology sets. The simulated naturalized flows are the source of the main hydrology inputs for the PBN model. A few PBN constructs such as the excess precipitation construct, agricultural demands and the trans-basin diversions were identified as needing an approach that would synchronize those inputs with the same future hydrologic conditions. The selected approach was based on the like-year method, used in previous PBN analyses for estimating these PBN input time series for future conditions. The like-year method determines values for the new time series based on values from a historical year with the most similar total annual flows at key locations. For consistency, all PBN model input time-series, except the generated 11 naturalized stream flows, used a like-year approach to simulate future conditions.

The synthetic naturalized flow datasets had both wetter and drier periods of flow than the historical base flow dataset. These flows also had, for some climates, an earlier shift in peak runoff. **Figure 3-4** shows an example of the peak runoff shifting from June in the no climate change condition to May in the two warmest climate conditions. Simulating these changes in the models through the synthetic hydrologic inputs incorporate identified risks by both FCU and Northern Water surrounding changes in runoff timing.

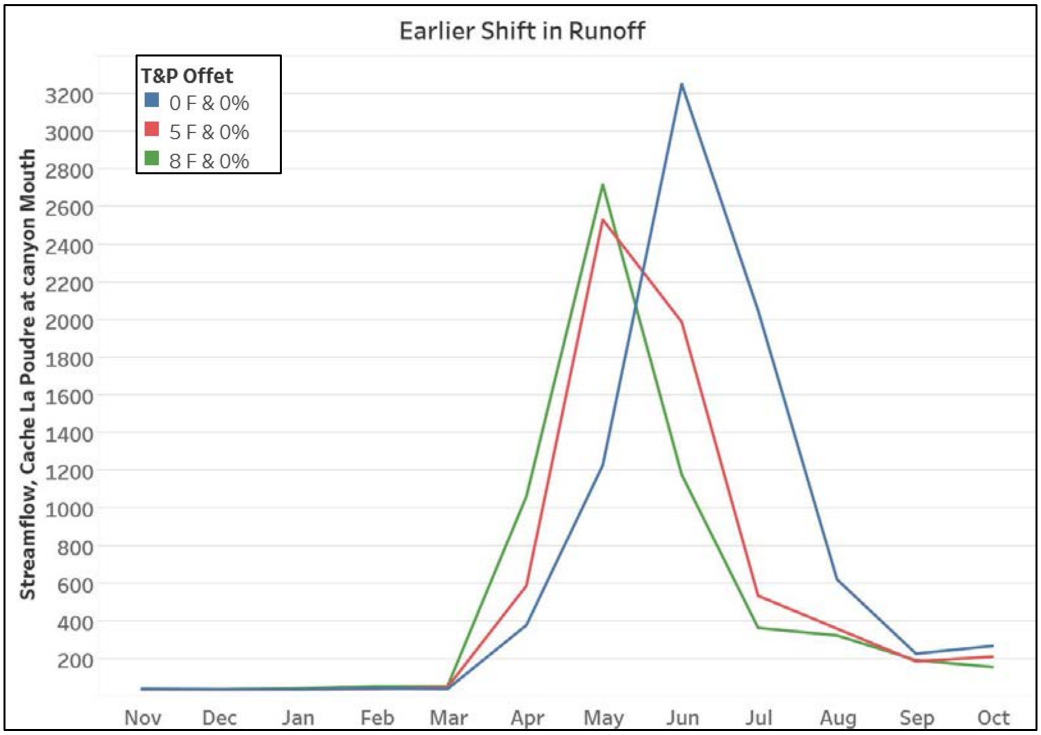


Figure 3-4 Streamflow for Selected Trace Depicting a Shift to Earlier Runoff for Warmer Climates

Figure 3-5 shows the average of the annual flows for all 100 traces for each of the 20 climate combinations for both the Poudre River at Canyon Mouth naturalized flows and the Lake Granby naturalized flows. Average annual streamflow volumes amongst the traces for the Poudre River at Canyon Mouth range from 70% of baseline flow (i.e., the flow based on historical temperature and precipitation, or delta T = 0 and delta P = 0) for the hottest, driest traces to 139% of baseline flow for the coolest, wettest traces. Flow changes at Granby were comparable. For comparison, under a plausible future climate that is 5 degrees F warmer than historical with the same average annual precipitation, the simulated average annual streamflow at the Poudre River at Canyon Mouth gage is 21,000 AFY (8%) less than historical.

		Delta P				
Basin	Delta T	-10%	-5%	0%	7%	15%
Cache La Poudre at Canyon Mouth	8 F	70% 189,516	79% 214,864	88% 241,156	103% 279,926	120% 326,717
	5 F	72% 197,600	82% 224,065	92% 251,456	107% 291,295	125% 339,726
	2 F	75% 204,550	86% 233,415	97% 263,366	113% 307,497	132% 361,271
	0 F	77% 209,967	88% 240,600	100% 272,680	118% 320,455	139% 378,560
Lake Granby	8 F	70% 190,797	80% 215,992	89% 241,377	102% 276,540	117% 316,072
	5 F	74% 200,493	84% 226,635	93% 252,835	107% 288,931	121% 328,746
	2 F	78% 210,964	88% 237,245	97% 263,351	111% 299,719	126% 340,232
	0 F	81% 218,725	90% 244,938	100% 270,981	113% 306,969	128% 347,893

Figure 3-5 Average Annual Flow Volume for Hydrologic Traces

Note: Each cell shows the mean of the average annual flows for the 100 traces with the corresponding T/P combination expressed in AFY and as a percentage of the average annual flow for the T=0, P=0 combination.

In recent water supply planning studies, including the Halligan Water Supply Project EIS, FCU has used a single 86-year hydrologic record that is a combination of historical data and a statistically developed synthetic period. The synthetic period includes the statistically developed 1-in-50-year critical drought used for previous planning studies and defined in FCU's water supply planning policy. The critical drought period has a 6-year duration with an average annual flow at the mouth of the canyon of 196,090 acre-feet. In order to compare that 6-year critical period with the most severe 6-year droughts in the synthetic hydrologic traces developed for this study, the minimum 6-year rolling average annual flow volumes were computed for each of the 2,000 hydrologic scenarios. This provides a proxy for comparing the 1-in-50-year drought used for past planning with the relative severity of the 6-year critical periods embedded in the WSVS synthetic hydrology.

Figure 3-6 shows the average magnitude of the minimum 6-year rolling average flow for the 100 traces in each of the 20 climate change combinations for the Cache La Poudre at Canyon Mouth gage, and also reports this value as a percentage of the 196,090 acre-feet annual flow used as the critical drought in past planning studies by FCU. The 100 hydrologic traces in the WSVS hydrologic dataset for the unaltered historical climate conditions (T=0, P=0%) have an average 6-year critical period flow at this location of 191,343 AFY, which is a 2% reduction from the historical critical drought period. The hottest/driest climate condition (T=+8, P=-10%) produces an average 6-year critical period annual streamflow that is 31% less than the critical period streamflow currently used for planning. The coolest/wettest climate condition (T=0, P=+15%) produces an average 6-year critical period annual streamflow that is 38% more than the critical period streamflow currently used for planning.

				Delta P		
Basin	Delta T	-10%	-5%	0%	7%	15%
Cache La Poudre at Canyon Mouth	8 F	69% 134,494	79% 154,857	90% 175,760	105% 206,438	124% 242,757
	5 F	71% 138,641	82% 160,128	93% 182,329	109% 214,181	129% 252,189
	2 F	72% 141,549	84% 164,188	96% 187,637	113% 222,273	134% 262,657
	0 F	74% 144,201	85% 167,066	98% 191,343	116% 227,311	138% 270,817

Figure 3-6 Minimum 6-year Average Annual Flow Volume for Climate Altered Hydrologic Traces in Acre-Feet per Year and as a Percentage of Hydrologic Traces Based on Historical Climate - Cache La Poudre at Canyon Mouth gage

Notes:

a) Each cell presents values based on the average of 100 traces for the pertinent climate condition.
b) The lower value in each cell is calculated from the lowest 6-year moving average value in the 86-year synthetic streamflow traces.
c) The upper value in each cell is the minimum 6-year moving average flow volume for that climate condition expressed as a percentage of the minimum 6-year moving average flow volume from the FCU planning hydrology.

Figure 3-7 shows the percentage of the 100 traces for each of the 20 climate adjustments at the Cache La Poudre at Canyon Mouth gage that capture at least one 6-year critical drought period that is worse than the critical planning drought from the current FCU hydrologic planning timeseries. The figure illustrates the minimum 6-year average flow in a synthetic 86-year hydrologic trace is very sensitive to average annual precipitation. A 5% decrease in average annual precipitation forces essentially all traces to have at least one 6-year critical period with less average streamflow than in the critical period currently used by FCU for water supply planning. Conversely, a 15% increase in average annual precipitation forces essentially all traces to have no 6-year critical periods with less streamflow than in the critical period currently used by FCU for water supply planning.

		Delta P				
Basin	Delta T	-10%	-5%	0%	7%	15%
Cache La Poudre at Canyon Mouth	8 F	100%	100%	89%	26%	2%
	5 F	100%	100%	80%	15%	1%
	2 F	100%	99%	64%	11%	1%
	0 F	100%	99%	55%	7%	0%

Figure 3-7 Percent of Hydrologic Traces with a Minimum 6-year Average Annual Flow Volume at Cache La Poudre at Canyon Mouth Gage Less Than Critical Planning Drought

These characteristics of the WSVS hydrology are important when interpreting the vulnerability study results relative to water supply policy criteria that are based on the 6-year duration, 1-in-50-year drought in the runoff data currently used for planning. The minimum 6-year moving average flow analysis demonstrates that the 1-in-50-year drought upon which the current water supply policy is based is highly sensitive to assumed climate conditions. This explains the sensitivity of system performance metrics based on the water supply policy to future climate variability, as described in Section 7.3.

4.0 WATER DEMANDS

Future water demand is a significant uncertainty to be evaluated in the WSVS. Water demand is a function of population, development density, success of water conservation measures, technology in water fixtures and irrigation systems, economic conditions and other factors that are difficult to predict. In addition, demand varies year to year based on weather conditions during the landscape irrigation season. As a result, the WSVS required a method for estimating future water demands under a range of assumed future conditions.

Future water demands for the FCU service area were estimated using a new Demand Estimation Tool developed for this project. Development of the Demand Estimation Tool is described in the Water Demand Forecasting Tool Technical Memorandum (RTI, 2019) contained in Appendix C. This section provides a brief description of the Demand Estimation Tool and the demand forecasts developed for use in the WSVS.

4.1 DEMAND FORECASTING TOOL

The Fort Collins Demand Estimation Tool incorporates the variables and computational algorithms used in the demand forecasting model, which was developed based on input by FCU staff and implemented by RTI. The demand model consists of individual linear regression models, each developed for the following groups of water customers: single family and duplex, multifamily, commercial small, commercial medium and commercial large customers. It was developed using processed historical customer-level water use data from 2001-2016 to estimate future water demand at a monthly time step. The independent variables used in the model to estimate water use under different future conditions are listed in **Table 4-1**. Not all independent variables were used to estimate water demand for all the customer groups.

Table 4-1 Independent Variables Used in the Regression Equations in the Demand Estimation Tool

Variable Name	Description
(Intercept)	Equation constant
daysover85	Numbers of days in the month with the max temp over 85
irrig_rain_mon	Total rain in the month, only for May through September, equals zero for the other months
summer	Equals 1 if May through Sept
bed	Number of bedrooms
units	Numbers of units
unemprate	Unemployment rate (monthly)
parcel_acr_CLg	Parcel size, acres for large commercial
parcel_acr_CMd	Parcel size, acres for medium commercial
parcel_acr_CSm	Parcel size, acres for small commercial
parcel_acr_MF	Parcel size, acres for multi-family parcels

Variable Name	Description
parcel_acr_SMDUP	Parcel size, acres for single family and duplex parcels
commindust	Equals 1 if primarily an industrial or commercial zone
downtown	Equals 1 if primarily a downtown zone
harmish	Equals 1 if primarily a harmony corridor or employment zone
residential	Equals 1 if primarily a residential zone
retail	Equals 1 if primarily a retail zone

The Demand Estimation Tool estimates future water demand using the demand regression models to predict the average water use, per premise, by month for each of the five water user types. Because water demand is estimated as a function of weather variables such as monthly rainfall and temperature, the Demand Estimation Tool output consists of monthly demands for a specific sequence of hydrologic years as input by the user. The base water demand is calculated, aggregating the premise level demand across customer groups, for a predicted number of premises. The total demand includes the base demand, the supply obligations for the large commercial users (LCUs) and the estimated general distribution losses. The water demand can be estimated for different user specified grouping areas, including the FCU service area, the City, or its Growth Management Area (GMA).

The Demand Estimation Tool operates as a module of the DMS. The underlying data for the tool is parcel-based derived through spatial processing of GIS layers for grouping the variables by areas and sectors, attaching water use data and other demand drivers for the regression models. The final GIS layer attribute table, or Master Table, plays an important role in the demand estimation method, providing information to group parcels by service areas and apply densities in planning zones, for current and future predictions of water use in developed and undeveloped areas. One of the main assumptions in estimating the demand with the Master Table is that future planning zone characteristics (e.g., distribution of commercial and residential premises) are similar to current developed areas in the same zone.

4.2 FUTURE WATER DEMANDS

Because key factors affecting future water demand such as population growth, land development density and economic conditions are all uncertain, the WSVS used a scenario approach to assess the effects of water demand on water resources system performance. Three demand scenarios were developed by FCU for use in the WSVS. The demand scenarios are based on the most likely proposed future development trajectories developed as part of the Fort Collins City Plan update. The updated City Plan was adopted by City Council on April 16, 2019. The WSVS demand scenarios were developed with significant input from the City Planning Department and are based on assumed buildout conditions and 2070 population. These estimates should be reviewed and updated as new population and land use trends emerge for the City. The expected residential development densities by zone, as well as the expected split between single-family development and multi-family development for the City Plan 2 and 3 development scenarios are included in Appendix C. The demand scenarios are:

- City Plan 2 – This scenario was developed to estimate future (2070) water demands for the City Plan Development Scenario 2 – Targeted Changes. This development scenario forecasts more dense residential development in some targeted areas of the City compared to current average residential density, mainly along existing commercial corridors.

- City Plan 3 – This scenario was developed to estimate future (2070) water demands for the City Plan Development Scenario 3 – Broad Changes. This development scenario expects even more dense residential development than in City Plan 2 across a broader set of planning zones, including a more significant shift towards multi-family units in lieu of single-family units. This scenario represents a reasonable upper bound to current expected development densities.
- City Plan 3 Plus 20% -- This scenario consists of a 20% increase of the City Plan 3 residential and general commercial demands and a portion of the LCU demands to represent unanticipated increased demands in the Fort Collins system due to factors not considered in the Demand Estimation Tool assumptions. For reference only, adding the demands associated with approximately 80% of currently undeveloped land outside the utility service area but inside the GMA plus the 20% increase in LCU demand results in nearly the same overall demands as represented by the City Plan 3 plus 20% scenario. This increase in demand could come from increased population, large commercial users, expansion of the service territory, or other factors that would stress supplies in all years and would be especially challenging in future hotter and drier climate conditions.

The demand scenarios used in the modeling system were created in the Demand Estimation Tool. For each demand scenario, the demand tool generated a time series of 86 years of monthly demands for all potential hydrologic scenarios. These time series were cataloged in the database and accessed when running the FCSys model. Note that none of the WSVS simulations include the effects of water use restrictions; thus, the demands developed by the Demand Estimate Tool were not reduced in accordance with the FCU Water Shortage Response Policy.

The number of future residential and commercial premises are estimated based on the dwelling unit densities in each zone district, the current density of commercial premises per zone district, the percent split of single-family versus multi-family development and a percent-built factor for each zone. The regression equations are used to estimate the monthly water consumption per premise for each of the five identified water use categories. The premise level monthly demand estimates are multiplied by the expected number of premises. The demand estimates include conveyance and distribution system losses. Details on the form of the regression equations and their coefficients are provided in Appendix C.

The components making up an estimate of the total FCU demand include:

- Residential and commercial indoor and outdoor demand, which includes a single estimate of commercial users with tap sizes between 6 and 8” not included in the LCU demands (Citydem node in the FCSys model);
- Large commercial users (LCU) with specified supply contract obligations, including Colorado State University, several breweries and several large manufacturers (LCU nodes in the FCSys model); and

- Contractual obligations to deliver C-BT water. These include obligations to City facilities and several homeowners' associations in the City, as well as agreements with surrounding water districts, municipalities and other entities. These are raw water demands as opposed to treated water demands. (CBTOblig node in the FCSys model).

The Demand Estimation Tool computes monthly demands for the Citydem node for each month in the 86-year simulation period based on the climate conditions in that month (tied to the hydrologic trace and climate condition being simulated) and the development scenario assumptions. LCUs and C-BT obligations are then added to the Demand Estimation Tool results to compute the total demand for a given scenario.

The Demand Estimation Tool as applied in the WSVS was used to generate monthly water demand values for the 86-year model period that represent one specific future condition. For example, for a water system simulation performed for 2070 conditions, the demand for every year in the 86-year simulation period will represent 2070 population and development conditions. Monthly and annual variability in demand are driven by climate factors. The purpose of the analysis is to investigate water resources system performance at a fixed point in the future (i.e., fixed population and development conditions) over a range of 86 years of variable hydrology. The WSVS analysis does not attempt to capture the incremental increase in demand from current conditions to some future condition over the 86-year simulation period.

The median average annual water demand in 2070 under City Plan 2 assumptions, including the effects of climate change is 37,700 AFY. The more aggressive growth assumptions in the City Plan 3 scenario result in a median average annual water demand of 39,200 AFY, for an increase of 4% compared to City Plan 2. The City Plan 3 Plus 20% scenario increased both the general residential and commercial portion of the total demand (i.e., Citydem node) and a portion of the LCU demand by 20%. However, the CBTOblig demands and the remaining portion of the LCU demands were kept constant. This resulted in a median total water demand of about 45,200 AFY. The average annual demand for 2065 based on previous FCU planning studies is 40,629 AFY. This was based on a future population of 178,000, 150 gallons per capita per day water use, and current C-BT obligations and LCU demands. This is referred to as the "Baseline demand" in this study.

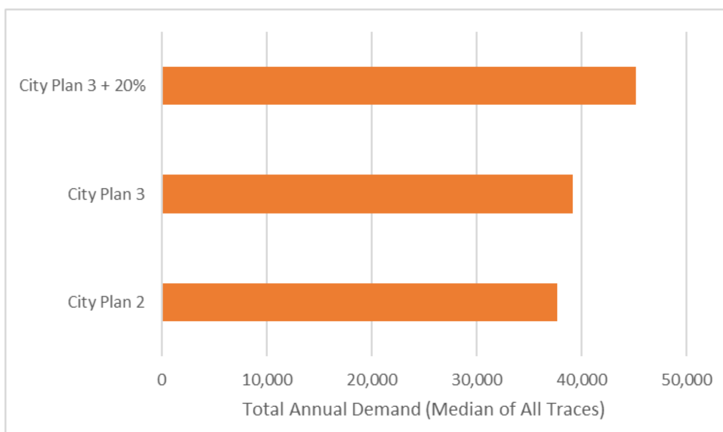


Figure 4-1 Total Annual Demand in 2070 Including Climate Change (Median of All 2,000 Possible Futures for Each Development Scenario)

Note: Average Annual Baseline Demand = 40,629 AFY

Figure 4-1 compares the total annual demands for these three scenarios. The impact of this range of demands on the FCU water resources system was explored in the WSVS scenarios described in Section 6.

Because water demand is partially a function of weather, the monthly demand simulated by the Demand Estimation Tool is unique to each hydrologic time series it is paired with. **Figure 4-2** shows the simulated CityDem node annual demand for a single representative trace under the City Plan 3 Demand Scenario with a subset of climate adjustments. As shown, the demand time series have the same general pattern but are shifted according to the climate combinations. Impacts of long-term climate change can vary annual demands by about 14%. Impacts from inter-annual climate variability can vary annual demands by up to 10% within a given trace and temperature and precipitation. This shows that both long-term climate change and inter-annual climate variability can impact annual demands more than growth assumptions in City Plan 2 or City Plan 3.

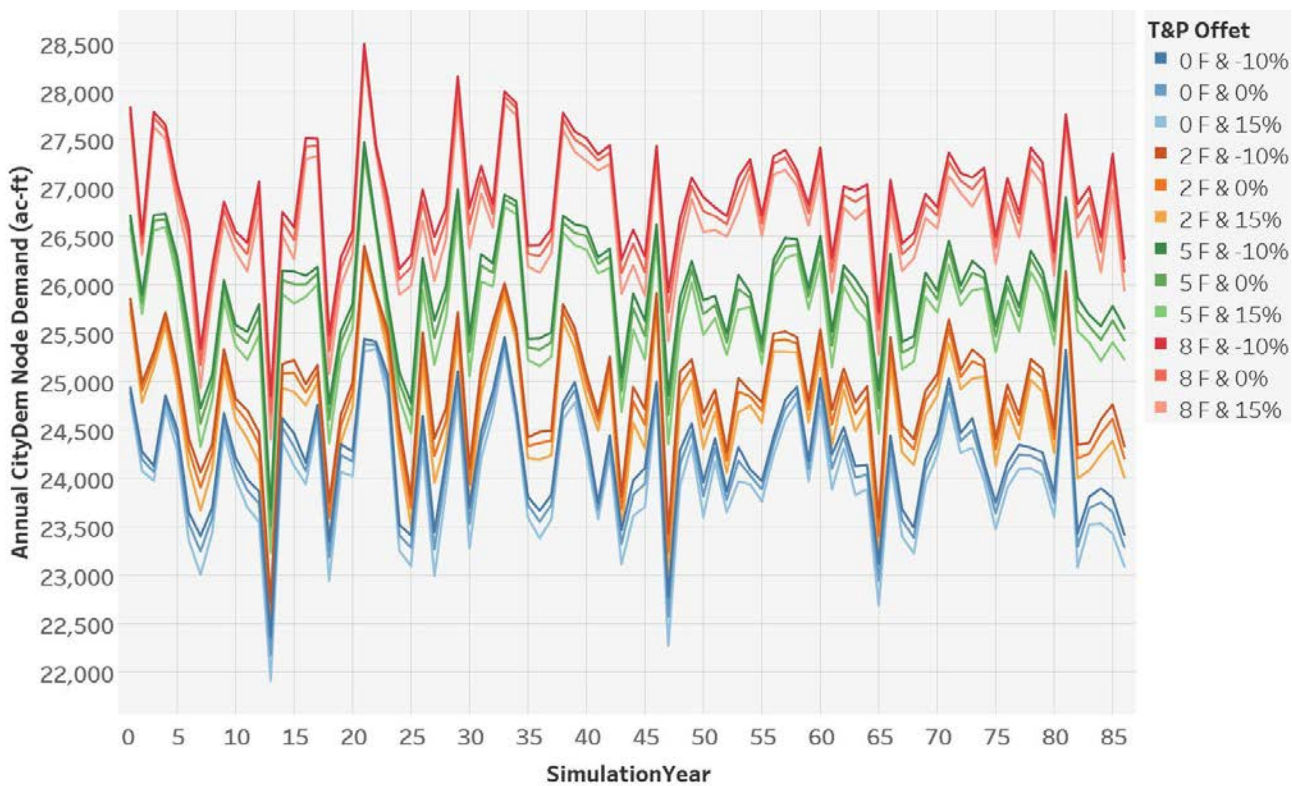


Figure 4-2 Annual Demand Variability in the CityDem Node for a Representative Trace with Select Climate Adjustments and City Plan 3 Development

Because 2,000 possible hydrologic futures were simulated for each of the demand scenarios (100 re-sequenced traces multiplied by 20 climate combinations for each), each scenario has an associated range of possible annual demands. **Figure 4-3** shows the median, minimum and maximum average annual demand for the 2,000 future possibilities generated for each of the two future development scenarios, as well as the City Plan 3 + 20% scenario. As shown in **Figure 4-3**, the average annual demands for City Plan 2 and City Plan 3 are typically lower than the "baseline demand". The baseline demand for the WSVS was developed from existing FCU demand planning estimates, modified to reflect similar demand estimate methods as developed for the Demand Estimation Tool. The WSVS City Plan 2 and City Plan 3 general residential and commercial demands are lower than baseline in all cases, but the LCU portions are larger. The LCUs and CBTOblig demands are based on contracts that are not dependent on climate, hydrology or other factors, so they are the same for all scenarios. The highest average demand scenario for City Plan 3, associated with a hydrologic trace with long periods of drought and a warmer climate, has a higher average annual demand than the baseline. This plot shows how the overall averages of the scenarios compare to each other, including variability of the minimum and maximum values; however, the interannual variability of the demand timeseries is seen in **Figure 4-2** above.

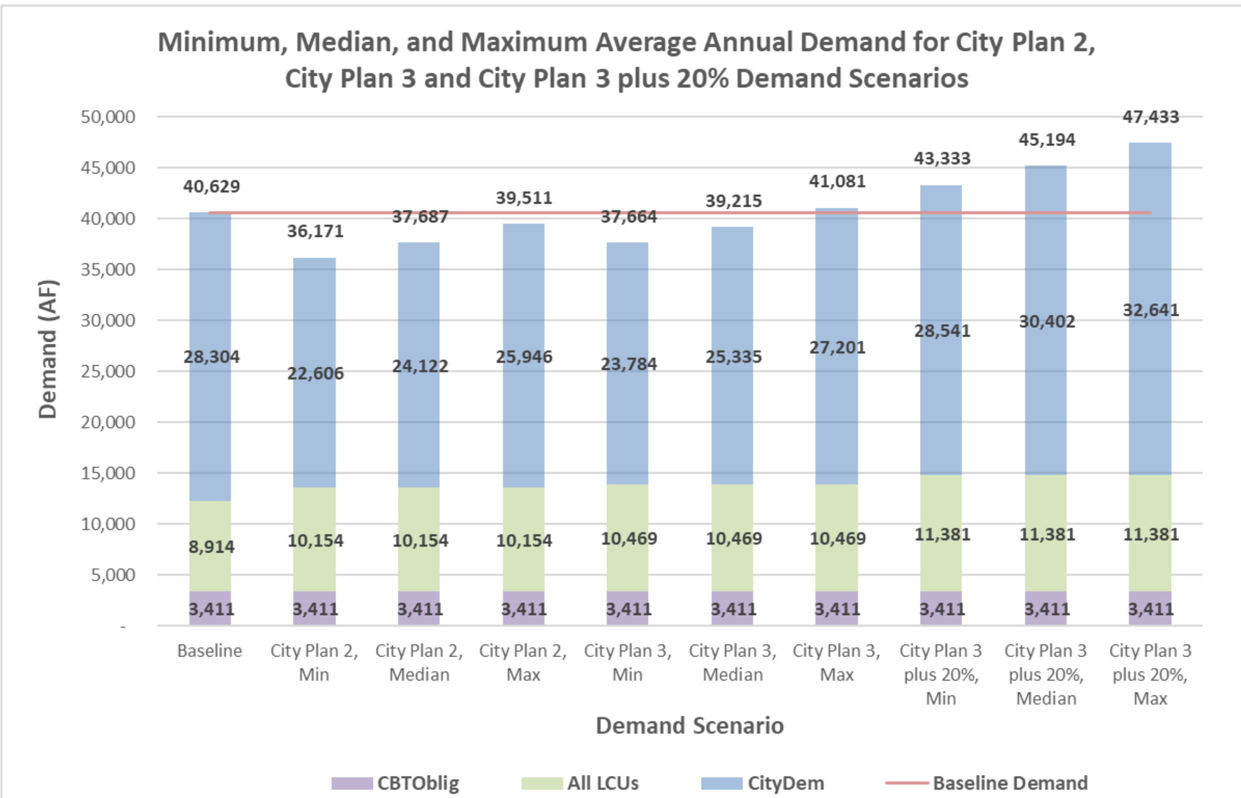


Figure 4-3 Comparison of 86-year Average Annual Demands for Demand Scenarios

Notes:

a) There are 2,000 timeseries of 86-years behind each demand scenario. The average annual demand was determined for each timeseries, and the minimum, median, and maximum values are included in the chart. The CityDem value represents the population and general commercial based demands, which vary based on weather inputs.
b) Baseline has an estimated population of 178,000. City Plan 2 has an estimated population of 179,000. City Plan 3 has an estimated population of 195,000.
c) City Plan 3 Plus 20% represents a demand scenario independent of an estimated population. This situation could present itself in a variety of ways. One example is presented earlier in Section 4.2.

The assumptions used to develop the WSVS demands are different than those used to develop the baseline demand. The baseline demand used a single population forecast and an assumed per capita use rate based on historical water use patterns and an allowance for uncertainty. The previous demand estimation methodology accounted for some variability in year to year demand based on hydrologic conditions, but in a less robust way than in the Demand Estimation Tool. The functionality of the Demand Estimation Tool provided the variability needed to investigate the sensitivity of the Fort Collins water resource system performance to a range of possible future demands in the WSVS.

Figure 4-4 and **Figure 4-5** show the effect of climate conditions on general residential and commercial demand for the City Plan 2 and City Plan 3 demand scenarios. Each cell in the tables shows the average annual demand over the 100 hydrologic traces for the given T and P combination, as well as the percent increase or decrease compared to the T=0/P=0 average annual demand for the specified demand scenario. It is seen that changes in precipitation would have minimal effect on average annual demand but increases in average temperature of 8 degrees F would increase municipal water demand by up to 12 percent. Because higher temperatures would also be associated with lower water supply, this condition could represent a significant threat to the FCU water resources system.

	Delta P				
Delta T	-10%	-5%	0%	7%	15%
8 F	112% 25,791	112% 25,742	112% 25,692	112% 25,622	111% 25,543
5 F	108% 24,783	108% 24,733	108% 24,683	107% 24,613	107% 24,534
2 F	104% 23,732	103% 23,682	103% 23,632	103% 23,562	102% 23,483
0 F	100% 23,026	100% 22,976	100% 22,926	100% 22,856	99% 22,777

Figure 4-4 Effect of Climate on Annual Water Demand (Citydem only) for City Plan 2

Note: The bottom value in each cell is the average of the 86-year average annual demand for CityDem in acre-feet across the 100 traces for the specified future climate condition. The top value in each cell is the percent difference from the T=0/P=0 cell.

	Delta P				
Delta T	-10%	-5%	0%	7%	15%
8 F	112% 27,043	112% 26,993	112% 26,942	111% 26,870	111% 26,789
5 F	108% 26,011	108% 25,960	107% 25,909	107% 25,838	107% 25,756
2 F	103% 24,936	103% 24,885	103% 24,834	103% 24,763	102% 24,681
0 F	100% 24,214	100% 24,163	100% 24,112	100% 24,040	99% 23,959

Figure 4-5 Effect of Climate on Annual Water Demand (Citydem only) for City Plan 3

Note: The bottom value in each cell is the average of the 86-year average annual demand for CityDem in acre-feet across the 100 traces for the specified future climate condition. The top value in each cell is the percent difference from the T=0/P=0 cell.

Figure 4-6 shows more detail on the effect that climate has on demand. This figure depicts the minimum, maximum and average annual demands across all years and traces for each of the climate scenarios and reiterates that demand is more impacted by temperature increases than by changes in precipitation. The difference between minimum and maximum annual demand for any climate variation is about 6,000 AFY. While the maximum and minimum in the figure did not necessarily come from the same trace, it is possible for FCU to see differences in annual demand this large between years.

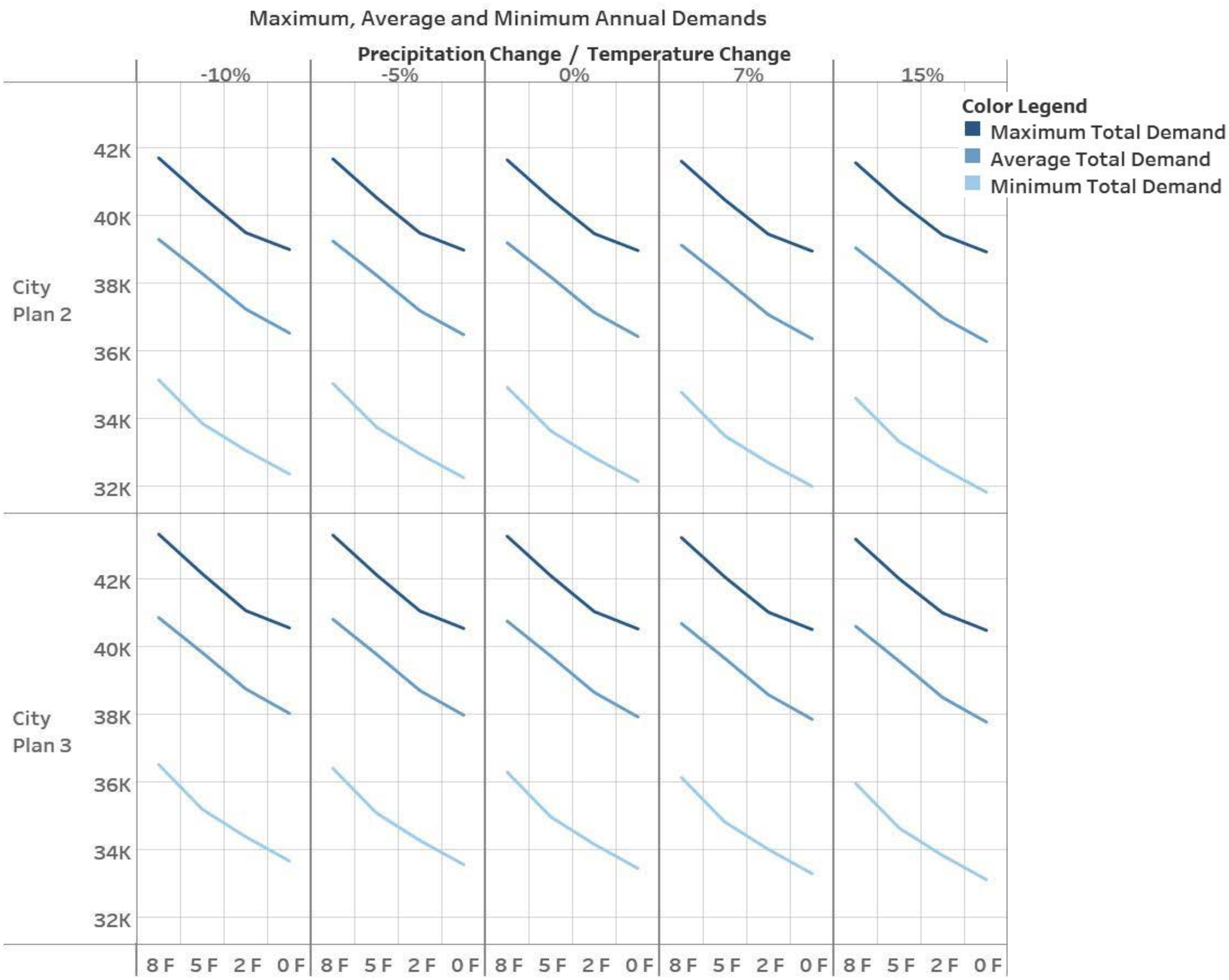


Figure 4-6 Maximum, Average and Minimum Annual Trace Demands

Notes:

a) Y-axis units are acre-feet
b) The shading of each line represents the maximum (darkest shade), average (medium shade) or minimum (lightest shade).
c) The maximum and minimum values are taken from the list of all 100 traces for each climate condition. Each point plotted represents the annual demand for a single year of a single trace.
d) The average values are taken from all years and all 100 traces. This data is most similar to what is plotted in Figure 4-4 and Figure 4-5, except this plot is the total demand and not only CityDem.

5.0 RISKS AND UNCERTAINTIES

This section summarizes the methodology and results of the process to identify and prioritize risks and uncertainties to the FCU water supply system. The purpose of the risk and uncertainty assessment was to look out 50 years and forecast events that could adversely affect FCU water supplies or infrastructure. The 50-year timeframe is the period adopted for the WSVS. It is recognized that anticipating conditions that may exist 50 years in the future is highly speculative. However, for purposes of the WSVS it is appropriate to investigate a broad range of possible future conditions to determine which conditions could stress the performance of the current water supply system.

The spatial scope of the WSVS includes source water areas and infrastructure upstream of the FCU water treatment plant. In addition to local Poudre River Basin supplies, the scope includes supply derived from the C-BT Project. Therefore, risks and uncertainties were identified by both FCU staff and Northern Water staff. Separate but consistent methods were used to identify and prioritize risks and uncertainties associated with FCU local supplies and with supplies provided by Northern Water from the C-BT Project.

A more detailed discussion of the risk and uncertainty analysis is in the Water Supply System Risk Identification Technical Memorandum (Stantec, 2018c), contained in Appendix B.

5.1 METHODOLOGY

Risks and uncertainties that could affect the future performance of the FCU water supply system were brainstormed in workshops held at Fort Collins Utilities and Northern Water. Identified risks and uncertainties were organized in the following categories that span the various aspects of the FCU water supply system.

- ***Climate and Hydrology*** risks relate to weather variability and other hydrologic factors, both short- and long-term, that can impact the potential yields from a watershed.
- ***Watershed*** risks relate to physical watershed conditions that can impact the yields available to FCU.
- ***Operational and Infrastructure*** risks relate to how FCU delivers physically and legally available water to its treatment facilities.
- ***Administrative and Legal*** risks relate to conditions, regulations, or policies that could impact the legal allocation or availability of water supplies.
- ***Demand*** risks relate to changes in required volume, timing and quality of water that will need to be delivered to water treatment facilities to meet customer needs.

Some risks are long-term, or chronic and would persist indefinitely and affect all future years. Other risks are short-term, or acute and would only occur for a short period of time (e.g., several months or a few years). Although long-term and short-term risks could have very different impacts on the FCU raw water system performance, both types of risks were assessed together in the WSVS.

The identified risks were rated as part of the prioritization process. Individual risks were rated by assigning a 1 to 5 score for both likelihood (possibility of the risk or uncertainty occurring) and impact (consequences to the FCU/C-BT water supply system if the risk or uncertainty were to occur) according to the definitions in **Table 5-1**. The composite score was calculated by multiplying the likelihood score by the impact score and was then used to prioritize risks.

Table 5-1 Definitions of Likelihood and Impact Used in Risk Rating Process

Score	Likelihood Definition	Impact Definition
1	***Rare*** – the risk will only occur in exceptional circumstances.	***Insignificant*** – If the risk occurs the impact to the water supply system would be negligible.
2	***Unlikely*** – the risk will occur in occasional circumstances.	***Minor*** – If the risk occurs the impact to the water supply system would be minimal.
3	***Possible*** – the risk will occur in some circumstances.	***Moderate*** – If the risk occurs there would be a noticeable impact to the water supply system.
4	***Likely*** – the risk will occur in a majority of circumstances.	***Major*** – If the risk occurs there would be substantial impact to the water supply system.
5	***Almost Certain*** – the risk will occur in almost all circumstances or is imminent.	***Extreme*** – If the risk occurs there would be extensive or catastrophic impact to the water supply system or customers.

5.2 FORT COLLINS WATER SUPPLY SYSTEM RISKS AND UNCERTAINTIES

Risks and uncertainties to the FCU water supply system were identified and prioritized by FCU staff members representing a variety of groups within the organization during a half-day workshop. Workshop attendees included representatives from water supply, water treatment, demand and conservation, watershed management, legal and water operations groups. FCU identified a total of 46 risks and uncertainties. Each of the identified risks and uncertainties were prioritized, selecting those that would be simulated. All risks with a composite score of 12 or above (out of a possible 25) were deemed impactful enough to warrant further examination and potential simulation. In addition, all risks that received an impact score of 4 or 5 were examined further, as these risks could be significantly impactful, even if their likelihood of occurring was low. Of these highly impactful risks, an outage of Joe Wright Reservoir (O8) and an outage of the Pleasant Valley Pipeline (O11) were prioritized for further analysis. An expanded description of each of the risks and the priority score they were given can be found in the *Water Supply System Risk Identification Technical Memorandum* contained in Appendix B. The prioritized risks and uncertainties were organized into five major threat groups that span the various risk categories. These threat groups are climate change, demands, critical outages, enhanced environmental stressors and shared infrastructure (i.e. risks or uncertainties due to lack of infrastructure ownership by FCU). **Table 5-2** lists all the key risks and uncertainties prioritized for simulation and indicates their threat group.

Table 5-2 List of Key Risks and Uncertainties Prioritized for Simulation

ID	Risk or Uncertainty Name	Threat Group	Description
O1	Outage - 24 Pipeline	CO	Short term outage due to flooding, landslides, wildfire, etc.

ID	Risk or Uncertainty Name	Threat Group	Description
O2	Outage - 27 Pipeline	CO	Short term outage due to flooding, landslides, wildfire, etc.
O3	Algal Blooms	EES	Algal blooms in storage reservoirs and rivers increases water quality issues and potential treatment problems.
C1	Longer duration droughts	CC	Multi-year and/or more severe droughts occur in the future that are not captured in the observed record.
A1	New Regulations	EES	New regulations (either federal or state) impact availability of yields from existing water rights.
W1	Wildfires	EES	Wildfires occur, causing a variety of impacts on water quality, runoff and threats to infrastructure.
C3	Change in precipitation type - Hydrology	CC	More precipitation falls as rain instead of snow during the Fall and Spring.
C4	Changes in frequency/ magnitude of precipitation events - Hydrology	CC	Precipitation events, particularly summer rainstorms, become less frequent and more intense.
C2	Changes in runoff timing	CC	Early higher runoff and lower late-season baseflow reduces yield from volumetric decrees that list specific diversion dates.
W2	Forest Health Degradation	EES	Forested area health decreases due to beetle kill, pollution, warming climate, etc.
A4	Changing state administration	CC	Policies around state water administration change, impacting yields from water rights
D3	Development Uncertainty	D	The composition of development in service area (e.g. density, type, outdoor area) is different that past.
A2	Increased Basin Demands	D	Higher demands across the entire Poudre River basin (due to climate change/population growth) impact use of water rights.
O5	Outage - Horsetooth Reservoir Intake	CO	Short term outage of reservoir outlet and intake to WTP; higher risk due to lack of redundancy.
O4	Outage - Michigan Ditch	CO	Short term outage due to flooding, landslides, wildfire, etc.
D2	Water Use Changes	D	Decrease in per capita use continues and how water is used (e.g. indoor vs. outdoor) changes.
D1	Service area growth and Regionalization	D	Ft. Collins expands its service area or enters into agreements to provide water to regional entities.
A9	Elimination or Interruption of Reuse Plan	SI	Platte River Power Authority decommissions Rawhide Energy Station, effectively eliminating the need for the Reuse Plan. In multi-year droughts, water from the Reuse Plan is reduced or unavailable.
D8	Change in precipitation type - Demands	CC	More precipitation falls as rain instead of snow during the Fall and Spring.
D9	Changes in frequency/ magnitude of precipitation events - Demands	CC	Precipitation events become less frequent and more intense.
A3	Changes to Northern Water C-BT Operations	SI	Allocation of C-BT water through setting of the quota and ways in which C-BT water can be managed, changes in the future.

ID	Risk or Uncertainty Name	Threat Group	Description
W3	Development in Watersheds	EES	Land development in watersheds (recreation, residential, O&G, mining) increases risk of water quality contamination.
D6	Hotter summer changes irrigation	D	A warmer climate increases the length of the irrigation season and hotter days increase demand during the summer.
O6	Outage - Chambers Reservoir	CO	Short term outage due to flooding, landslides, wildfire, etc.
O8	Outage - Joe Wright Reservoir	CO	Short term outage due to flooding, landslides, wildfire, etc.
O11	Outage - Pleasant Valley Pipeline	CO	Short term outage due to flooding, landslides, wildfire, etc.
Note: CC = Climate Change, D = Demands, CO = Critical Outages, EES = Enhanced Environmental Stressors, SI = Shared Infrastructure			

5.3 COLORADO-BIG THOMPSON SYSTEM RISKS AND UNCERTAINTIES

Risks and uncertainties to the C-BT Project were identified by staff members from Northern Water during a half-day workshop. Staff from Northern Water represented at the workshop included experts in water supply, watershed management, water quality and operations. While the primary goal was to generate risks around the C-BT system that would impact FCU, Northern Water generated risks across their entire C-BT collection and storage system. These same staff members then scored the identified risks using the rubric described in Section 3.1 based on their perceptions and professional judgment. Therefore, scoring is presented as a *perceived* threat to the water supply system; the actual impact to the water supply system was quantified later for selected key risks using the FCU water resources simulation models.

The scope of the Northern Water risk and uncertainty evaluation included the C-BT source watersheds, collection system and storage reservoirs. Risks to the delivery and distribution system were only considered insofar as they could affect deliveries to FCU. As with the FCU risk assessment process, the planning horizon was 50 years and risks and uncertainties were organized in the five categories of Climate and Hydrology, Watershed, Operations and Infrastructure, Legal and Administrative and Demand. Fifty-three risks and uncertainties were identified. The identified risks and uncertainties were prioritized, identifying those that would be simulated in the Fort Collins modeling system for quantitative analysis. An expanded description of each of the risks and the priority score they were given can be found in the *Water Supply System Risk Identification Technical Memorandum* contained in Appendix B. Similar to the process used by FCU, the first step to prioritize risks was to include all risks with a composite score of 12 or above (out of a possible 25). Northern and FCU felt these risks were impactful enough to warrant further examination and potential simulation. Additionally, all risks that received an impact score of 4 or 5 were further examined (regardless of their composite score) as these risks could be significantly impactful even if their likelihood of occurring was low. Of these highly impactful risks, those prioritized were:

- Conveyance system to Horsetooth Reservoir Outage (ON12)
- Adams Tunnel Outage (ON18)
- Farr Pump Plant Outage (ON17)
- Lake Granby Dam/Dike System Outage (ON19)

- Colorado River Hydrologic Uncertainty / Major Outage of C-BT Project (AN2)
- Windy Gap Plant Outage (ON20)

The prioritized risks and uncertainties were then summarized around the same five major threat groups used by FCU: climate change, demands, critical outages, enhanced environmental stressors and shared infrastructure. **Table 5-3** lists the key risks and uncertainties prioritized for simulation and their threat group.

Table 5-3 List of Northern Water Prioritized Risks and Uncertainties

ID	Name	Threat Group	Description
CN1	Longer Duration Droughts	CC	Long-term droughts that have longer durations than occurred in past.
WN1	Changes in wildfire characteristics	EES	Increase in extent and severity of wildfires in high elevation forests degrades water quality, increases sediment loads and changes runoff characteristics.
CN2	Increased frequency of extreme dry years	CC	Years like 2002 and 2012 become more frequent.
ON1	Green Mountain Replacement Pool Inadequacy	D	If a change in hydrology reduces water supply in the Blue River drainage, the 52,000 acre-ft replacement pool may be inadequate to mitigate against a variety of future risks This could reduce Northern's ability to divert out-of-priority water.
WN2	Wildfires - Upstream of Grand Lake/Shadow Mountain	EES	Increased occurrence of wildfire leads to short term reduced capacity and ability to use Grand Lake/Shadow Mountain Reservoir. Long term channel and sediment changes.
WN3	Watershed forest health degradation	EES	Poorer forest health leads to increase in wildfire risk, water quality impacts, hydrology impacts and increased sediment load.
AN1	Environmental Regulations (changes, new, compliance)	EES	New regulations or changes in federal permitting compliance may lead to more water used for environmental mitigation/flows.
CN3	Changes in runoff volume	CC	Long-term reductions in runoff volume due to hotter, drier climate reduce overall yield.
ON3	Power Arm Outage	CO	Failure of Power Arm prevents moving water into Carter Lake
ON4	Southern Water Supply Project Outage	CO	Failure of Southern Water Supply Project prevents delivering water to southern allottees.
ON2	Unit No3 of Flatiron Facility Outage	CO	Failure of Unit 3 in the Flatiron Pump Station prevents pumping water into Carter Lake.
WN5	Increased sediment loading	EES	Increased sediment loading from several causes reduces reservoir or conveyance capacity and affects water quality.
WN4	Wildfires - East Slope	EES	Increased occurrence of wildfires in Big Thompson River basin degrades water quality and may prevent ability to use Big Thompson

ID	Name	Threat Group	Description
			River to move C-BT water. Watershed above Lake Estes has lower wildfire impact risk but higher likelihood.
AN2	Colorado River Hydrologic Uncertainty / Major Outage of C-BT Project	CC/CO	Possible changes in C-BT operations based on hydrologic uncertainties and a large C-BT Project outage.
ON12	Conveyance Systems to Horsetooth Outage	CO	Variety of events could cause outages or reduced in deliveries in conveyance system components to Horsetooth Reservoir.
ON18	Adams Tunnel Outage	CO	Tunnel failure prevents moving all C-BT/Windy Gap water to East Slope.
ON17	Farr Pump Plant Outage	CO	Pump station failure prevents moving water from Lake Granby to Grand Lake and Adams Tunnel.
ON19	Lake Granby Dam/Dike System Outage	CO	Reduced capacity due to safety reduction or other outage issue limits ability to move water to Grand Lake and Adams Tunnel.
ON20	Windy Gap Plant Outage	CO	Pump station failure prevents transfer of Windy Gap water into the C-BT delivery system.
Note: CC = Climate Change, D = Demands, CO = Critical Outages, EES = Enhanced Environmental Stressors			

5.4 SIMULATION APPROACH FOR SELECTED RISKS AND UNCERTAINTIES

The impacts of the selected high priority risks and uncertainties on the water supply system were quantified using the FCU modeling system to provide objective information about which risks and uncertainties represent the most significant threats.

The risk and uncertainty simulation process required identification of the water supply feature being impacted by each key risk/uncertainty, the duration of the impact and determination of the models that should be used to simulate its effects. Some risks or uncertainties, although prioritized, were not explicitly simulated in the models though their specific impacts could be qualitatively described. Appendix B provides additional detail on how each of the risks and uncertainties was simulated in the FCU modeling system.

As described in Section 2, the following three models are linked in the FCU modeling system to represent FCU's water supply resources.

- The CBTQ simulates the anticipated quota for C-BT allottees based on hydrology, operations of the major reservoirs in the C-BT system and other factors.
- The PBN model simulates the water allocation and storage for water users in the Poudre River basin.
- The FCSys simulates the operation of infrastructure used to deliver yields from sources to FCU's water treatment plant.

Table 5-4 presents the adopted simulation approach for the prioritized risks and uncertainties related to the FCU water supply system. For risks with a simulation approach that is applied for a fixed period of time (e.g., June-October, 5 years), the simulated year in which the risk occurs was fixed (e.g. year 10 of the simulation) across all three models. Because 100 different hydrologic traces were simulated, risks occurring in the same simulated year were tested across a variety of hydrologic conditions (e.g., they could occur during short droughts, multi-year droughts, wet periods, or drought recovery periods).

Table 5-5 presents the simulation approach for the prioritized risks and uncertainties related to the C-BT water supply system.

Table 5-4. Simulation approach for FCU water supply system risks and uncertainties

ID	Risk or Uncertainty Name	Model for Simulation	Simulation Approach
O1	Outage – 24” Pipeline	FCSys	100% outage between October and March, when impact would be most severe to operations. Will be combined with 27” Pipeline Outage in model.
O2	Outage – 27” Pipeline	FCSys	100% outage between October and March, when impact would be most severe to operations. Will be combined with 24” Pipeline Outage in model.
O3	Algal Blooms	FCSys	C-BT water use will be shut off between June-October.
C1	Longer duration droughts	All	Incorporated into new stochastic hydrology
A1	New Regulations- Water quality and environmental	Not Simulated	New regulations impact wastewater discharge, minimal impact to water supply
W1	Wildfires	FCSys	Outage of non-C-BT supply between June-September, followed by 10-year, 20% reduction in non-C-BT-supply.
C3	Change in precipitation type - Hydrology	All	Incorporated into new stochastic hydrology
C4	Changes in frequency/magnitude of precipitation events - Hydrology	All	Incorporated into new stochastic hydrology
C2	Changes in runoff timing	All	Incorporated into new stochastic hydrology
W2	Forest Health Degradation	Not Simulated	Gradual water supply impacts over a long period of time that cannot be effectively simulated
A4	Changing state water rights administration	Not Simulated	Water supply impact of existing water rights minimal, greater potential impact on new or transferred water rights
D3	Development Uncertainty	FCSys/PBN	Captured in demand scenario modeling
A2	Increased Basin Demands	Not Simulated	A separate sensitivity analysis around this was completed by FCU and found no significant impact on water availability.
O5	Outage - Horsetooth Reservoir Outlet	FCSys	Horsetooth Reservoir empties in October, then 100% storage capacity reduction for 9

ID	Risk or Uncertainty Name	Model for Simulation	Simulation Approach
			months, though water can still flow through the reservoir.
O4	Outage - Michigan Ditch	FCSys	100% reduction for 24 months
D2	Water Use Changes	FCSys	Captured in demand scenario modeling
D1	Service area growth and regionalization	FCSys	Apply a percent increase to demands in new demand model based on how much demands may increase.
D8	Change in precipitation type - Demands	FCSys	Captured in demand scenario modeling
D9	Changes in frequency/magnitude of precipitation events - Demands	FCSys	Captured in demand scenario modeling
A3	Changes to Northern Water C-BT Operations	FCSys/PBN	Various factors cause C-BT quota to be 25% for 10 years.
W3	Development in Watersheds	Not Simulated	Minimal land in watersheds available for development
D6	Hotter summer changes irrigation	FCSys	Captured in demand scenario modeling
O6	Outage - Chambers Reservoir	Not Simulated	Mainly used to pass through yields, assumed that operational use could be maintained during outage
O8	Outage - Joe Wright Reservoir	FCSys	100% reduction in capacity for 24 months starting in November. All inflows bypassed.
O11	Outage - Pleasant Valley Pipeline	FCSys	100% reduction from April-October
A9	Elimination or Interruption of Reuse Plan	FCSys	A 100%, 75%, 50% and 25% reduction in the water available from the reuse plan for the entire simulation

Table 5-5 Simulation approach for C-BT Project water system risks and uncertainties

ID	Name	Model for Simulation	Simulation Approach
CN1	Longer Duration Droughts	CBTQ	Incorporated into new hydrology.
WN1	Changes in wildfire characteristics	Not Simulated	
CN2	Increased frequency of extreme dry years	CBTQ	Incorporated into new stochastic hydrology.
ON1	Green Mountain Replacement Pool Inadequacy	CBTQ	Reduce inflows into model to account for loss of out-of-priority diversions.
WN2	Wildfires - Upstream of Grand Lake/Shadow Mountain	Not simulated	Potential quota changes captured in other risks.
WN3	Watershed forest health degradation	Not simulated	Gradual water supply impacts over a long period of time that cannot be effectively simulated

ID	Name	Model for Simulation	Simulation Approach
AN1	Environmental Regulations (changes, new, compliance)	CBTQ	Reduce inflows into model to account for loss due to increased environmental flows.
CN3	Changes in runoff volume	CBTQ	Incorporated into new stochastic hydrology.
ON3	Power Arm Outage	Not simulated	Doesn't impact quota setting or deliveries of C-BT supply to FCU
ON4	Southern Water Supply Project Outage	Not simulated	Doesn't impact quota setting or deliveries of C-BT supply to FCU
ON2	Unit No3 of Flatiron Facility Outage	Not simulated	Doesn't impact quota setting or deliveries of C-BT supply to FCU
WN5	Increased sediment loading	Not Simulated	Shadow Mountain Reservoir is mostly a pass-through reservoir, so may not be greatly affected by reduced capacity.
WN4	Wildfires - East Slope	CBTQ	Reduction in Big Thompson-captured inflows. No delivery of C-BT water to certain water users (e.g. Greeley) through Big Thompson River.
ON12	Conveyance Systems to Horsetooth Outage	FCSys	Doesn't impact quota setting. 100% reduction in C-BT delivery to Horsetooth Reservoir from January – June. Existing water in Horsetooth Reservoir still useable.
ON18	Adams Tunnel Outage	FCSys/PBN	100% reduction in West Slope yields for a single year.
ON17	Farr Pump Plant Outage	FCSys/PBN	60% reduction in West Slope yields for a single year.
ON19	Lake Granby Dam/Dike System Outage	FCSys/PBN	100% reduction in West Slope yields for a single year.
AN2	Colorado River Hydrologic Uncertainty / Major Outage of C-BT Project	FCSys/PBN	A reactive response that is a reduction in West Slope inflows resulting in a 25% C-BT quota for 10 years.
ON20	Windy Gap Plant Outage	CBTQ	100% reduction in West Slope yields for a single year.

6.0 RISK SCENARIOS

Risk scenarios were developed by FCU to represent combinations of future conditions for which a vulnerability analysis was desired. Scenarios are comprised of single or multiple risks described in Section 3 and are designed to allow FCU to understand how its water resources system would behave under a range of future stressful conditions. This section summarizes the scenario development process and briefly describes the planning scenarios selected for analysis. More detail on this process is provided in the Scenarios for Vulnerability Analysis Technical Memorandum (Stantec, 2018b) in Appendix F.

6.1 BASELINE CONDITIONS

To quantify the impacts of risks and uncertainties that make up each scenario, baseline conditions were established in each of the three models that comprise the Fort Collins Modeling System: the C-BT Quota Model, the Poudre Basin Network Model and the Fort Collins System Model. The baseline conditions across all three models establish the basic model initial settings and do not include any identified risks, new demand model projections or climate altered hydrology. The baseline conditions are intended to represent the most reasonable future for planning purposes under the future demand historically used by FCU in its previous modeling.

Baseline conditions are described in Appendix F. Key aspects of the baseline conditions include:

- Constant annual demand of 40,629 AFY (the baseline demand described in Section 4)
- Current FCU and C-BT water supply infrastructure
- Halligan Reservoir Enlargement of 8,125 AF as currently proposed
- C-BT carryover storage “on”
- Current water rights portfolio with assumed future acquisitions
- Current operation of FCU’s water supply infrastructure

Results of water supply system performance under the baseline conditions were used to test the functionality of the updated model constructs and new modeling system.

6.2 SCENARIO DEVELOPMENT METHODS

In general, a WSVS scenario consists of three parts:

- A climate condition, defined as one of the 20 temperature and precipitation combinations, which determines 100 hydrologic traces representing climate variability around that climate condition as described in Section 5.

- A demand condition, defined as one of the two future City Plan demand scenarios described in Section 4. (The City Plan 3 + 20% demand scenario encompassing conditions beyond those currently anticipated by the City Planning Department was only included in the Increased Demands risk scenario described below because it represents a risk that demands would significantly exceed the range of demands associated with conditions currently being planned for by the City.)
- A system risk condition, defined as a combination of one or more of the risks and uncertainties described in Section 5.

The process for creating WSVS scenarios is shown in **Figure 6-1**

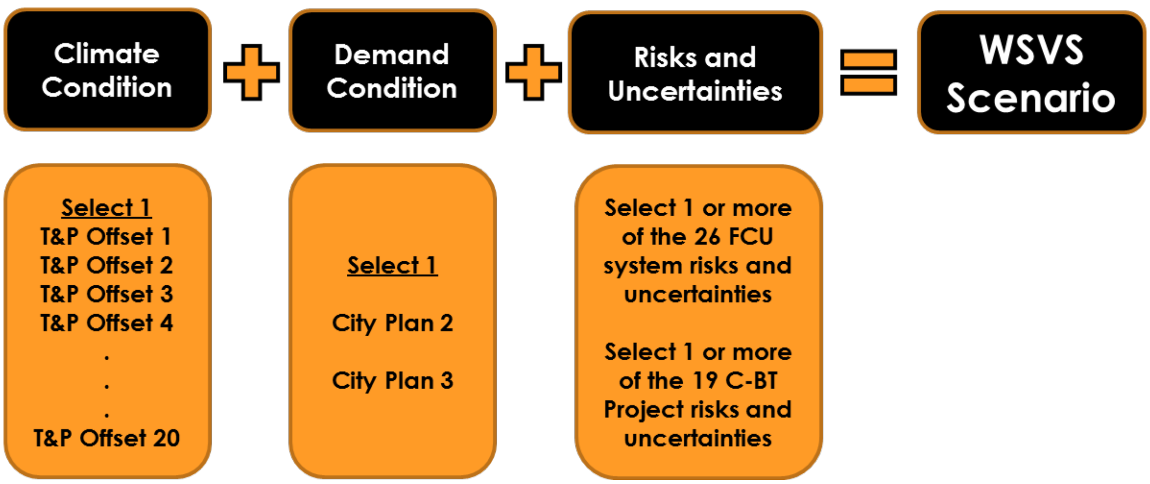


Figure 6-1 Process of Creating WSVS Scenarios

6.3 ADOPTED PLANNING SCENARIOS

FCU Staff, in coordination with Northern Water, identified 13 scenarios for simulation, including the baseline scenario. The 12 non-baseline scenarios were selected to represent a range of future conditions believed to be possible and potentially impactful to the FCU water resources system. They represent both long-term or chronic conditions (i.e., those that occur over the entire simulation period) and short-term or acute conditions (i.e., those that occur for only a short period of time). The WSVS scenarios are briefly described below.

- Climate Change Impacts –This scenario includes the full hydrologic ensemble of 100 traces and captures the full range of potential future climate change conditions resulting in 2,000 hydrologic scenarios. It uses a constant annual future demand of 40,629 acre-feet. It does not include additional system risks. It is used for isolating the potential effects of climate change on FCU system performance.

- Loss of Storage –This scenario captures the impacts to the water supply system if the Halligan Reservoir expansion (8,125 AF) does not happen and if FCU loses its C-BT Carryover Storage account in Horsetooth Reservoir. Decisions regarding both actions are ultimately beyond FCU's control. This scenario was simulated with the full 2,000 hydrologic scenarios for both the City Plan 2 and City Plan 3 demand scenarios.
- Increased Demands –This scenario includes the three demand scenarios described in Section 4 – City Plan 2, City Plan 3 and City Plan 3 Plus 20%. It does not include additional system risks. It is useful in isolating the potential effects of increased demand on FCU system performance. Each of these demand scenarios was simulated with the full 2,000 hydrologic scenarios.
- No Halligan Enlargement – The baseline condition includes the 8,125 AF expansion of Halligan Reservoir as currently proposed. At the time of this study the Halligan Reservoir enlargement project has not been permitted and therefore there is no guarantee it can be implemented. Because of the uncertainty around that assumption, this scenario is included to represent a future condition without the expansion of Halligan Reservoir. This scenario was simulated with the full 2,000 hydrologic scenarios for both the City Plan 2 and City Plan 3 demands.
- Poudre River System, Acute Outage – Infrastructure to deliver yield from the Poudre River to the city is potentially vulnerable to failures due to either natural disasters (landslides or wildfires) or emergency maintenance outages. This scenario captures the impact of a short-term simultaneous outage of the 24-inch Pipeline, the 27-inch Pipeline and the Pleasant Valley Pipeline. This scenario was simulated with the full 2,000 hydrologic scenarios for both the City Plan 2 and City Plan 3 demands.
- C-BT System, Environmental Impacts – This scenario quantifies impacts on C-BT quota allocations due to environmental issues resulting from wildfires in the receiving East Slope watershed or restricted use of Horsetooth as a water source because of algal blooms. This scenario was simulated with the full 2,000 hydrologic scenarios for both the City Plan 2 and City Plan 3 demands.
- Poudre River System, Environmental Impacts –This scenario quantifies impacts on water supply performance due to algal blooms or environmental issues resulting from wildfires in source watersheds (e.g. increased sediment deposition) that would limit FCU's diversions from the Poudre River. This scenario was simulated with the full 2,000 hydrologic scenarios for both the City Plan 2 and City Plan 3 demands.
- C-BT System, Acute Outage –There are a variety of potential causes for a short-term outage of critical C-BT delivery infrastructure such as an outage of the Adams Tunnel or Farr Pumping Plant. This scenario captures the impact of this C-BT infrastructure risk to the performance of the FCU water supply system. This scenario was simulated with the full 2,000 hydrologic scenarios for both the City Plan 2 and City Plan 3 demands.

- C-BT System, Long-Term Reduction – For purposes of the WSVS, FCU assumed that in the event of a long-term C-BT Project outage, the C-BT quota will be set to 25% for a 10-year period. This assumption was made by FCU based on total storage capacity in the C-BT system and the potential length of this type of outage. It is intended to capture the possible effects of a wide range of conditions that could affect C-BT deliveries over an extended period of time. This scenario was simulated with the full 2,000 hydrologic scenarios for both the City Plan 2 and City Plan 3 demands.
- Horsetooth Reservoir Outage – Lack of redundancy with the Horsetooth Reservoir outlet works puts deliveries of FCU's C-BT yield from this reservoir at risk. Recent problems with the outlet works have shown that this type of risk can occur. This scenario was simulated with the full 2,000 hydrologic scenarios for both the City Plan 2 and City Plan 3 demands.
- Reuse Plan Changes –This scenario is actually two scenarios which capture impacts to FCU water supply system performance due to changes to the Reuse Plan that would reduce the available supply to FCU. One scenario reduced the use of the Reuse Plan by 50% and another eliminated it altogether. These scenarios were simulated with the full 2,000 hydrologic scenarios for both the City Plan 2 and City Plan 3 demands.

7.0 VULNERABILITY ASSESSMENT

7.1 INTRODUCTION

This section summarizes the results of the Water Supply Vulnerability Study. It presents the result of key modeling analyses using visualization templates developed specifically for this project. Many thousands of model simulations were performed, and dozens of metrics were explored as means of understanding the response of the FCU water supply system to different stressors. This section includes selected displays; many other sets of results were separately provided to FCU, in the form of Tableau files.

As described in Section 5, many factors could negatively impact FCU's ability to reliably meet future water demands. These factors include hydrologic risks due to climate variability and climate change; increased demands due to population growth or changes in development density; and risks to the water supply system such as legal and regulatory changes, environmental factors, aging infrastructure, etc. The impacts of these various risks on the FCU water supply system were investigated in a systematic manner based on the steps outlined below and shown in **Figure 7-1**.

- Determine the system's baseline scenario performance before the addition of altered hydrology or demands.
- Investigate how potential climate change could affect the performance of the baseline system.
- Assess the impacts of increased demands generated by the new Demand Estimation Tool in combination with the climate-adjusted hydrologies.
- Evaluate the superposition of the risk scenarios described in Section 6 with the climate hydrologies and each City Plan demand scenario.
- Identify the individual risks and risk combinations with the greatest potential to adversely affect the FCU system performance.

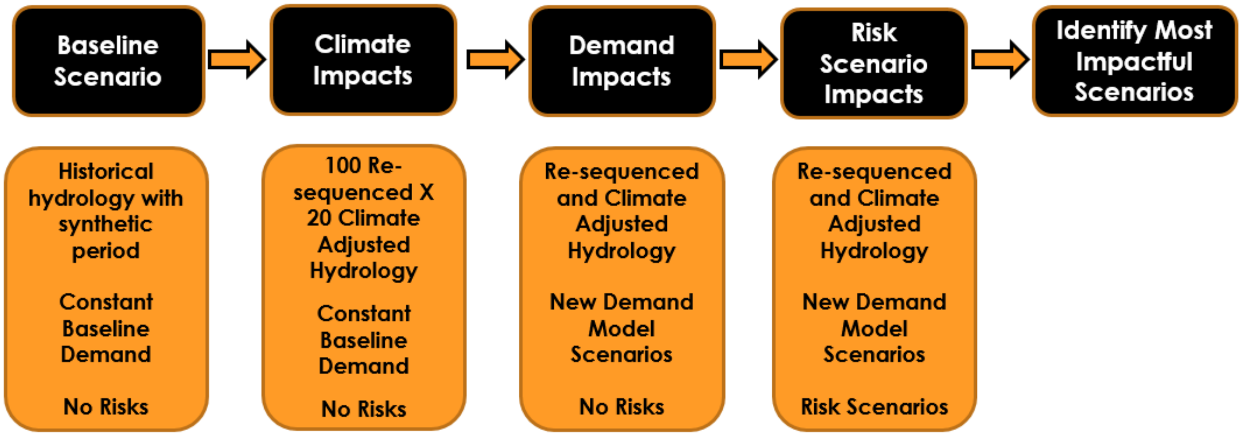


Figure 7-1 Method for Risk Evaluation

Many performance metrics were identified to help quantify the impacts of these risks. As the WSVS progressed, FCU staff found that the following four performance metrics were most useful for identifying the impactful risks.

- Average annual total demand shortage in years when shortages occur
- Reliability (i.e., frequency) of maintaining 20%of annual demand in storage (storage reserve factor)
- Percentage of years in which conditions would trigger any level of water use restrictions per the current water supply planning policy and Water Shortage Response Policy
- Indoor demand reliability

Section 2 describes the relationship between metrics (measures of system performance) and level of service goals (metric values that define acceptable vs unacceptable performance). For purposes of the WSVS, the current FCU water supply planning policy criteria described in Section 2.2 were used as level of service goals by which to assess the impacts of the various risks and uncertainties.

As described previously, WSVS simulations were performed without applying demand reductions due to implementation of water use restrictions, consistent with the Water Shortage Response Policy. As such, the metric for "percentage of years in restrictions" represents the percentage of years one or more of the water supply planning policy criteria would not be met and FCU would have to implement some type of management response (e.g., water use restrictions, emergency supplies, other demand management strategies). The restriction metric captures times when a violation of any of the water supply planning policy criteria (100% demand reliability, 100% SRF reliability) would occur. Because the WSVS modeling does not capture any possible carryover benefit of restrictions or management measures from one month or year to the next, results for this metric overstate the actual percentage of years these conditions would occur if management measures were implemented. However, the metric is still valuable for relative comparison of water supply system performance impacts between different future scenarios.

FCU decided that additional level of service goals would not be considered when evaluating system performance for the WSVS. Establishment of new level of service goals based on the results of the vulnerability assessment modeling was considered a policy decision, and thus it was postponed until the Water Supply and Demand Management Policy is updated based on the results of the WSVS.

The following sections describe the results of the WSVS modeling.

7.2 BASELINE PERFORMANCE

Assumptions for baseline conditions were established in the three models included in the WSVS: The C-BT Quota Model, the Poudre Basin Network Model and the Fort Collins System Model and were described in Section 6. The baseline simulation included a constant annual future demand of 40,629 AFY. It did not include any identified risks or climate altered hydrology. Instead, the historical hydrology with a synthetic period was used, to be consistent with previous modeling efforts by FCU. The conditions in which the baseline scenario was run were intended to represent the most reasonable future condition in which historical conditions persist and no additional improvements are made to the FCU water supply system beyond the proposed Halligan Reservoir enlargement and currently anticipated water acquisitions.

Figure 7-2 compares two sets of model runs: the baseline simulation, as defined above and the baseline settings, run under current climate conditions (T=0, P=0), across all 100 traces and averaged. Ideally, the metrics from both sets of runs would be identical, meaning the new modeling method that utilizes re-sequenced hydrologic traces does not perform significantly better or worse than the method previously used by FCU.

It can be seen in **Figure 7-2,** that both the baseline simulation and the current climate conditions simulations perform similarly for the existing system, including the proposed Halligan Reservoir enlargement. Both sets of simulations are able to meet all demands, including Reuse Plan demands, with 100% and 99.1% reliability (i.e., there is a shortage in only 9 of the 1,032 months of simulation). Indoor demands are met 100% and 99.8% of the time (2 months of shortage out of 1,032). The results also showed that the system maintained the required 20% storage reserve factor 98.8% and 97.1% of the total simulated months (i.e., the 20% storage reserve factors were not maintained in only 12 and 30 out of the 1,032 months of simulation). Note that none of the WSVS simulations include the effects of water use restrictions.

Figure 7-2 also shows the average lengths of shortages and the average volumes of those shortages when they occur. For example, when FCU cannot meet the 20% storage reserve factor, the average number of consecutive months of shortage is 1.2 months for the baseline simulation and an average of 2 months for the current conditions scenario. The average monthly shortage volume is 2,121 AF for the baseline simulation and 2,358 for the current conditions scenario. These values are manageable within current policies and available management strategies.

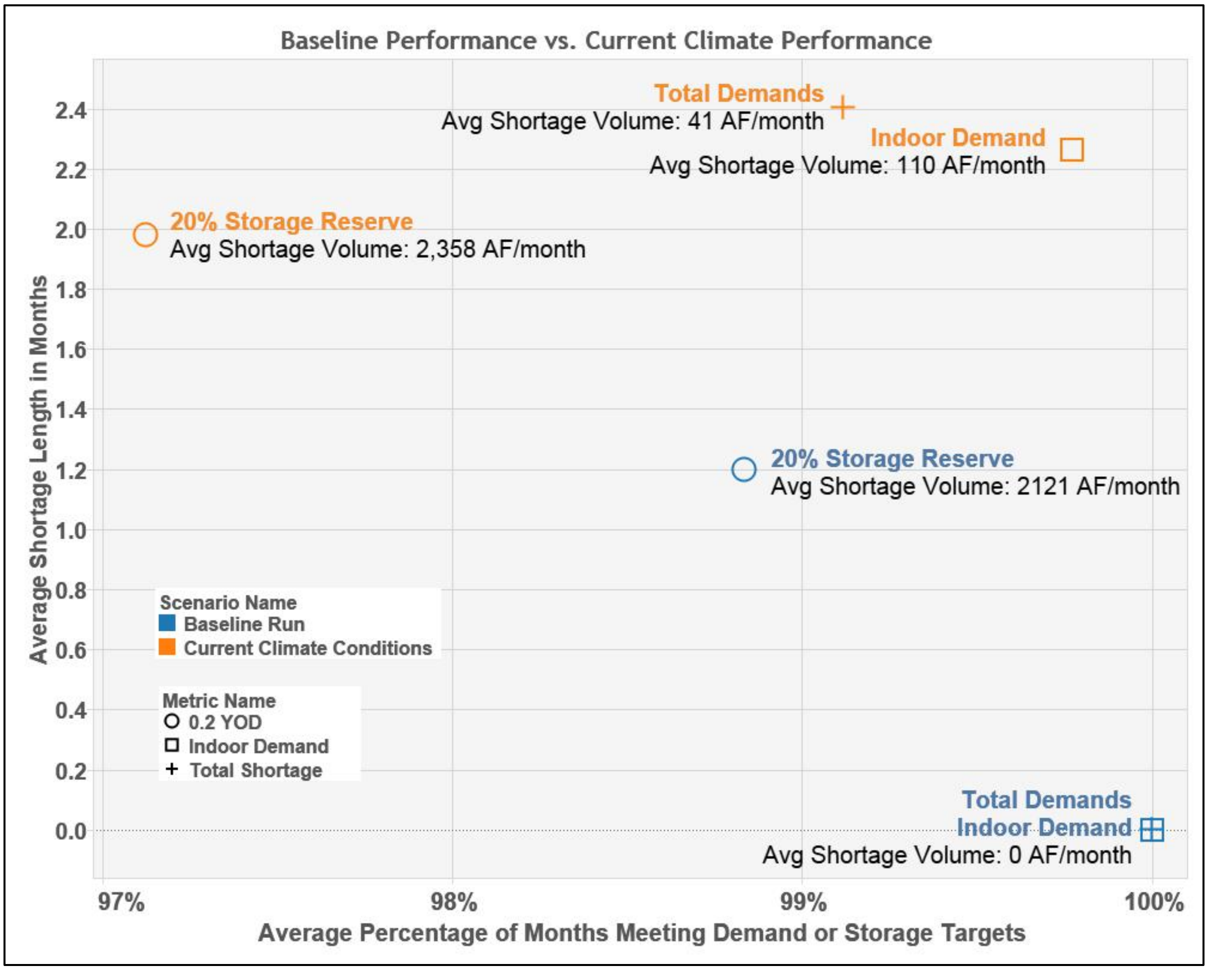


Figure 7-2 Baseline Performance Compared to Current Climate Performance for Three Key Metrics

These results demonstrate that the updated modeling method used for the WSVS is consistent with past FCU methods. The results also demonstrate that FCU has been successful in planning for and developing a water rights portfolio and water supply infrastructure to meet its customers' water needs under future baseline conditions and planned operation of its raw water systems. As shown in Section 4, the baseline demands used in this part of the analysis are similar to the future City Plan 2 and City Plan 3 demands developed for the WSVS; therefore future performance of the current water resources system under either of these other demand forecasts should be similar to the baseline results described above. It is noted again, that the baseline conditions for WSVS include the proposed Halligan Reservoir enlargement of 8,125 AF. As shown in subsequent sections, this additional storage is critical to maintaining desired system performance under more stressful future conditions.

7.3 CLIMATE VARIABILITY AND CLIMATE CHANGE VULNERABILITY RESULTS

After the baseline analysis, the Climate Change Impact scenario was simulated to evaluate the vulnerability of the FCU raw water system to climate variability and climate change. This scenario applied the 20 combinations of temperature and precipitation changes to the baseline model with a constant annual demand of 40,629 AFY without simulating any system risks, thereby isolating the potential effects of climate on the FCU system performance.

The reliability metric can be calculated either on an annual basis or a monthly basis. In the annual calculation, a shortage in one month of the year counts the entire year as a failure, whereas the monthly calculation is more of a true reliability calculation.

Figure 7-3 shows both the annual and monthly reliability for three key metrics for the current climate scenario. The blue shapes are monthly reliability calculations and the orange shapes are annual reliability calculations. The different shapes represent the three different metrics; total demand, indoor demand and 20% storage reserve. Annual reliability is always less than or equal to the monthly reliability.

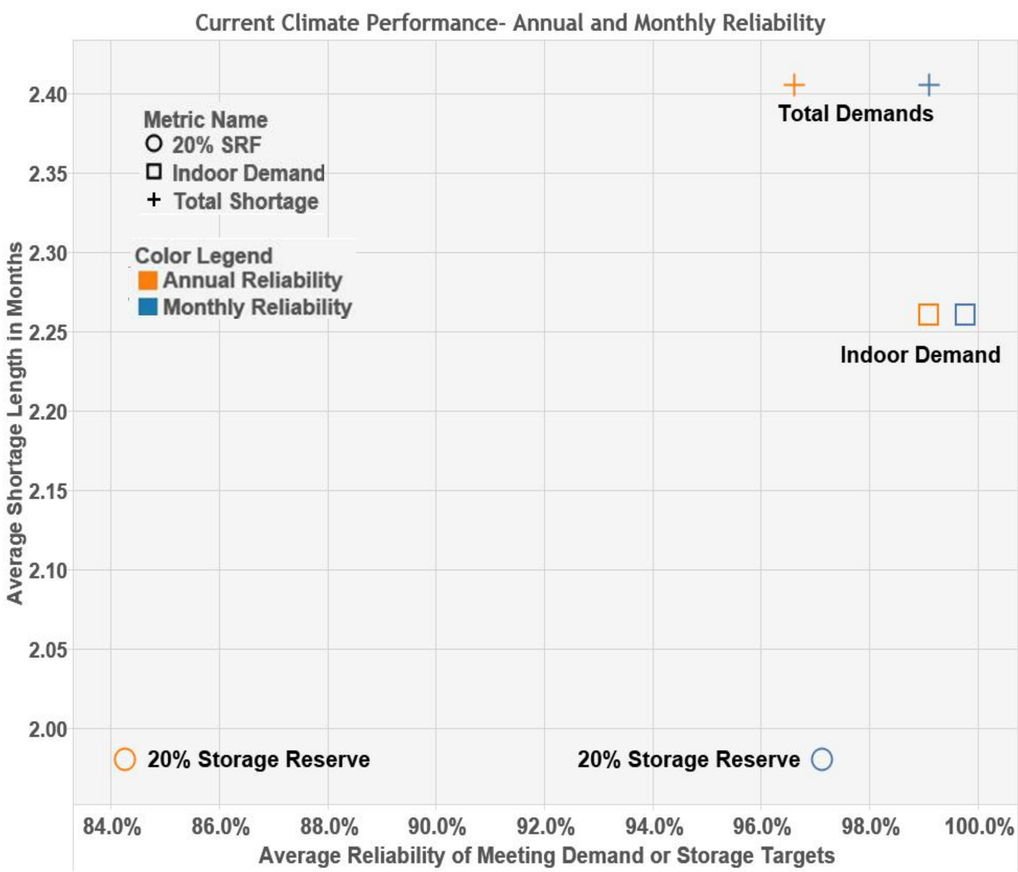


Figure 7-3 Comparison of Annual and Monthly Reliability

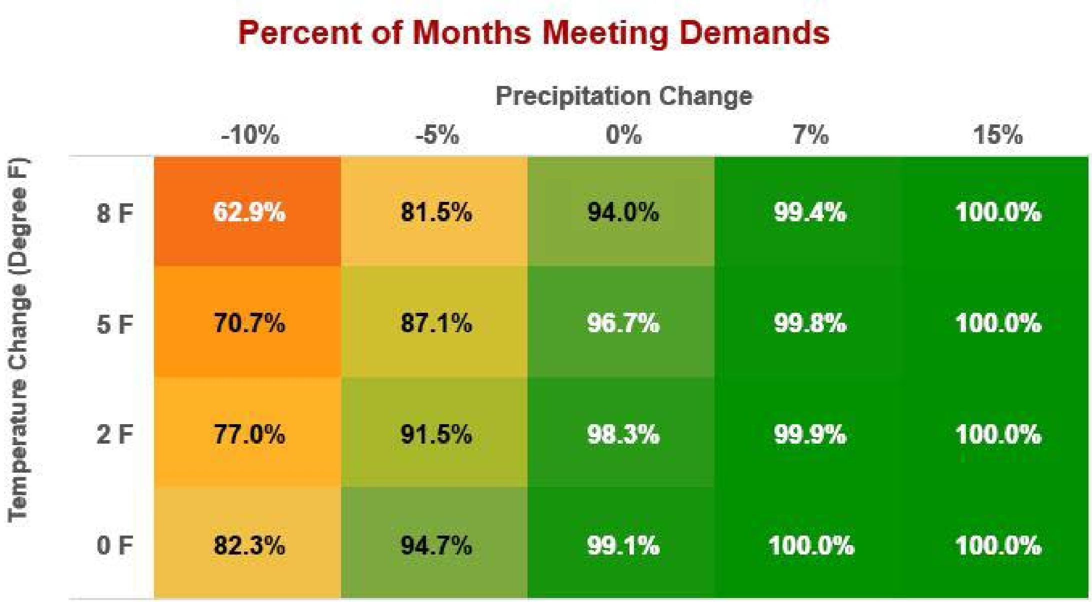
Reviewing annual reliability is perhaps more intuitive for many of the metrics, but the annual calculation can mask important information. If shortages occur only in one month every year, the annual reliability may be very low, even though the system may be performing without shortages for the majority of the year. Conversely, reviewing monthly reliability may be a bit more difficult to grasp, but is more of a true reliability calculation. If shortages occur only one month every year, the overall monthly reliability will be high, but there is no way to tell from the monthly reliability if the shortages occurred in each year or if the shortages occurred in a single year because of a drought. Only by looking at both annual and monthly reliability metrics is the full story available.

These results show that for the metrics related to the current water supply planning policy, the 20% storage reserve factor has the lowest reliability and thus, is the most difficult criterion to meet for baseline conditions. Normal operations would have to be modified (e.g., through implementation of water use restrictions, alternate operating rules, or acquisition of emergency supplies) in about 3% of the months and 16% of the years. This is typical of FCU's historical experience of requiring watering restrictions 1 in every 10 years.

7.3.1 Results for Selected Metrics

The results summarized in the following “heat maps” depict the average value of the specified metric over all 100 hydrologic traces in each of the 20 T/P climate combinations. As described in Section 3, hydrologic traces represent climate conditions with 0 to 8 degrees F warmer annual temperatures and – 10% to +15% change in annual precipitation.

Figure 7-4 shows the average percentage of months in which all system demands were met. At the 0-degree temperature increase and 0% precipitation change level (i.e., the 0/0 cell), total demands are met in 99.1% of the months of simulation. The heat map shows how system performance responds to climate conditions. As climate gets warmer and drier, the reliability of meeting total system demands decreases (i.e., shortages occur more frequently). In the extreme condition of 8 degrees warmer and 10% less precipitation, total system demands can only be met in 62.9% of months. Results suggest that the FCU water resources system can tolerate warmer temperatures when annual precipitation is at or above historical conditions. If annual precipitation decreases or remains constant, any temperature increase would have a significant adverse impact on FCU system performance.



Percent of Months Meeting Demands

Temperature Change (Degree F)	Precipitation Change: -10%	-5%	0%	7%	15%
8 F	62.9%	81.5%	94.0%	99.4%	100.0%
5 F	70.7%	87.1%	96.7%	99.8%	100.0%
2 F	77.0%	91.5%	98.3%	99.9%	100.0%
0 F	82.3%	94.7%	99.1%	100.0%	100.0%

Figure 7-4 Average Monthly Reliability of Meeting Total Demands for All Climate Conditions

Note: The value in each cell is the average of the percentage of months in which total demands are met across the 100 traces for the specified future climate condition.

Figure 7-5 shows the average annual shortage volume in meeting total demand in the months when total demand could not be met. Except for the most extreme climate conditions, average annual shortage volumes are small compared to the total demand of 40,629 AFY.

Average Annual Shortage Volume (ac-ft/year)

Temperature Change (Degree F)	Precipitation Change				
	-10%	-5%	0%	7%	15%
8 F	4,979	3,294	2,170	1,029	2
5 F	4,349	2,865	1,872	1,061	
2 F	3,502	2,301	1,283	448	
0 F	3,036	1,845	920	659	

Figure 7-5 Average Annual Total Demand Shortage Volume for All Climate Conditions

Notes:

a) Blank, green cells had no shortages.

b) The value in each cell is the average annual shortage volume (difference between total annual demand and annual volume of water supplied) averaged across the 100 traces for the specified future climate condition.

FCU's Water Supply and Demand Management Policy requires at least 20% of annual demand be maintained in storage at all times for possible use in emergencies. **Figure 7-6** is a heat map for reliability of meeting the 20% storage reserve factor objective. It shows that with no changes in precipitation or temperature, the 20% storage reserve factor could be maintained in 97.1% of the simulated months across all 100 re-sequenced hydrologic traces. Any warmer or drier shift in climate from the 0/0 cell results in significant challenges in meeting the storage reserve factor policy. It is noted that these Climate Change Impact simulations assume the proposed Halligan Reservoir enlargement project is implemented. The effect of not enlarging Halligan Reservoir was investigated in the No Halligan Enlargement scenario, which is described in a following section.

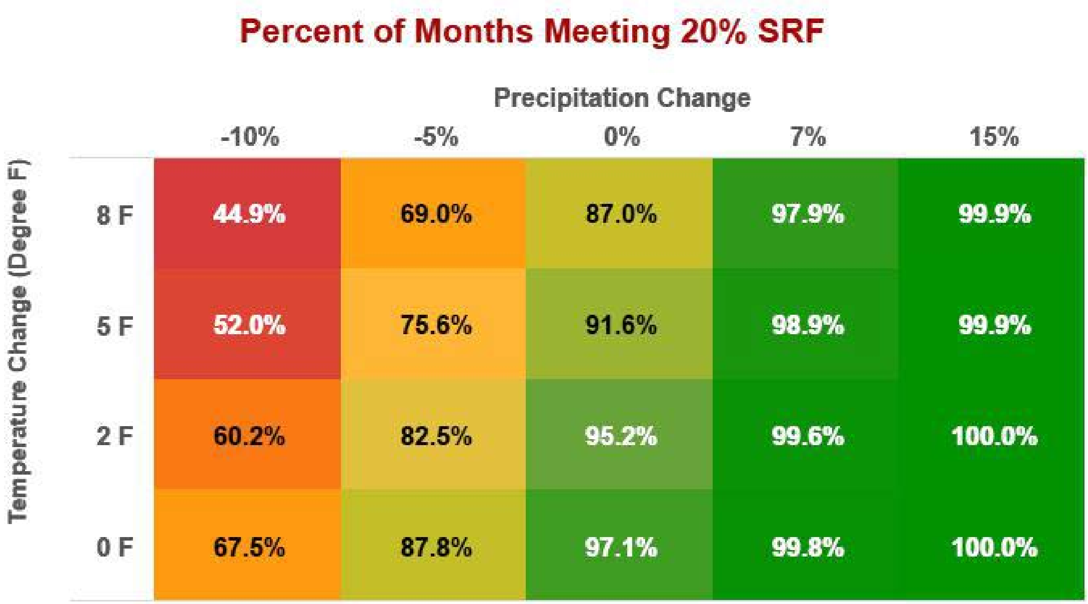


Figure 7-6. Average Monthly Reliability of Meeting 20% Storage Reserve Factor for All Climate Conditions

Although these Climate Change Impact simulations were performed without applying demand reductions due to implementing water use restrictions, the number of years in which restrictions would have been implemented according to FCU's Water Supply Shortage and Response Plan (City of Fort Collins, 2014) was calculated. The Plan has four levels of water use restrictions that are triggered based on the anticipated amount of supply shortage. The metric calculation counts all years when water use restrictions of any level would have been triggered. It represents times when one or more of the water supply planning policy criteria would not be met and FCU would have to implement some type of management response (e.g., water use restrictions, emergency supplies, other demand management strategies).

Figure 7-7 shows the average percent of years restrictions would have been activated for each climate combination. In this analysis water use restrictions are a surrogate for any operational measure implemented to respond to a water shortage condition. FCU could choose to implement other measures such as alternate operating strategies or acquisition of emergency supplies in lieu of declaring water use restrictions. The heat map in **Figure 7-7** shows that future climate has a significant effect on the frequency with which water use restrictions or other measures would be implemented. With baseline demands and no other risks applied, a 5 degree F warmer annual temperature and 5% less annual precipitation would require application of management measures in an average of 6 years in 10. In contrast, a future climate with 5-degree warmer annual temperature and 7% more annual precipitation would require application of management measures in an average of less than 1 year in 10.

Percent of Years Needing Restrictions

Temperature Change (Degree F)	Precipitation Change				
	-10%	-5%	0%	7%	15%
8 F	90.3%	73.3%	45.2%	12.5%	1.3%
5 F	85.2%	63.8%	32.9%	7.0%	0.7%
2 F	82.2%	53.3%	22.7%	3.4%	0.2%
0 F	75.3%	43.4%	16.1%	1.8%	0.1%

Figure 7-7 Average Percentage of Years During Which Water Use Restrictions Would Be Implemented Based on Current FCU Policy, for All Climate Conditions

Note: "Restrictions" is a surrogate for any demand management or emergency supply enhancement measures FCU would implement in response to potential violations of the water supply planning policy

As described in Section 2.2, failure to meet indoor demands with 100% reliability would have severe adverse public health and safety impacts on FCU customers. **Figure 7-8** shows that without any changes to temperature or precipitation, FCU can reliably meet indoor demands 99.8% of the time (2 months of shortage in 86 years when no restrictions are applied). In an extreme hotter and drier future, the reliability of meeting indoor demands drops to 83.5%.

Again, it is noted that all model simulations in the WSVS use full water demands in every year without application of water use restrictions. FCU would implement water use restrictions and other management measures long before indoor shortages would occur. Past experience has shown that customers in Fort Collins are capable of significantly reducing their water use in response to droughts or emergency conditions such as wildfires. Additional analysis will be needed to determine whether available management measures would be effective in eliminating the risk of indoor water demand shortages for the most severe future climate conditions.

Percent of Months Meeting Indoor Demands

Temperature Change (Degree F)	Precipitation Change -10%	-5%	0%	7%	15%
8 F	83.5%	92.8%	98.0%	99.8%	100.0%
5 F	87.0%	95.1%	98.9%	99.9%	100.0%
2 F	90.5%	97.1%	99.5%	100.0%	100.0%
0 F	93.1%	98.3%	99.8%	100.0%	100.0%

Figure 7-8 Average Indoor Demand Reliability for All Climate Conditions

7.3.2 Monthly Distribution of Shortage Periods

Figure 7-9 shows the 100-trace average count of monthly shortages. The upper plot is for the current climate conditions (T=0, P=0) and the lower plot is for the most severe climate condition (T=+8, P=-10). Note the scales of the two plots are different. In both climate conditions, the fewest number of shortages occur in the late spring and early summer months of May, June and July while storage is replenished and streamflows are the greatest. In the current climate conditions, shortages occur most often in March, April, September and October. These are shoulder seasons 1) before the spring runoff peaks when reservoir levels may still be low or 2) after the peak demands of summer have depleted reservoir storage levels. This pattern also appears in the most stressful climate future but is not as pronounced. The shortages are more evenly distributed over all months except than May and June because the stress of the climate provides little time to recover from a shortage.

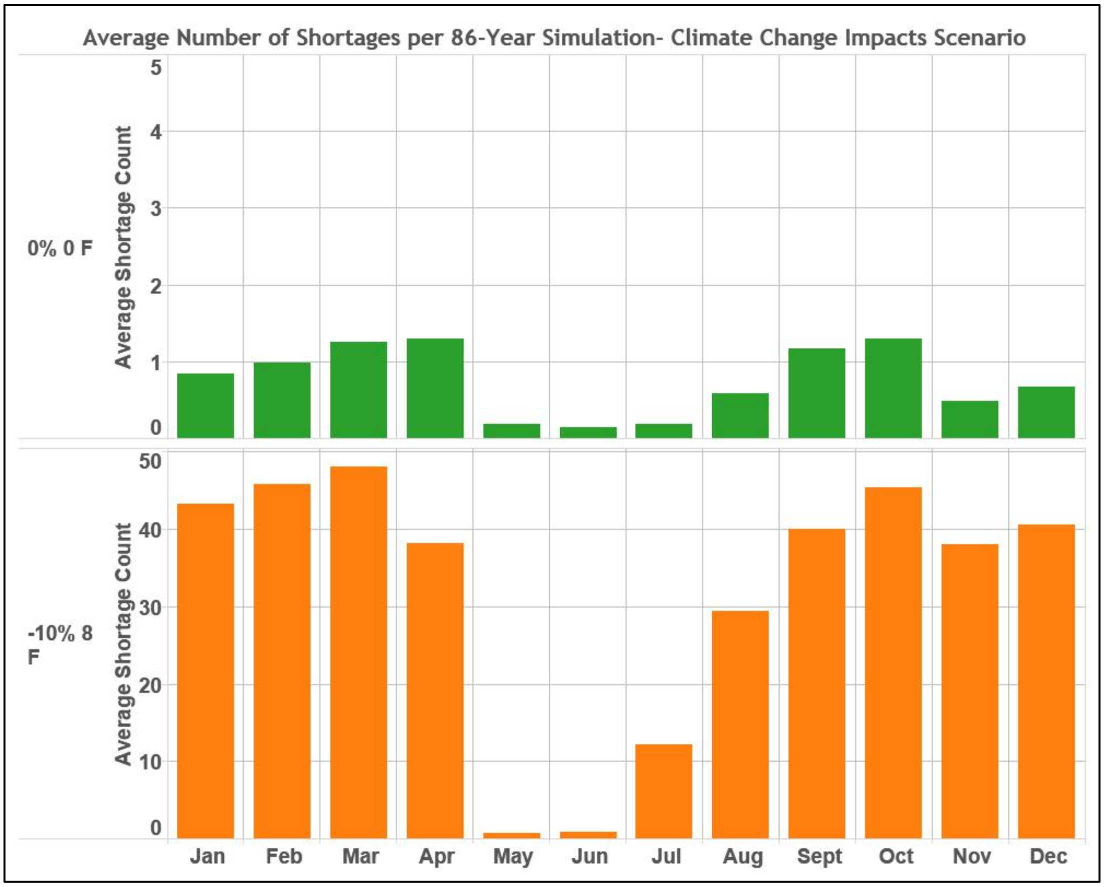


Figure 7-9 Average Monthly Distribution of Shortages for Climate Change Impacts Scenario

Notes:

a) The value in each bar is the average number of shortages in each month for an entire 86-year simulation period averaged across the 100 traces for the specified future climate condition.

b) The y-axis scales differ between the two plots.

7.3.3 Effect of Future Climate on C-BT Quota Calculated by CBTQ Model

The effects of climate change can be seen in the C-BT quotas estimated by the CBTQ model. C-BT quota is a direct output of the model. The C-BT quota determines the annual amount of water available to Fort Collins from the C-BT Project; this represents a significant source of supply to the FCU water resources system. Lower quotas mean less C-BT water is available to Fort Collins to supplement its local Poudre River supplies.

Figure 7-10 shows a series of box plots of the range of average quotas set for each of the 20 temperature and precipitation combinations. Each dot in the figure represents the average of the 86 annual quotas calculated for a single re-sequenced hydrology trace in the 86-year simulation period.

Figure 7-11 shows the variability and ranges of modeled quotas for four selected climates. The quota model produced a full range of quotas that have not been seen historically. Even for current conditions (0% precipitation and 0-degree temperature changes), the quota model produced some 10% quotas and 100% quotas.

For the current precipitation conditions (0% precipitation increase) and for drier climates (-5% and -10% precipitation), quotas tend to decrease as temperatures rise. However, for the much wetter condition (+15% precipitation), quotas tend to increase when temperatures rise. This is because the warmer temperatures create an increase in demand and the increase in precipitation augments supply such that a higher quota can be set. The average quota historically has been about 70%. The CBTQ model estimates quotas similar to the historical average for current and wetter future climates, but lower quotas (i.e., less C-BT supply for FCU) for drier future climates.

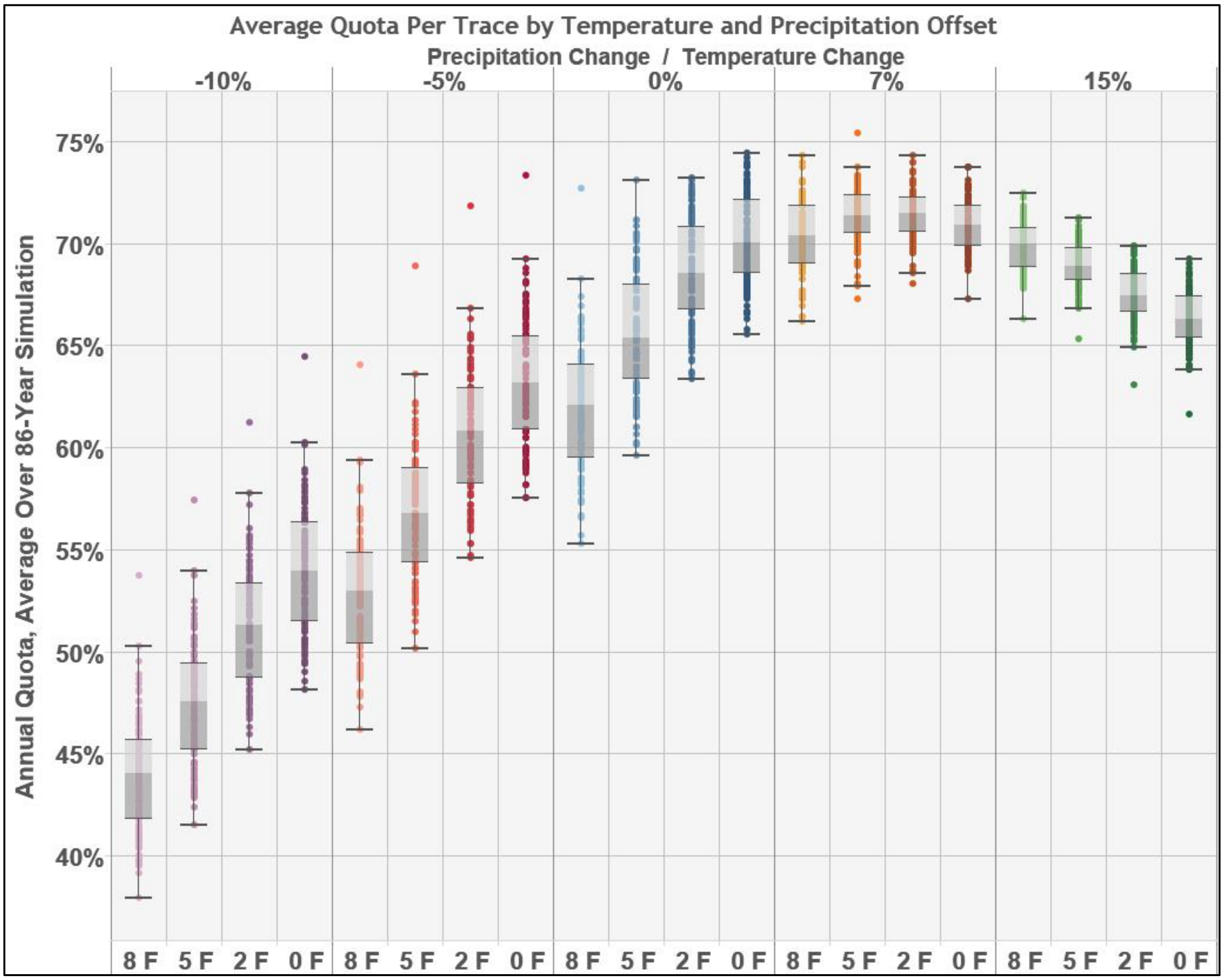


Figure 7-10 Annual C-BT Quota from CBTQ Model by Temperature and Precipitation Offset, Averaged over 86 Years for Baseline Scenario

Notes:

a) Poorer performance indicated by lower quota towards bottom of graph.
b) Each dot is the average of the annual quotas for an 86-year hydrologic trace. 100 traces (dots) are shown in each box plot.
c) Average quota historically is 70%.

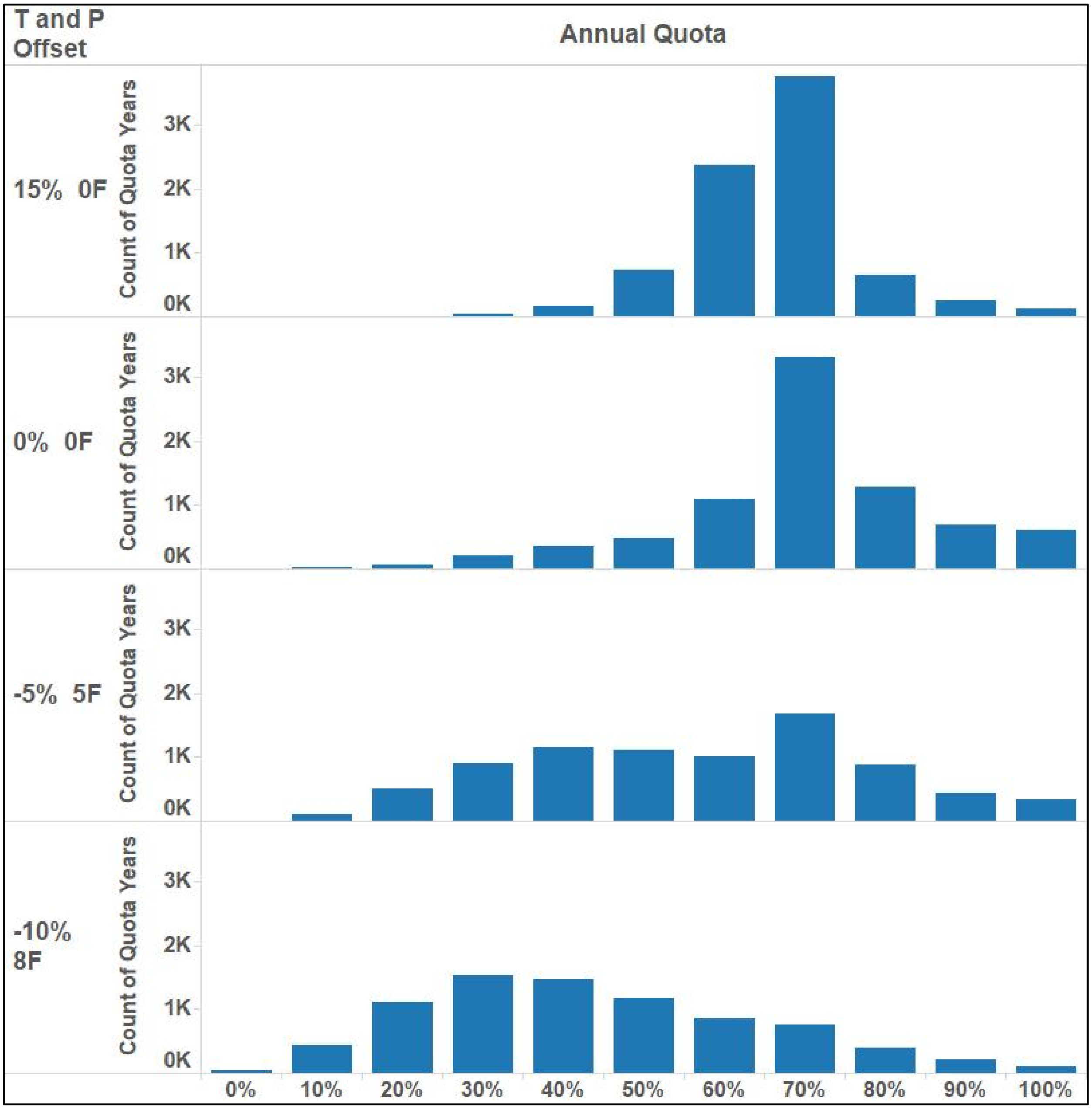


Figure 7-11 Range and Variability of Annual Quotas for all Traces and Selected Climates

Notes:

a) Each bar sums the number of times each Quota percentage was set for all 100 traces of the selected climate offsets.

b) Selected climates get warmer and drier with each plot moving down

7.4 DEMAND VULNERABILITY RESULTS

The Increased Demands Scenario was simulated to assess the sensitivity of the FCU water resources system to variable demands in 2070 which incorporate climate variability, some of which are an increase over the baseline water demand. This scenario includes the three demand scenarios described in Section 4 – City Plan 2, City Plan 3 and City Plan 3 Plus 20%. **Table 7-1** summarizes the average annual demands for the future conditions evaluated in the Increased Demands Scenario.

The Increased Demands Scenario does not include additional system risks. Each demand scenario was simulated for all 100 hydrologic traces for each of the 20 temperature and precipitation climate combinations. As described in Section 4, model simulations apply the same demand assumptions for all 86 years of the simulation period. That is, all years in the model represent the future 2070 condition described by the assumed demand scenario. The WSVS simulations do not account for a gradual increase in demand over time but focus only on the future condition. Additional analysis would be needed to evaluate FCU water system performance in intermediate years between current conditions and 2070.

Table 7-1 Summary of Average Annual 2070 Demands for Demand Scenarios

Demand Scenario	2070 Population	Minimum Average Annual Demand for 86-Year Simulation for Current Climate Conditions (AFY)	Median Average Annual Demand for 86-Year Simulation for Current Climate Conditions (AFY)	Maximum Average Annual Demand for 86-Year Simulation for Current Climate Conditions (AFY)
Baseline	179,000		40,629[(a)]	
City Plan 2	178,000	36,171	37,687	39,511
City Plan 3	195,000	37,664	38,215	41,081
City Plan 3 + 20%	234,000[(b)]	43,333	45,194	47,433

Notes:

a) Not based on application of Demand Estimation Tool or 86-year simulation. Included for comparison to previous studies.

b) Population is 20% increase over City Plan 3 population. This demand scenario incorporates other factors besides population increase, so all demand increase compared to City Plan 3 demand may not be due to population increase.

Results of the modeling for the Increased Demands Scenario are shown in the parallel line plots below (**Figure 7-12** through **Figure 7-14**). These plots show the values of the specified metric for the three demand scenarios as a function of temperature across the range of change in average annual precipitation. Each set of lines applies to one of the values for the assumed change in precipitation. Within a precipitation column, temperature decreases (i.e., improves in terms of influence on water supply) from left to right. The upper panel y-axis shows the average annual demand shortage in acre-feet per year only during times of shortage. Lines that rise to the top of the graph have worse system performance as they show more demand shortage over the simulation. The lower y-axis shows the average number of years with shortages. Lines that rise to the top of the graph have worse system performance because more of the years have shortages.

Key results from the analysis of the Increased Demands Scenario are summarized below.

- Results for each of the metrics show similar trends. This simplifies the interpretation of results and suggests FCU could select the most convenient or best-understood metric to assess relative system response to future demand increases.
- The City Plan 2 and City Plan 3 scenarios result in very similar system performance across the range of climate conditions in the WSVS. This indicates City planning decisions affecting growth within the range encompassed by these two scenarios will have only minor impacts on total water demand, although they could play a significant role in reducing per capita water demand.
- Under City Plan 2 and City Plan 3, the current water supply planning policy criteria (no shortages, no water use restrictions and 20% storage reserve factor at all times) can only be satisfied for the wettest future climate (+15% precipitation). For a moderate climate change condition (T=+5, P=-5%), additional supply or demand management measures would be required in about 23% of years (20 out of 86) and would need to make up for an average annual shortage volume in those years of about 2,500 AFY (**Figure 7-12**). For the same moderate climate change condition, the storage reserve factor would fail to be maintained in about 20% of months (**Figure 7-13**), putting FCU water supply at greater risk under emergency conditions. If management measures were not implemented, the FCU system would be in a condition when water restrictions would be declared under the current water supply policy in about 6 years in 10 (**Figure 7-14**).
- The City Plan 3 Plus 20% demand condition, which assesses an unanticipated future demand increase, results in significantly worse performance than the City Plan 3 condition. Current water supply planning policy criteria could not be satisfied under any future climate condition simulated for the WSVS. For a moderate climate change condition (T=+5, P=-5%), if management measures were not implemented, the FCU system would be in a condition when water restrictions would be declared under the current water supply policy in about 8 years in 10.
- Without the 20% demand increase, the City Plan 2 and City Plan 3 showed the FCU system would perform well in the future at current or wetter precipitation conditions and no changes in temperature. When temperatures rise or precipitation decreases, system performance decreases.

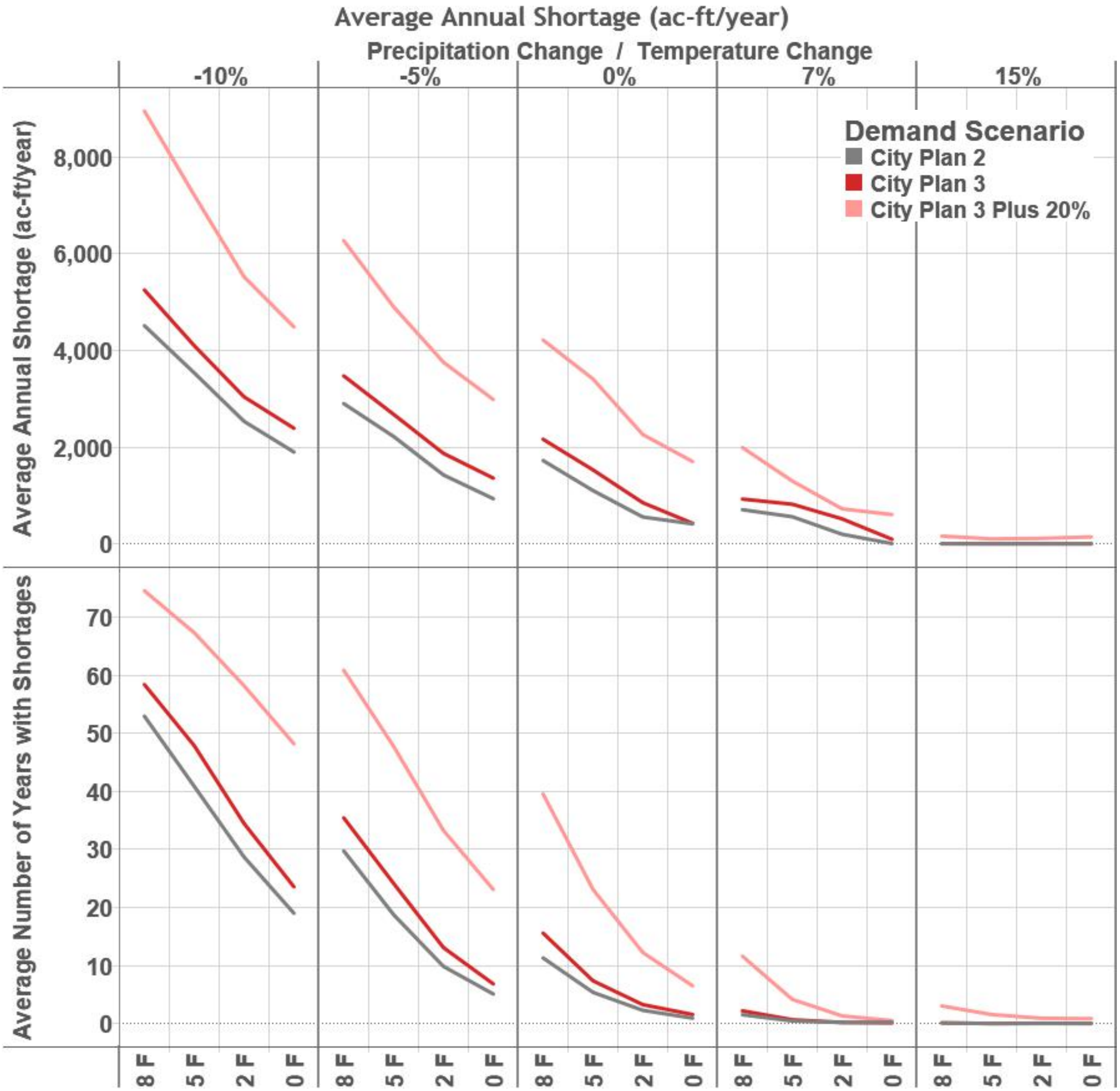


Figure 7-12 Average Annual Total Demand Shortage for Increasing Demand Scenarios and All Climate Conditions

Notes:

a) Demands represent 2070 population and development conditions.
b) Average annual shortage metric is calculated as the sum of annual shortages over the 86-year simulation period divided by the number of years when shortages occurred.
c) Average number of years with shortage is based on 86 years in the model simulation period.
d) Poorer performance indicated by greater shortage towards top of graph.

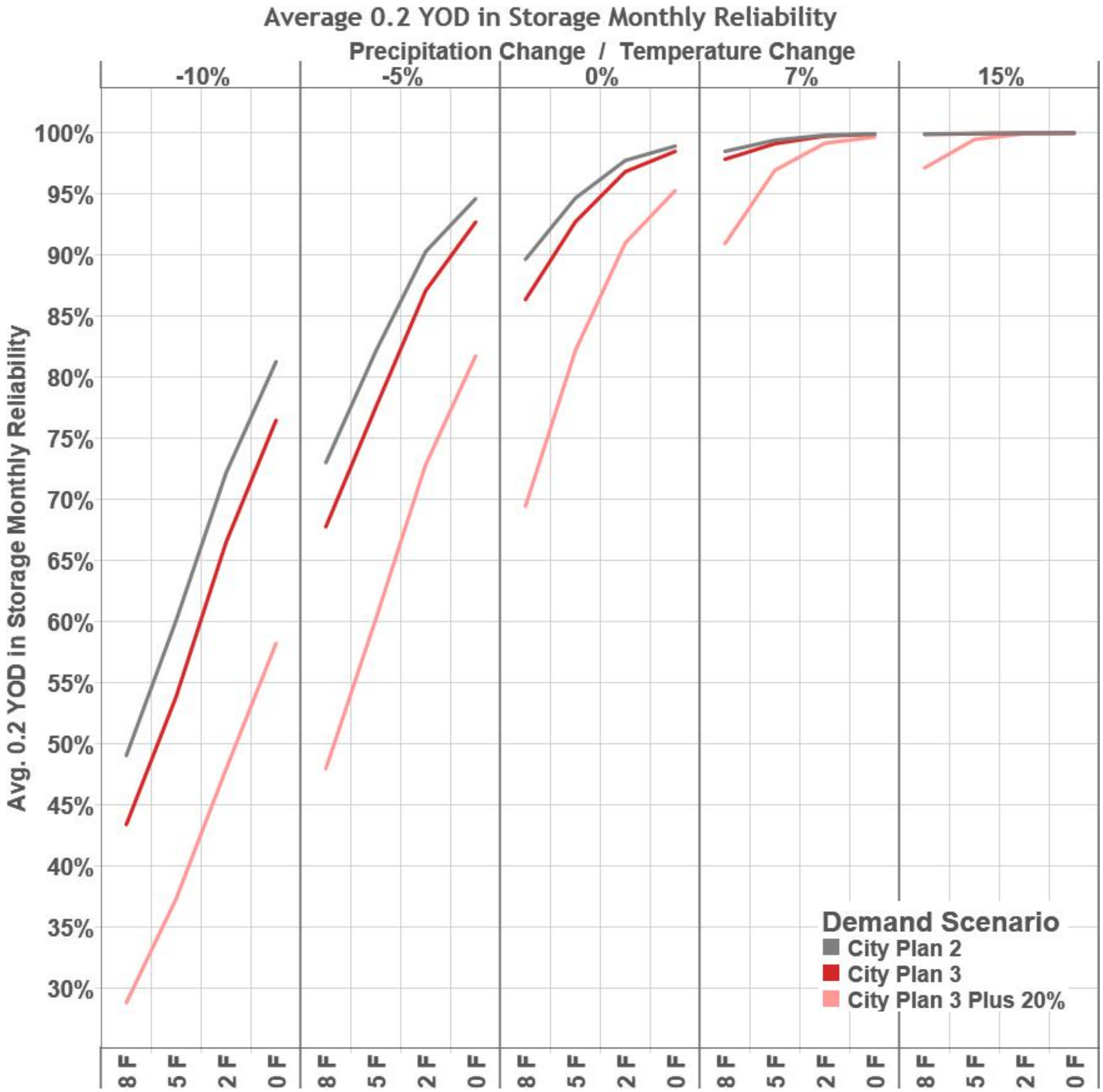


Figure 7-13 Average Monthly Reliability of Meeting 20% Storage Reserve Factor for Increased Demands Scenario and All Climate Conditions

Notes:

a) Demands represent 2070 population and development conditions.
b) Poorer performance indicated by lower reliability towards bottom of graph.

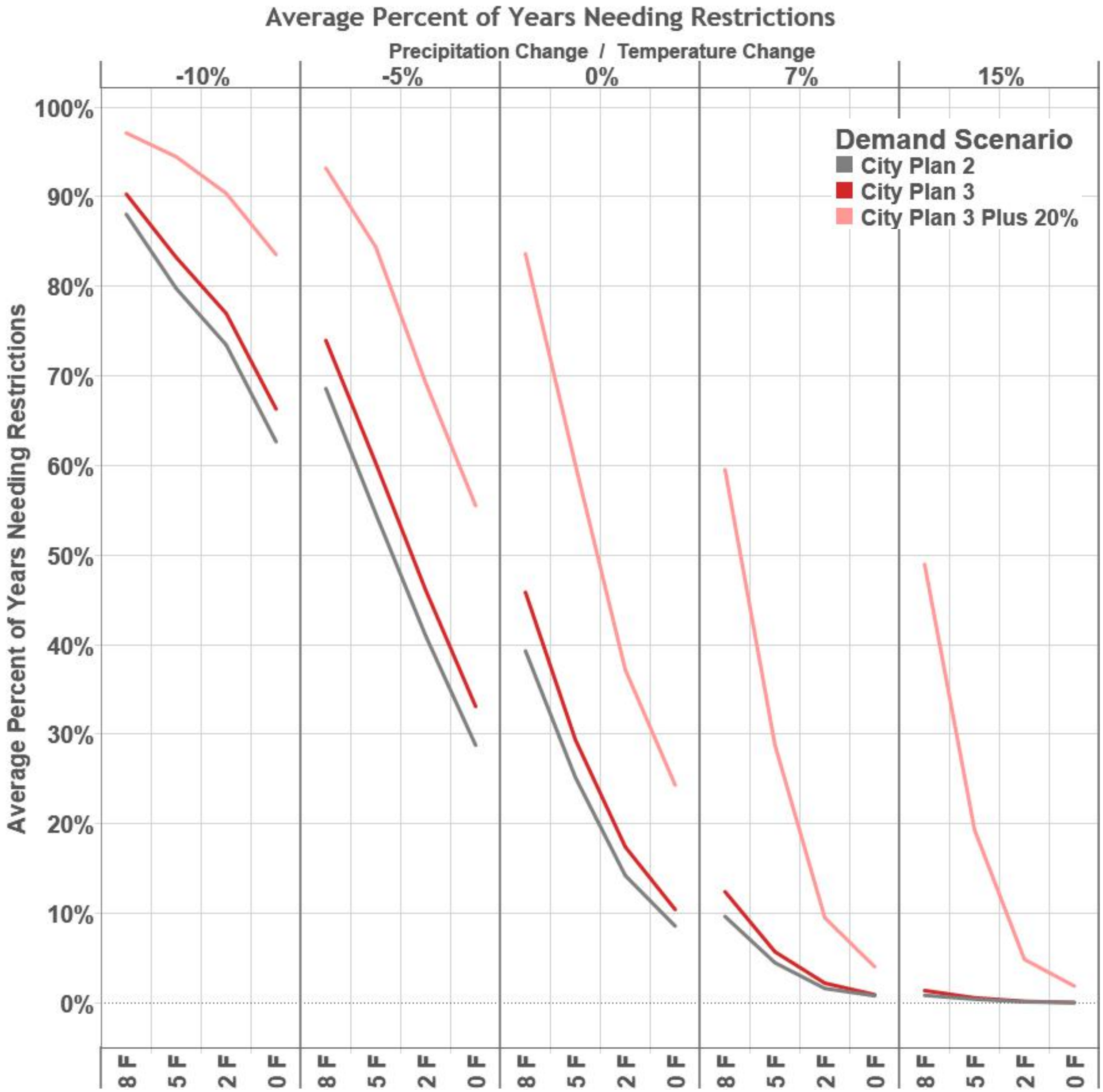


Figure 7-14 Average Percent of Years When Water Use Restrictions Would be Declared for Increased Demands Scenario

Notes:

a) Demands represent 2070 population and development conditions.
b) Poorer performance indicated by more restriction need towards top of graph
c) “Restrictions” is a surrogate for any demand management or emergency supply enhancement measures FCU would implement in response to potential violations of the water supply planning policy

Any values of indoor demand reliability less than 100% suggest potential critical conditions. **Figure 7-15** shows that under all climate conditions except 7% and 15% increase in precipitation, all three demand scenarios could create risks for the current FCU water resources system if demand management measures were not implemented. FCU would aggressively implement demand management or emergency supply measures if there was threat of not meeting all indoor demands. For example, indoor demand reliability would be greatly improved by implementing water use restrictions that reduce outdoor demand in summer and preserve more water in storage for use in meeting indoor demands in winter before the next runoff period.

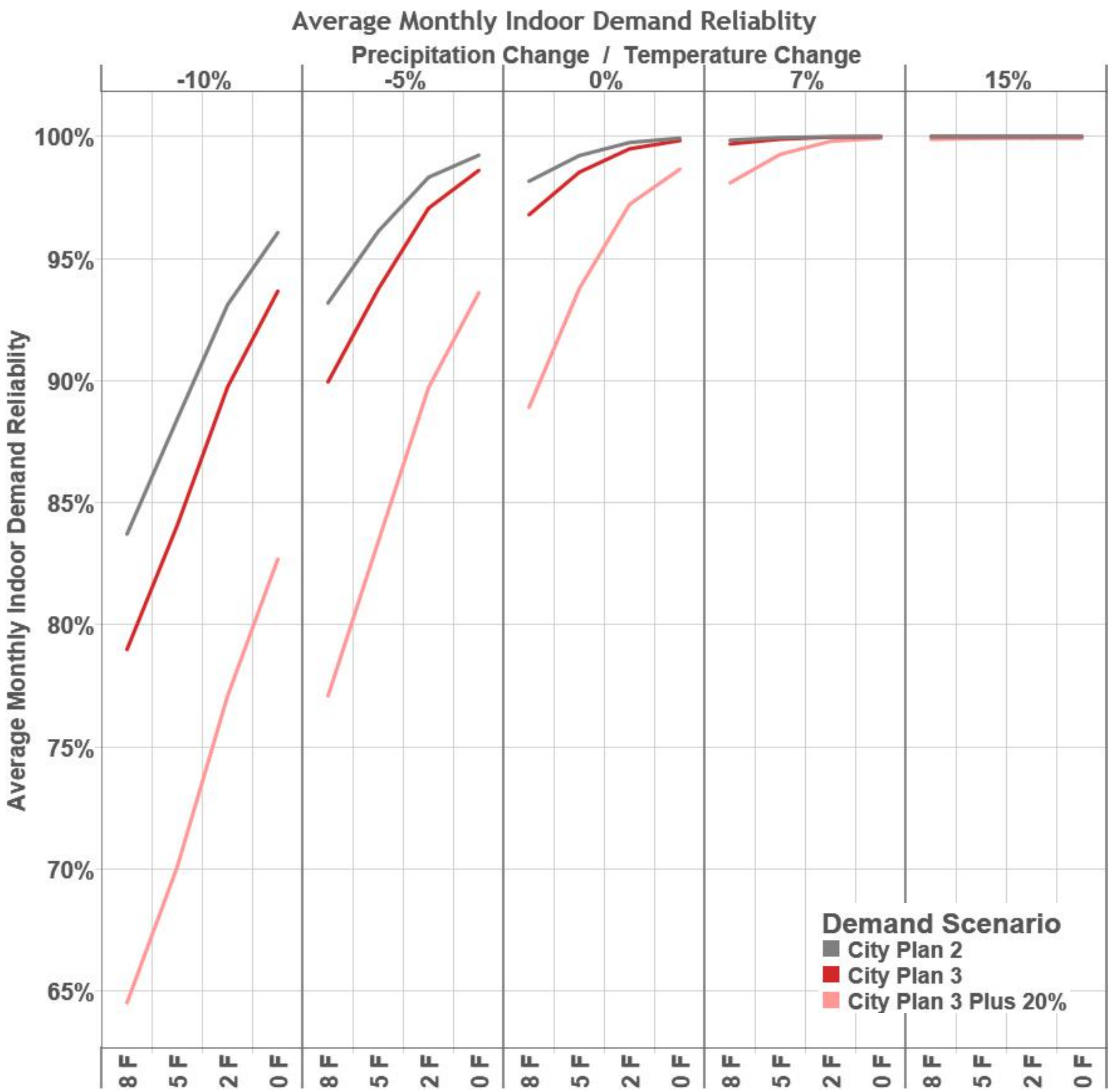


Figure 7-15 Average Monthly Indoor Demand Reliability for Increased Demands Scenario

Notes:

a) Demands represent 2070 population and development conditions.
b) Poorer performance indicated by lower reliability towards bottom of graph.

Due to the way the City Plan 3 scenario was developed, it represents the most reasonable upper bound for future demands based on current expected growth patterns and trajectories. Therefore, results of the vulnerability simulations for the City Plan 3 demand scenario at 0 temperature and precipitation change (0/0) can be considered a reasonable basis to compare the effects of the demand risks to the effects of climate change uncertainty. **Table 7-2** compares the influence of demand increases under current climate with the influence of climate change under baseline demands for four selected metrics related to the current water supply planning policy criteria. Results show that over the range of future climate and demand conditions considered in the WSVS, modest climate change and modest demand increases have similar impacts on the ability to meet the water supply policy criteria. However, the most severe climate change condition will create greater challenges for meeting the current policy criteria than the highest future demand forecast.

Table 7-2 Comparison of Influence of Demand Increases Under Current Climate with Influence of Climate Change Under Baseline Demand

Climate/Demand Condition	Average Number of Years When Total Demand is Not Met	Average Annual Demand Shortage in Years When Shortages Occur	Average Number of Months when 20% Storage Reserve Factor is Not Met	Average Percentage of Years in Restrictions if No Management Measures are Implemented
Current Climate[a]				
City Plan 2 Demand	1	412 AFY	11	7
City Plan 3 Demand	2	424 AFY	15	9
City Plan 3 + 20% Demand	6	1,700 AFY	49	21
Constant Annual Demand [b]				
T=0, P=+15 Climate	0	0 AFY	0	0
T=0, P=0 Climate	3	920 AFY	30	14
T=+5, P=-5% Climate	27	2,865 AFY	252	55
T=+8, P=-10% Climate	58	4,979 AFY	569	78

Notes:

a) Current Climate: Demands vary annually based on each trace. Results are averaged over all 100 traces for climate T=0, P=0

b) Baseline Demand: Demands are constant between years. Results are averaged over all 100 traces for climate scenarios listed

7.5 RISK SCENARIO RESULTS

Each of the identified vulnerability scenarios from Section 6 were run for the City Plan 2 and City Plan 3 demand levels for all hydrologic traces and climate combinations. Exceptions are the baseline simulation, which was run for a constant demand and historical climate only; the Climate Change Impacts scenario, which was run for constant demand only; and the Increased Demands scenario, which was run for the two City Plan demand levels plus the City Plan Plus 20% demand described above. The results shown in this section, unless otherwise noted, are for the City Plan 3 demand scenario. Results with the City Plan 2 demand scenario are similar but have slightly better metric values than the results with the City Plan 3 demand scenario.

The discussion of the risk scenarios is organized around a series of key metrics. Performance of the scenarios based on each metric is discussed, then the scenarios are compared according to the overall vulnerability they pose to the Fort Collins raw water system.

7.5.1 Comparison of Scenarios Based on the Average Annual Demand Shortage Metric

Figure 7-16 compares system performance for all the scenarios based on the average annual demand shortage metric. This metric is calculated for a given model run by summing the volume of the demand shortage (difference between the volume of total annual demand and actual volume of water supplied in each year) across the full 86-year simulation period and dividing by the number of years in which demand shortages occur. Results are displayed as parallel line plots. Each set of lines applies to one of the values for the assumed change in precipitation. Within a precipitation column, temperature decreases (i.e., improves in terms of influence on water supply) from left to right. The upper panel y-axis shows the average annual demand shortage in acre-feet per year only during times of shortage. The lower y-axis shows the average number of years with shortages.

Parallel line plots are effective in displaying the relative performance of all the risk scenarios across the range of climate conditions simulated in the WSVS. As expected, the greatest annual shortages for nearly every risk scenario are seen in simulations with lower precipitation. Greater precipitation can lessen the effects of the risks on FCU's water supply system despite warming temperatures. Most of the risk scenarios have a similar impact on the average annual shortage metric, as future climate temperature and precipitation change. The exception is some of the short-term risk scenarios for wetter future climates; these anomalies are discussed in a following section.

The risk scenario with the greatest average annual demand shortage is the Increased Demands Scenario (City Plan 3 Plus 20%) for simulations with reduced precipitation. Other scenarios that perform poorly for drier conditions are the Loss of Storage Scenario (no Halligan Reservoir enlargement and no C-BT carryover storage in Horsetooth Reservoir) and the Reuse Plan Change 1 Scenario (elimination of Reuse Plan). In scenarios with greater precipitation, the Poudre River System – Environmental Impacts Scenario has the greatest average annual demand shortage. This scenario simulates the effects of algal blooms and wildfires by eliminating the use of water from Horsetooth Reservoir for one year and preventing full use of the water supply pipelines from the Poudre River for 10 years.

The following plots and paragraphs discuss results for several categories of similar risk scenarios.

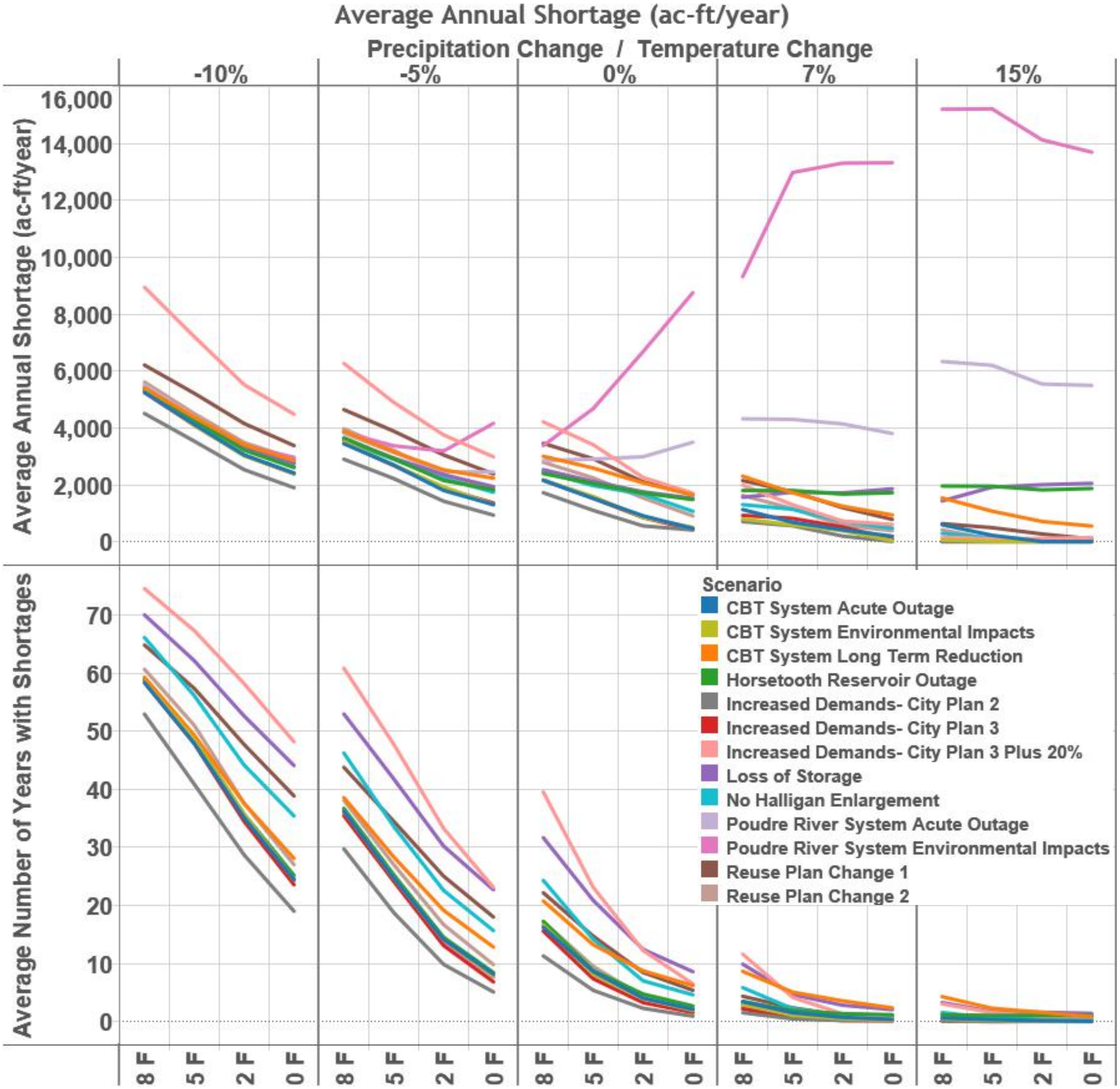


Figure 7-16 Average Annual Shortage and Number of Years with Shortages - All Scenarios

Notes:

a) Average annual shortage metric is calculated as the sum of annual shortages over the 86-year simulation period divided by the number of years when shortages occurred.

b) Average number of years with shortage is based on 86 years in the model simulation period.

c) Poorer performance indicated by greater shortages towards top of graph.

Figure 7-17 shows the average annual demand shortage for the two reuse plan scenarios. Reuse Plan Change 1 eliminates the reuse plan for the entire simulation period whereas Reuse Plan Change 2 reduces the reuse plan by 50% for the entire simulation period. Again, during simulations with increased precipitation, the average annual demand shortage is low, while simulations with decreased precipitation show higher annual demand shortages. This is particularly true when the reuse plan is eliminated in the Reuse Plan Change 1 scenario. Comparison with other scenarios shows that reductions to, or elimination of the reuse plan are some of the more potentially impactful risks evaluated in the WSVS.

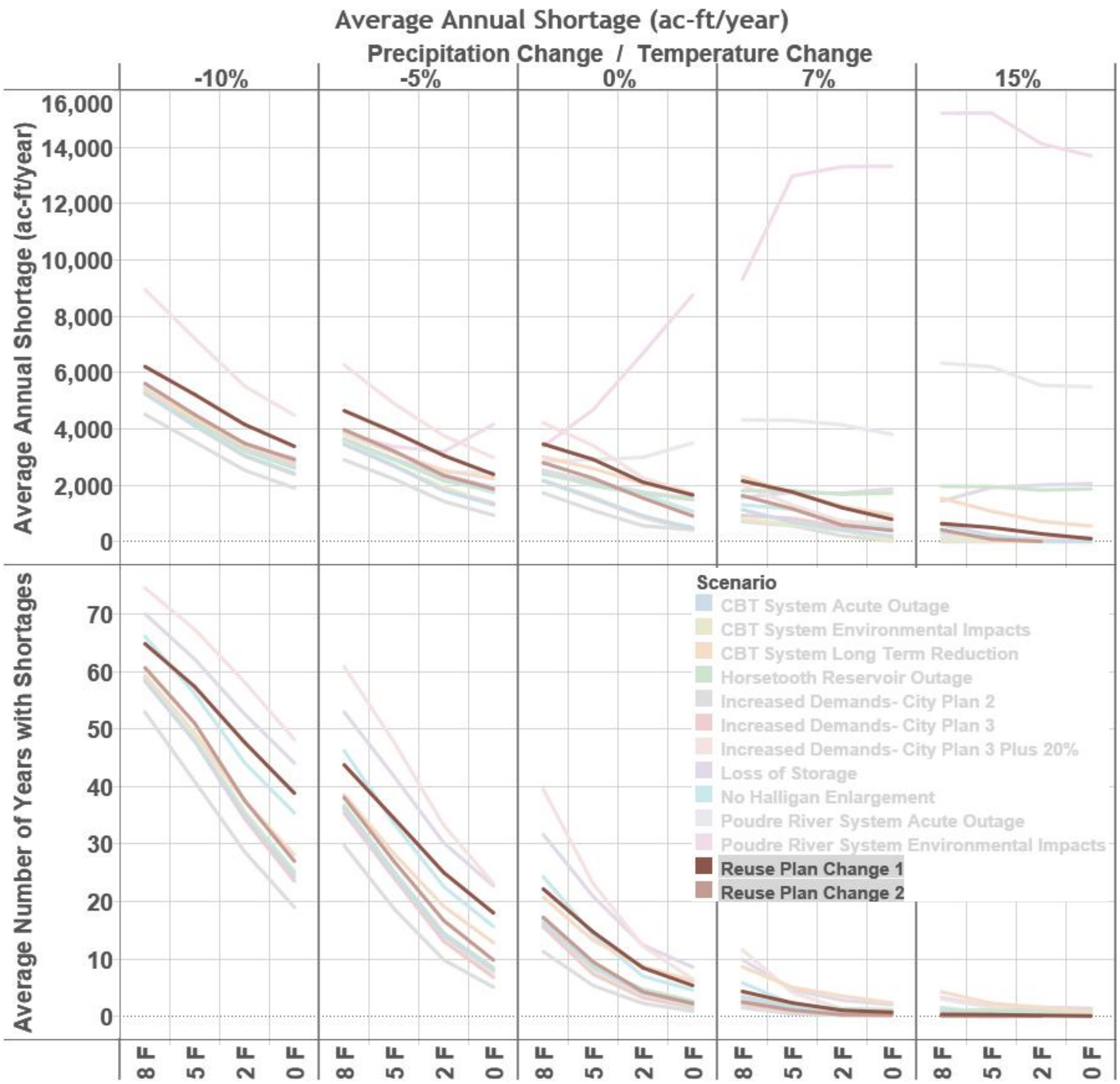


Figure 7-17 Average Annual Shortage and Number of Years with Shortage - Reuse Plan Change Scenarios

Notes:

a) Average annual shortage metric is calculated as the sum of annual shortages over the 86-year simulation period divided by the number of years when shortages occurred.
b) Average number of years with shortage is based on 86 years in the model simulation period.
c) Poorer performance indicated by greater shortages towards top of graph

Figure 7-18 shows the average annual shortage metric for the No Halligan Expansion scenario and the Loss of Storage Scenario. As shown, unless there is an increase in precipitation, there are significant shortages in meeting the future demand. The Loss of Storage scenario combines the risk of not having the Halligan Expansion with the risk of not being able to use C-BT carryover storage in Horsetooth Reservoir. Without the ability to use these two storage facilities, overall annual demands cannot be met. These scenarios demonstrate the importance of storage to FCU's system.

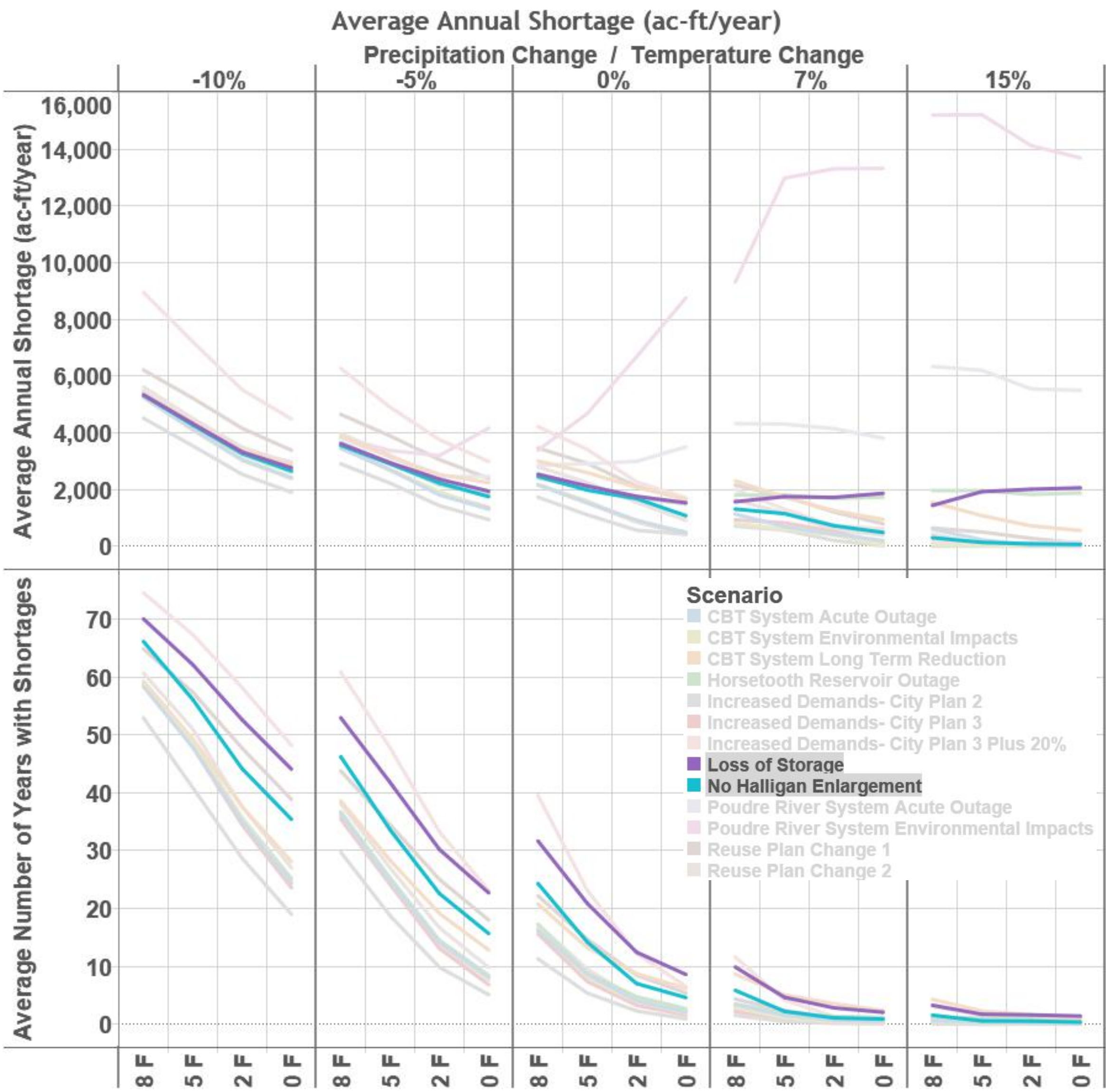


Figure 7-18 Average Annual Shortage and Number of Years With Shortage - Loss of Storage and No Halligan Enlargement Scenarios

Notes:

a) Average annual shortage metric is calculated as the sum of annual shortages over the 86-year simulation period divided by the number of years when shortages occurred.
b) Average number of years with shortage is based on 86 years in the model simulation period.
c) Poorer performance indicated by greater shortages towards top of graph

Figure 7-19 shows results for the C-BT System Long Term Reduction Scenario. In this scenario, the C-BT Quota is set to 25% for 10 years following a randomly selected dry year. This scenario shows more shortages than many of the other scenarios in both wet and dry years. As described in Section 1.2, FCU receives approximately half of its water supply from the Poudre River and half from the C-BT and/or Windy Gap Projects, on an annual basis. Therefore, it is logical that the very low quota simulated in this scenario would impact FCU's ability to meet demands, regardless of the climate conditions.

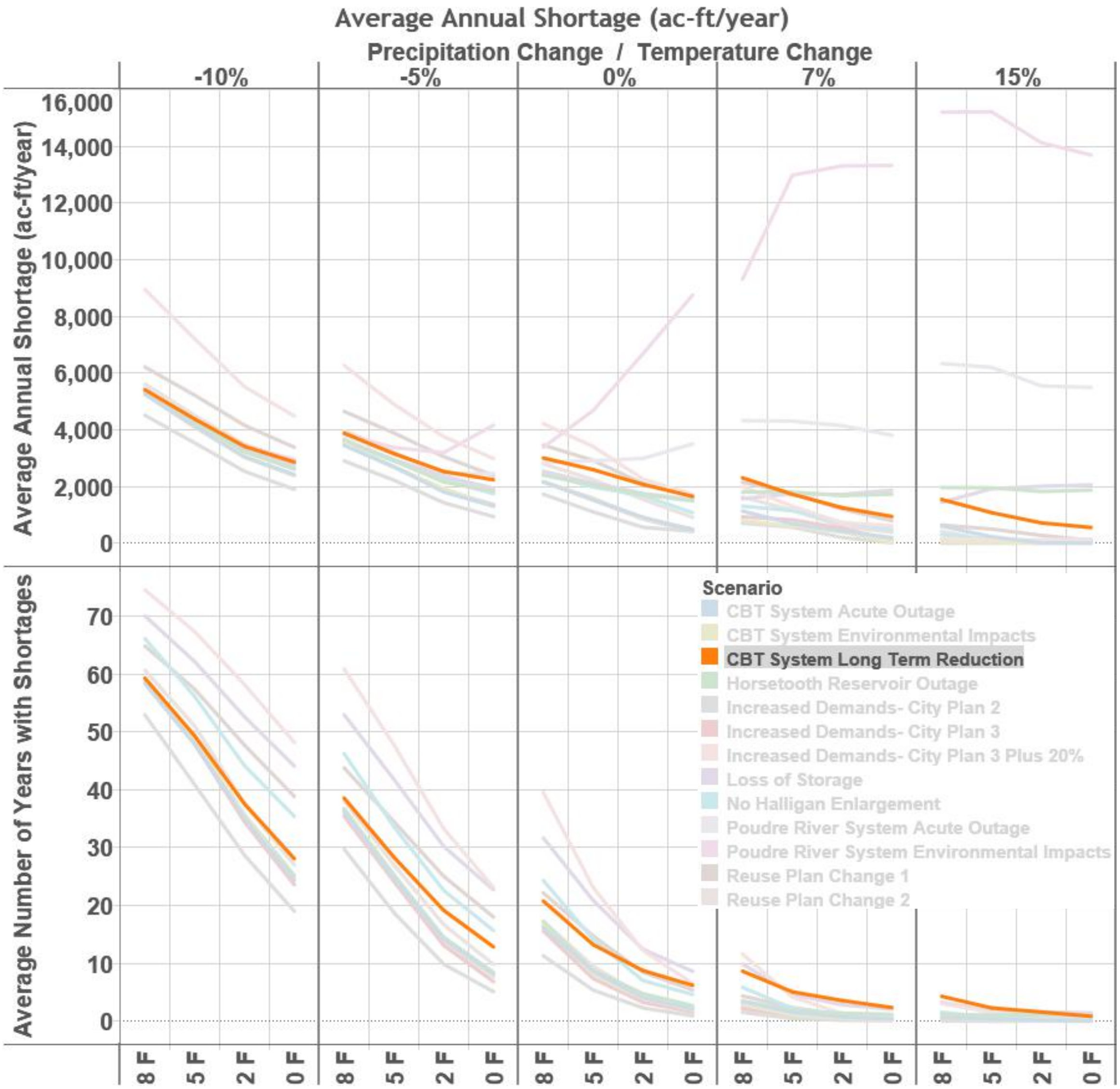


Figure 7-19 Average Annual Shortage and Number of Years With Shortage – C-BT Long Term Reduction Scenario

Notes:

a) Average annual shortage metric is calculated as the sum of annual shortages over the 86-year simulation period divided by the number of years when shortages occurred.
b) Average number of years with shortage is based on 86 years in the model simulation period.
c) Poorer performance indicated by greater shortages towards top of graph

Figure 7-20 shows results for the two Poudre River short-term outages. The average annual shortage increases substantially for the wetter climates because the number of years with shortages due to climate influence decreases. These short-term risks, associated with infrastructure outages or water quality degradation, occur for only a few months during the 86-year simulation period, so effects on system performance are relatively brief but severe. This generates a high value for the average annual shortage metric. The comparison in the figure demonstrates the fundamental difference in FCU water resources system response to short-term vs long-term risks. Because all other metrics are calculated over the entire 86-year simulation period they are not effective in isolating effects of short-term risks. Additional analysis will be required to more fully understand effects of short-term risks on system performance.

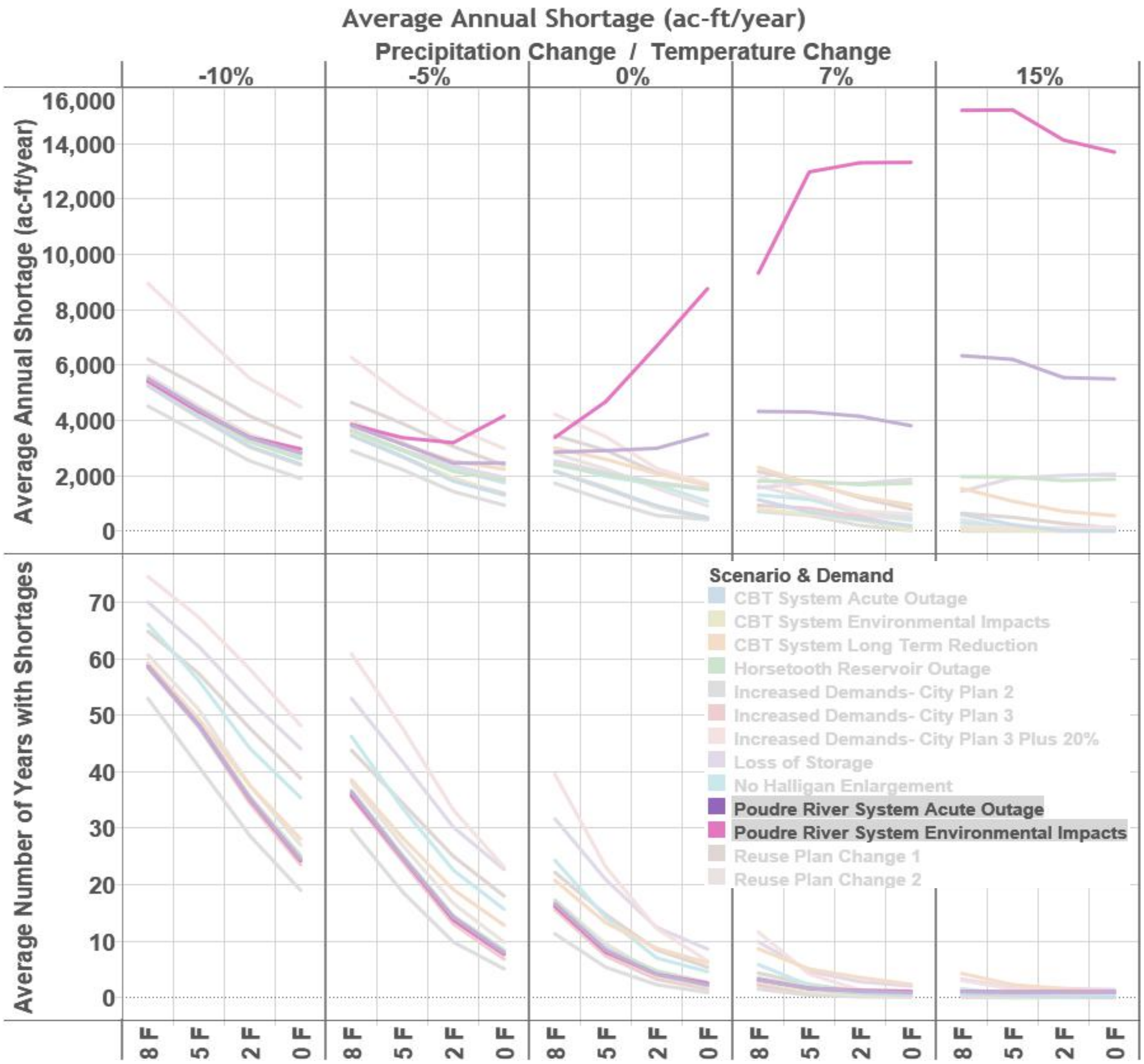


Figure 7-20 Average Annual Shortage and Number of Years with Shortages - Poudre River Short Term Risks

Notes:

a) Average annual shortage metric is calculated as the sum of annual shortages over the 86-year simulation period divided by the number of years when shortages occurred.
b) Average number of years with shortage is based on 86 years in the model simulation period.
c) Poorer performance indicated by greater shortages towards top of graph.

7.5.2 Comparison of Scenarios for the Storage Reserve Factor Metric

The next set of parallel line graphs, starting with **Figure 7-21**, depict the performance of the scenarios with respect to the reliability of maintaining 20% of the annual demand in storage as a storage reserve factor (SRF). The SRF typically equates to about 1.5 months of summer demands or 4 months of winter demands. The current water supply planning policy sets the SRF target of 20% of annual demand at 100% reliability (i.e., at all times) as insurance against unforeseen future conditions or emergencies. For this metric, scenario lines at the bottom of the graph have worse performance as they are less often able to maintain the 20% SRF.

The 20% SRF reliability metric behaves similarly for all the risks scenarios as the assumed future climate is varied. As was the case with the average annual shortage metric, the scenarios with the worst performance for the 20% SRF metric are the City Plan + 20% demands, the changes to the reuse plan, Loss of Storage and No Halligan Enlargement and the C-BT Long-Term Reduction.

The water supply planning policy goal of 20% SRF with 100% reliability cannot be met for any of the risk scenarios, with the exception of some short-term risks and the City Plan 2 demand scenario under the wettest and coolest climate conditions. Under nearly all future conditions, FCU would have to implement water supply enhancement or demand management measures to maintain the 20% SRF reliability goal at all times. Under the most severe climate condition (T=8, P=-10%), the 20% SRF goal can be met only 30% to 50% of the time across the range of risk scenarios. It is expected that significant water resources system improvements, likely consisting of additional storage, would be needed to maintain the 20% SRF goal for any of the WSVS risk scenarios in this severe climate condition.

Results for categories of similar risk scenarios are described in the following paragraphs.

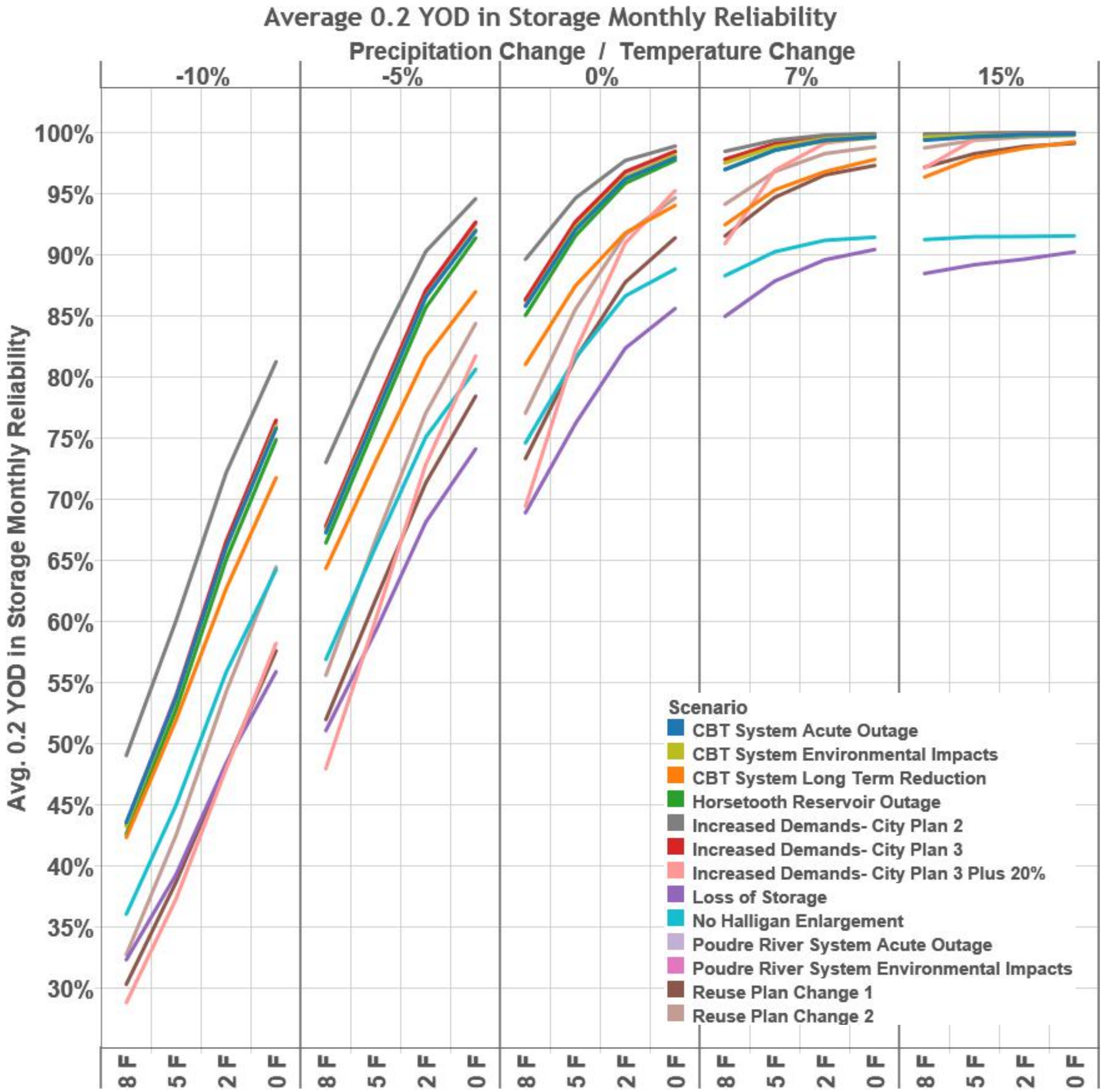


Figure 7-21 Storage Reserve Metric for All Risk Scenarios

Notes:

a) Poorer performance indicated by lower reliability towards bottom of graph.
b) YOD = years of annual demand.
c) Water supply planning policy goal is 100%

The Loss of Storage and the No Halligan scenarios have very poor performance for the storage reserve factor reliability metric (**Figure 7-22**). The Loss of Storage scenario assumes No Halligan Enlargement of 8,125 AF and no use of C-BT Carryover storage. FCU does not have many reservoirs and without these storage accounts, overall storage reserves are reduced and the ability to keep 20% of the annual demand in storage becomes very difficult. Even in wet future climate conditions, the performance of this metric is low. In these conditions, there is more supply than for the drier climates but because these two risk scenarios have less reservoir storage, it is still more difficult to maintain the 20% SRF goal than under the other risk scenarios with more reservoir storage. These results point out the importance of the proposed Halligan Water Supply Project.

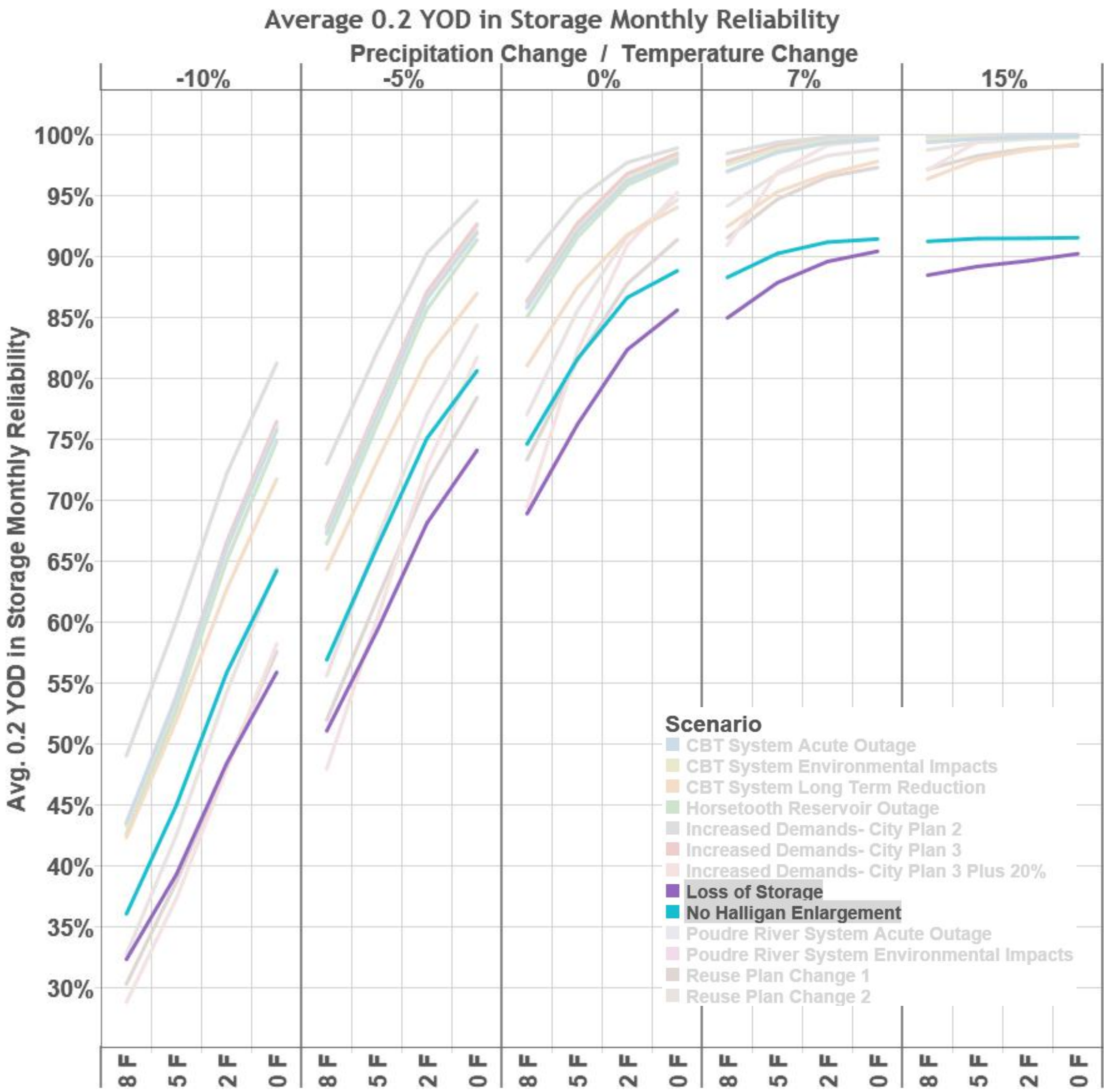


Figure 7-22 Storage Reserve Metric- Loss of Storage and No Halligan Enlargement Scenarios

Note: Poorer performance indicated by lower reliability towards bottom of graph

The Reuse Plan is a very important mechanism for increasing water supply in the FCU system. **Figure 7-23** shows impacts to the storage reserve metric without the Reuse Plan and with a 50% reduction in the ability to utilize the Reuse Plan. Lack of this supply requires heavier dependence on storage, thus depleting it beyond the 20% SRF threshold.

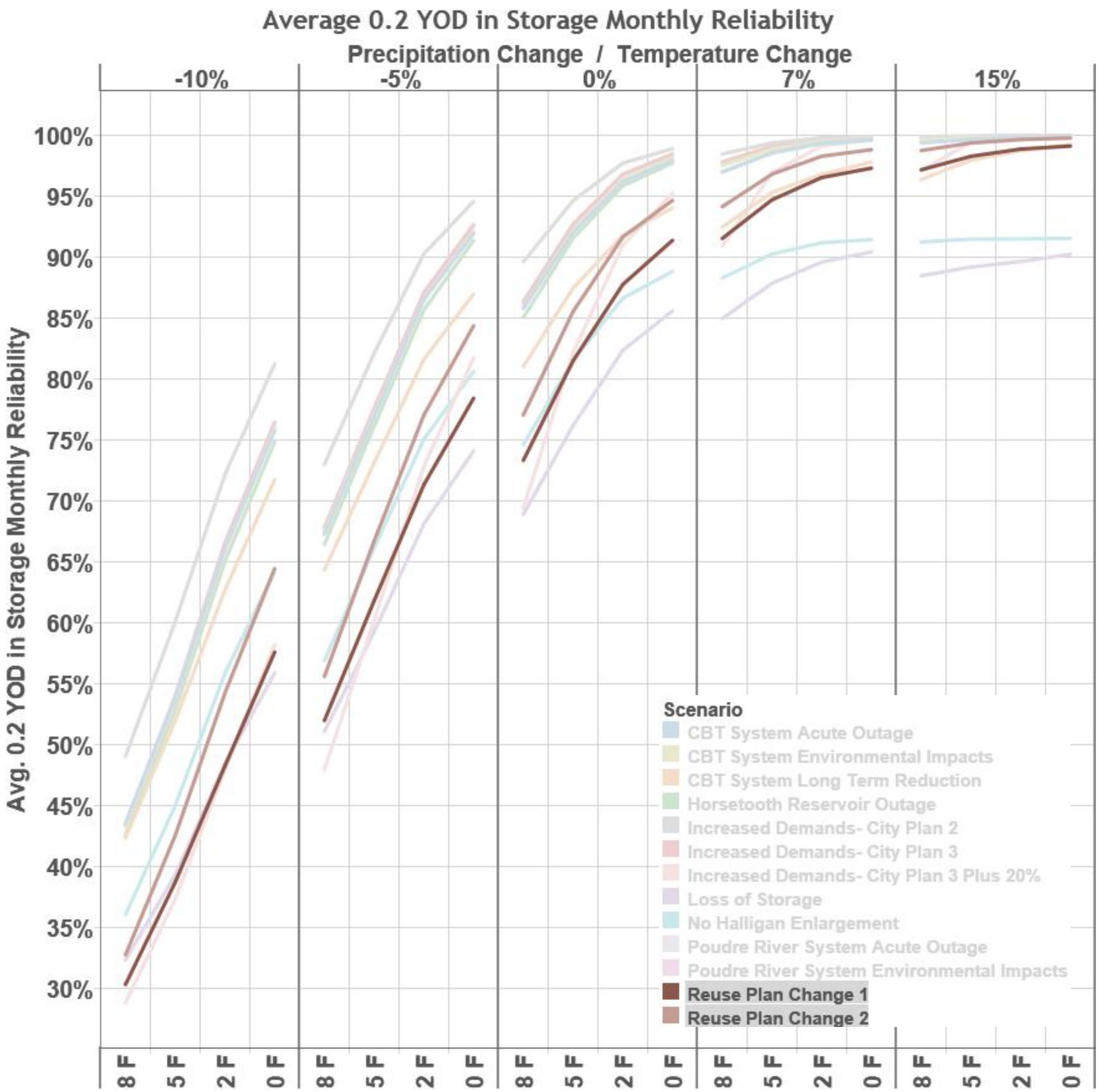


Figure 7-23 Storage Reserve Metric- Reuse Plan Change Scenarios

Note: Poorer performance indicated by lower reliability towards bottom of graph

A long-term reduction in C-BT supply simulated by a 25% quota for 10 consecutive years affects the storage reserve factor metric similarly to the Reuse Plan Change scenarios. C-BT water is an important supply for FCU and is also a critical component of the Reuse Plan. **Figure 7-24** shows that when this supply is significantly curtailed for a decade, the ability to meet the 20% SRF is diminished. Even scenarios with 15% increases in precipitation and no increase in temperature have a reliability of 99.3% for the 20% SRF metric and are thus, unable to meet the 100% reliability goal in the water supply planning policy.

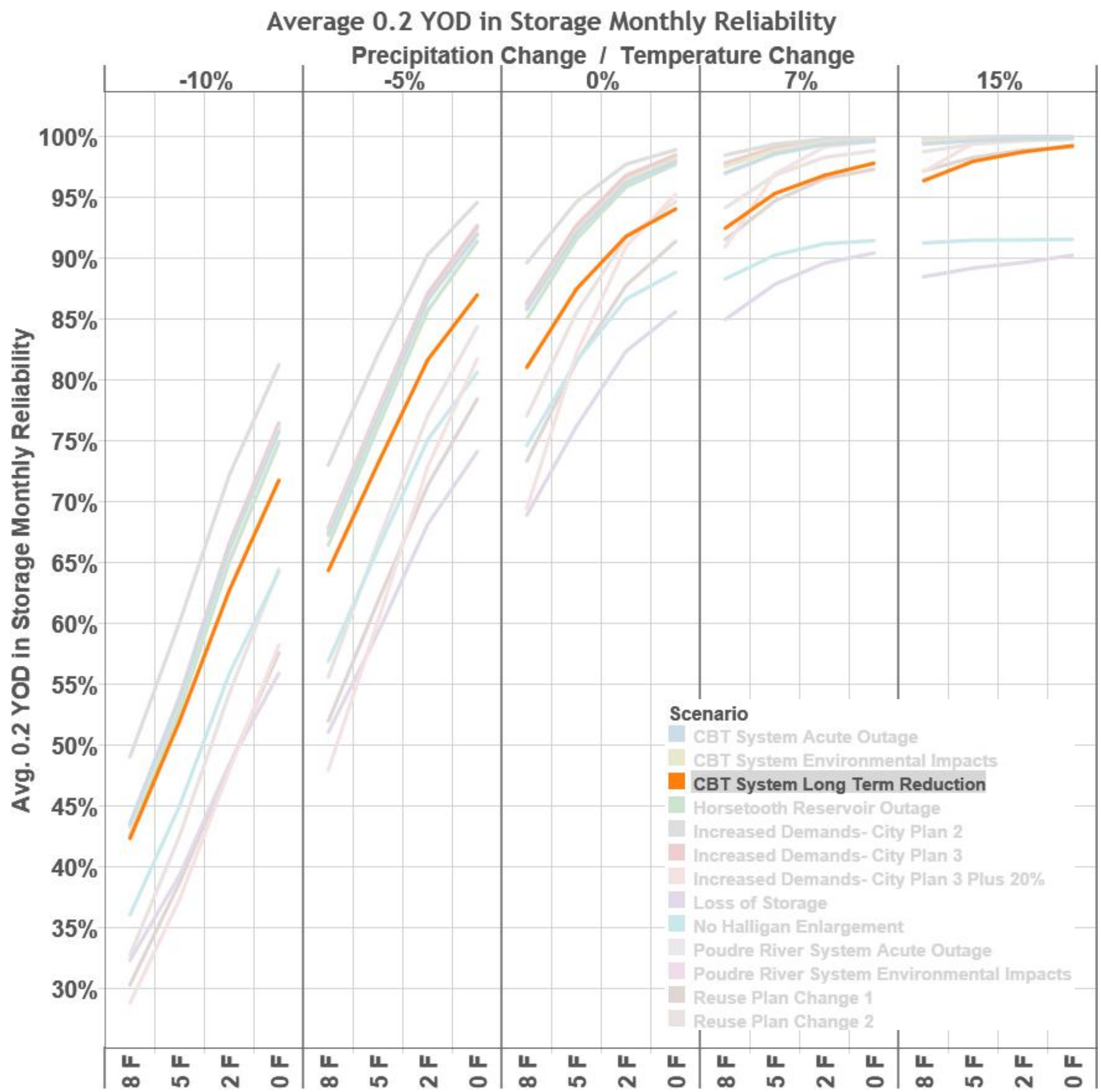


Figure 7-24 Storage Reserve Metric – C-BT Long Term Reduction Scenario

Note: Poorer performance indicated by lower reliability towards bottom of graph

7.5.3 Comparison of Scenarios Based on the Years in Restrictions Metric

A metric was calculated to determine how often water use restrictions would have been implemented during a model run based on the Fort Collins water shortage policy, assuming no demand management or emergency supply strategies were implemented. Water use restrictions could be triggered by impending shortages in meeting demand or total reservoir storage falling below the 20% SRF target. Because the current water supply planning policy sets a goal of meeting all demands during the 1-in-50-year drought and maintaining the 20% SRF without implementing water use restrictions, this “years in restrictions” metric provides a relative comparison of the threat of each risk scenario to cause violations of the policy.

WSVS simulations do not include demand management measures or changes to normal water resources system operations like FCU has implemented in the past and could implement in the future in response to droughts or other emergencies. Thus, the results should not be interpreted as an estimate of the frequency of declaring water use restrictions based on current FCU policy, but more as a proxy for the relative frequency with which FCU would have to implement responses based on its water shortage policy. Response of the FCU water resources system to water use restrictions is complex and implementing restrictions during one drought year may have continuing benefits by conserving supplies, thereby reducing or eliminating shortages in future dry years. It is noted that the limited storage in the FCU water supply system, relative to the annual demand, constrains the potential benefits of demand management in one year, on system performance in subsequent years. Despite complex interaction of operations during drought or emergency periods, the results of the “years in restrictions” metric are useful for comparing the relative threat of triggering water shortage response policy actions among the different risk scenarios.

The figures below show the percentage of years in which the FCU water system would have been in any stage of water restrictions based on the current Fort Collins water shortage policy. **Figure 7-25** shows results for this metric for all scenarios. Lines near the top of the graph indicate more time spent in restrictions and therefore, worse system performance.

Virtually all risk scenarios would drive the need for demand management or water supply enhancement actions to avoid violations of the water supply planning policy criteria. Future temperature and precipitation significantly affect the threat of being in conditions that would trigger water use restrictions to meet the other policy criteria.

The following paragraphs discuss results for categories of similar risk scenarios.

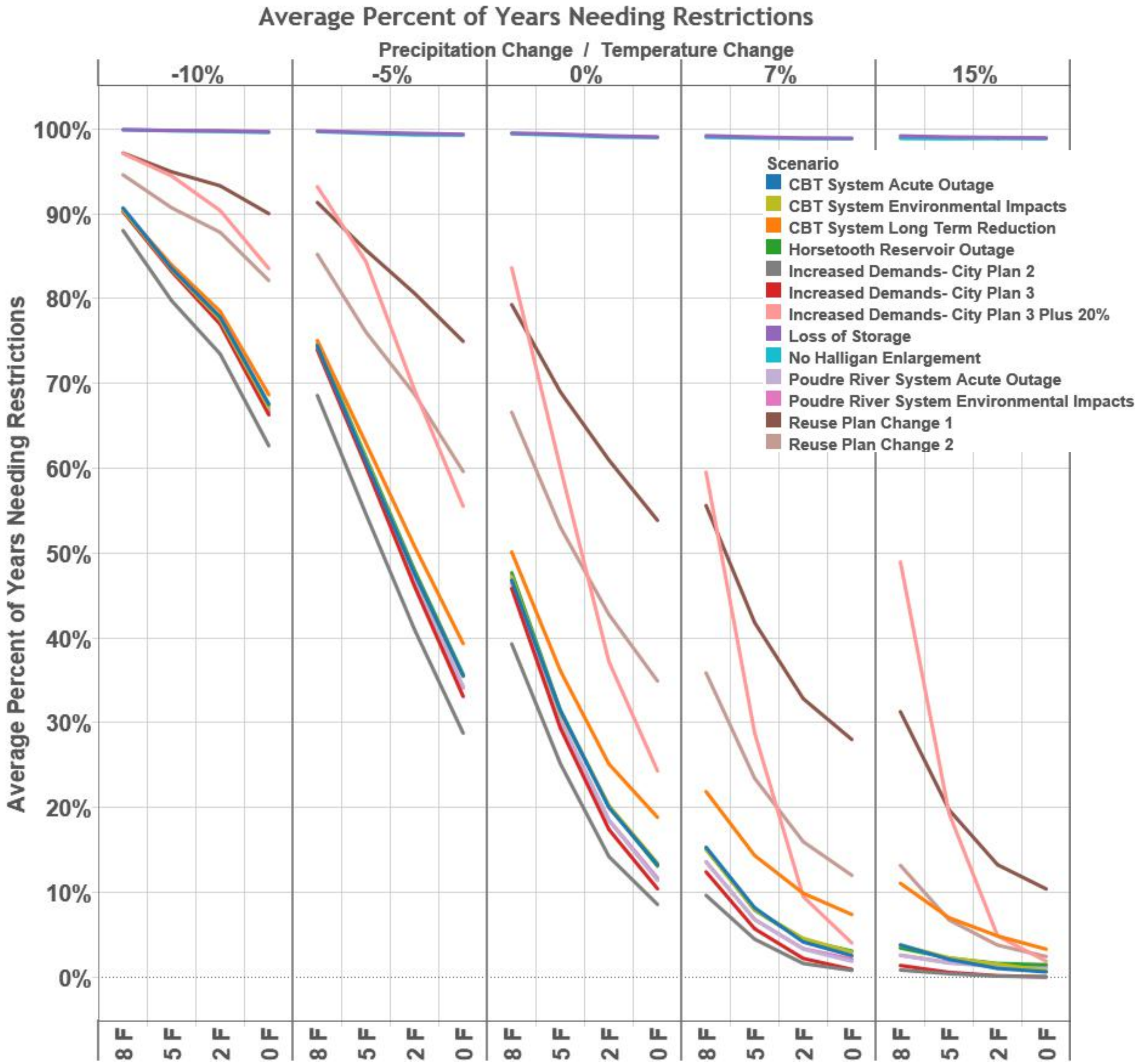


Figure 7-25 Years in Restrictions Metric for All Risk Scenarios

Notes:

a) Poorer performance indicated by greater frequency of being in restrictions towards top of graph
b) “Restrictions” is a surrogate for any demand management or emergency supply enhancement measures FCU would implement in response to potential violations of the water supply planning policy

Figure 7-26 shows that the No Halligan Enlargement and the Loss of Storage scenarios would require some level of restrictions throughout the simulations in at least 99% of years in the absence of implementing management measures. The proposed Halligan Reservoir Enlargement is a critical component of FCU's future water supply system and without it, current water supply planning policy criteria could not be met in most years.

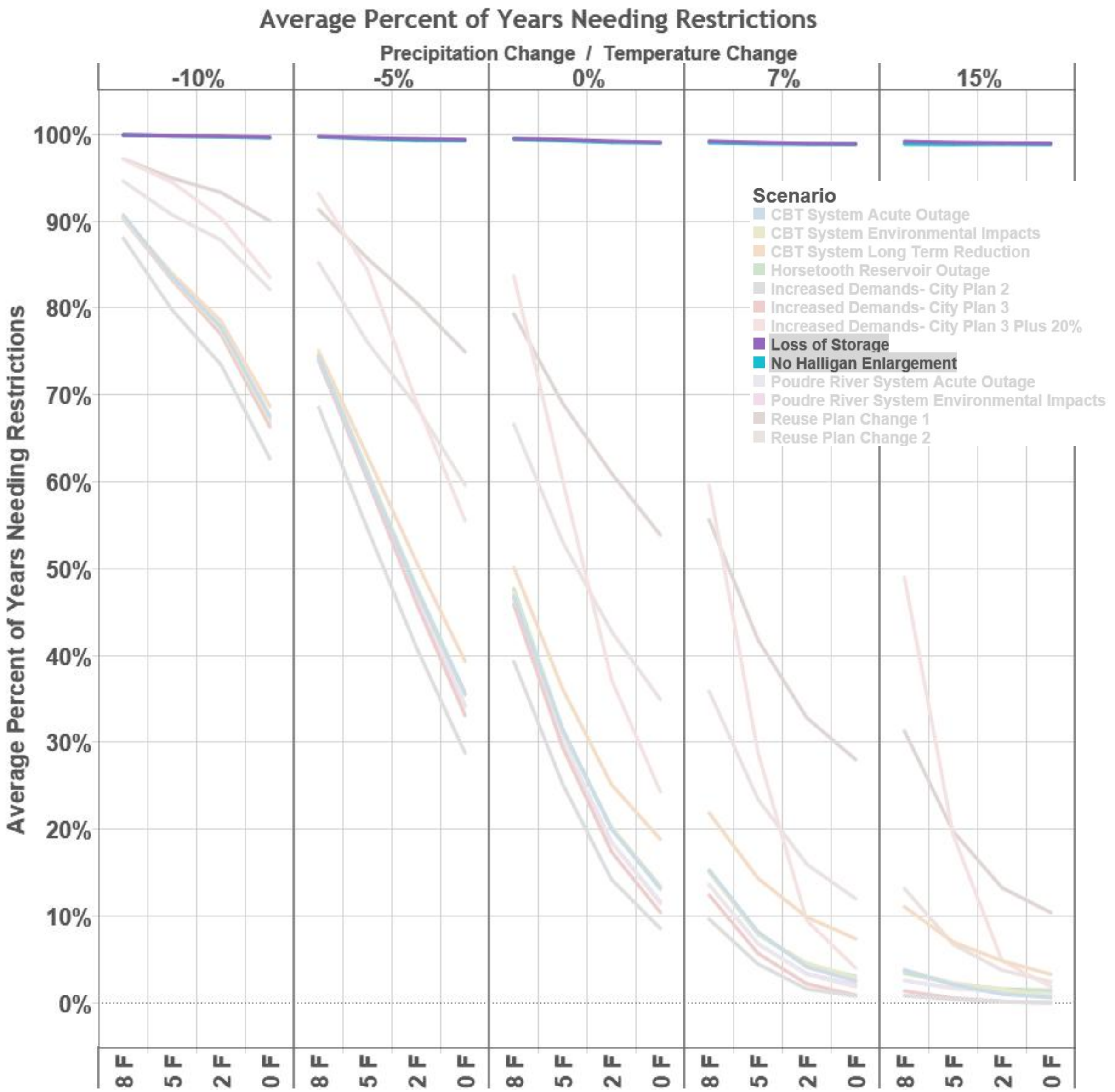


Figure 7-26 Years in Restrictions Metric- Loss of Storage and No Halligan Enlargement Scenarios

Notes:

a) Poorer performance indicated by greater restriction needs towards top of graph
b) "Restrictions" is a surrogate for any demand management or emergency supply enhancement measures FCU would implement in response to potential violations of the water supply planning policy

Figure 7-27 shows that any change to the reuse plan would increase the average percentage of years the system would be in restrictions without implementation of management measures. Either a 50% or a 100% reduction in the reuse plan would impact the system significantly, requiring the need for frequent restrictions or other demand management or supply enhancement measures.

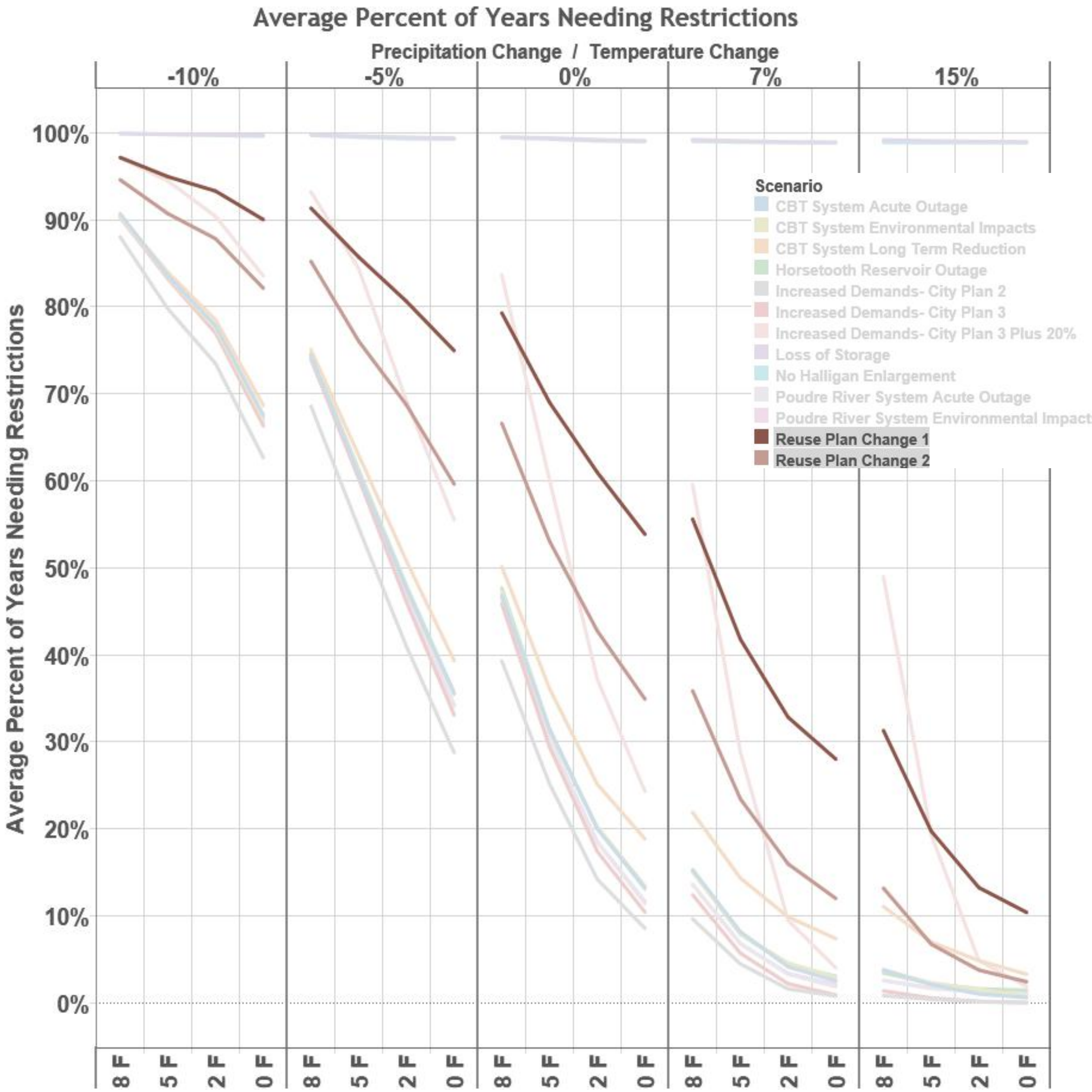


Figure 7-27 Years in Restrictions Metric - Reuse Plan Change Scenarios

Notes:

a) Poorer performance indicated by greater restriction needs towards top of graph
b) “Restrictions” is a surrogate for any demand management or emergency supply enhancement measures FCU would implement in response to potential violations of the water supply planning policy

7.5.4 Comparison of Scenarios Based on Indoor Demand Reliability Metric

The next set of figures, starting with **Figure 7-28,** show the reliability of meeting indoor demands for each of the risk scenarios. For modeling purposes, indoor demand is defined as the sum of February demand for the CityDem and LCU nodes in the FCSys model. Meeting all indoor demands with 100% reliability is a critical performance objective for FCU. Any situation with less than 100% reliability represents a public health crisis and a serious risk. It is important to note that watering restrictions or other demand management strategies were not modeled as a part of this study. FCU would take proactive steps to implement restrictions or obtain emergency supplies if there was a threat of not meeting indoor demands for all its customers. So, in practice, the actual indoor demand reliability would be much higher for any of the risk scenarios than calculated for the WSVS simulations. Results in this section are merely an indication of the relative threat among the risk scenarios for indoor demand shortages without implementation of appropriate management strategies.

Figure 7-28 is a parallel line plot showing the average indoor demand reliability metric for all risk scenarios and all climate conditions. Similar to the other metrics, the indoor demand reliability metric is strongly influenced by climate conditions. All risk scenarios for current and drier climates present a significant threat to meeting indoor demands with 100% reliability.

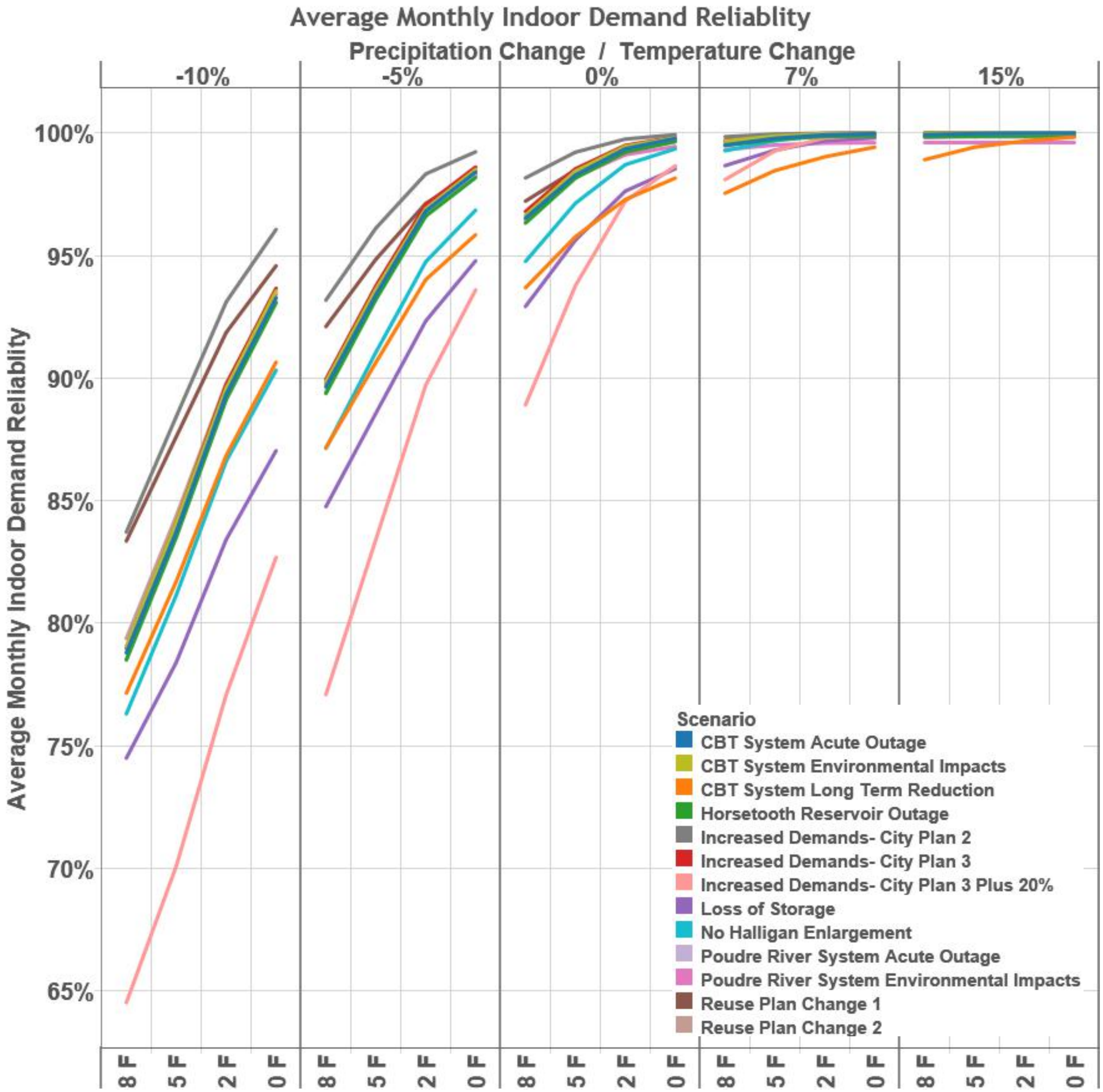


Figure 7-28 Indoor Demand Reliability Metric for All Risk Scenarios

Note: Poorer performance indicated by lower reliability towards bottom of graph. Water supply planning policy goal is 100%.

Figure 7-29 shows the performance of the Loss of Storage and the No Halligan Enlargement scenarios. Even under current climate conditions (T=0/P=0%), a reduction in storage due to loss of C-BT Carryover and/or the proposed Halligan Reservoir enlargement would create shortages in meeting indoor demands.

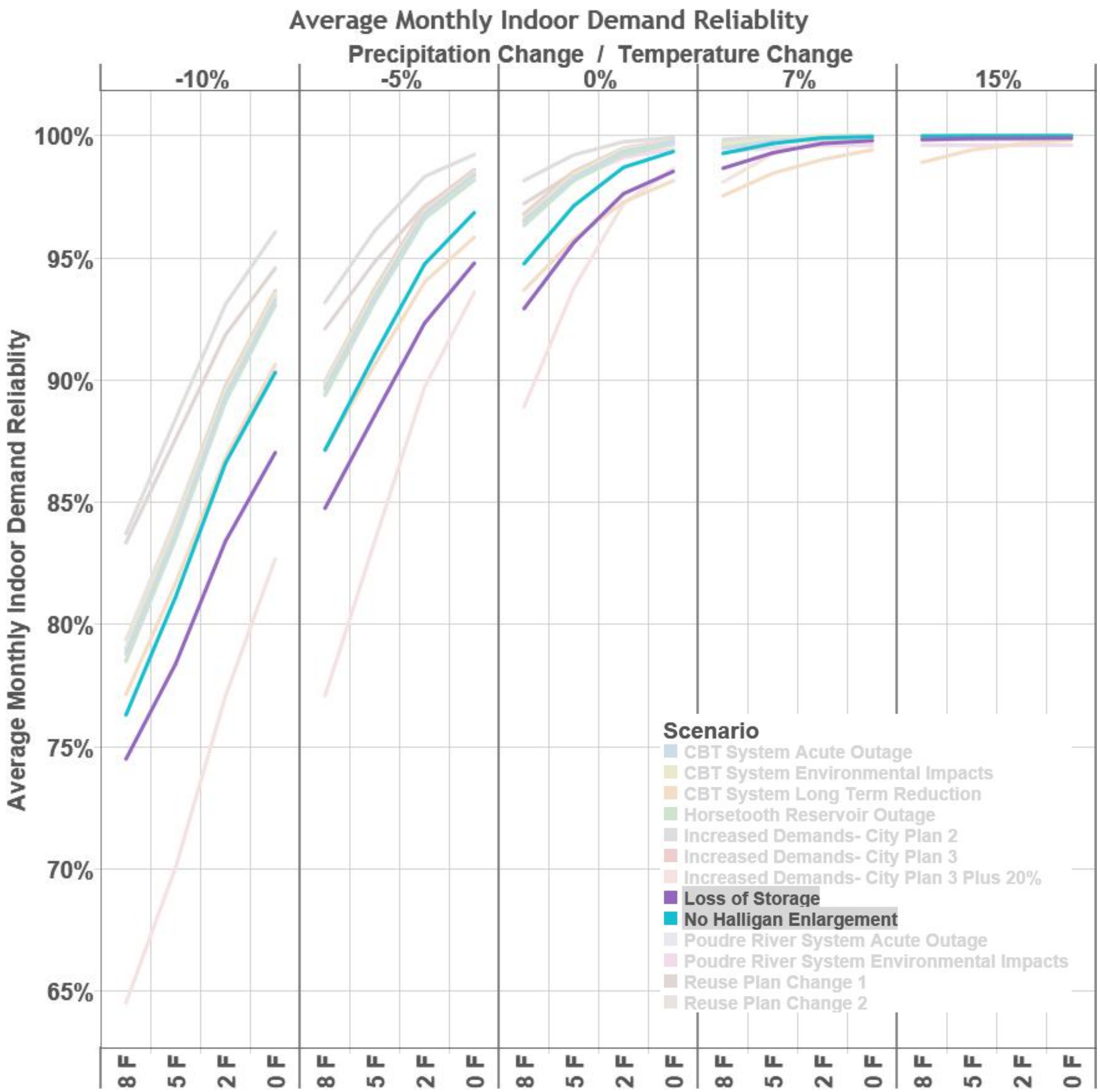


Figure 7-29 Indoor Demand Reliability Metric - Loss of Storage and No Halligan Enlargement Scenarios

Note: Poorer performance indicated by lower reliability towards bottom of graph

Figure 7-30 shows the C-BT Long Term Reduction Scenario represents a critical risk to the ability to reliably meet indoor demands. Even with a 7% increase in precipitation and no change in temperature, the current system is unable to meet indoor demands with 100% reliability. This risk is driven strongly by temperature increases. In the wettest future (+15% precipitation), this is the only risk with decreasing indoor demand reliability as temperature increases.

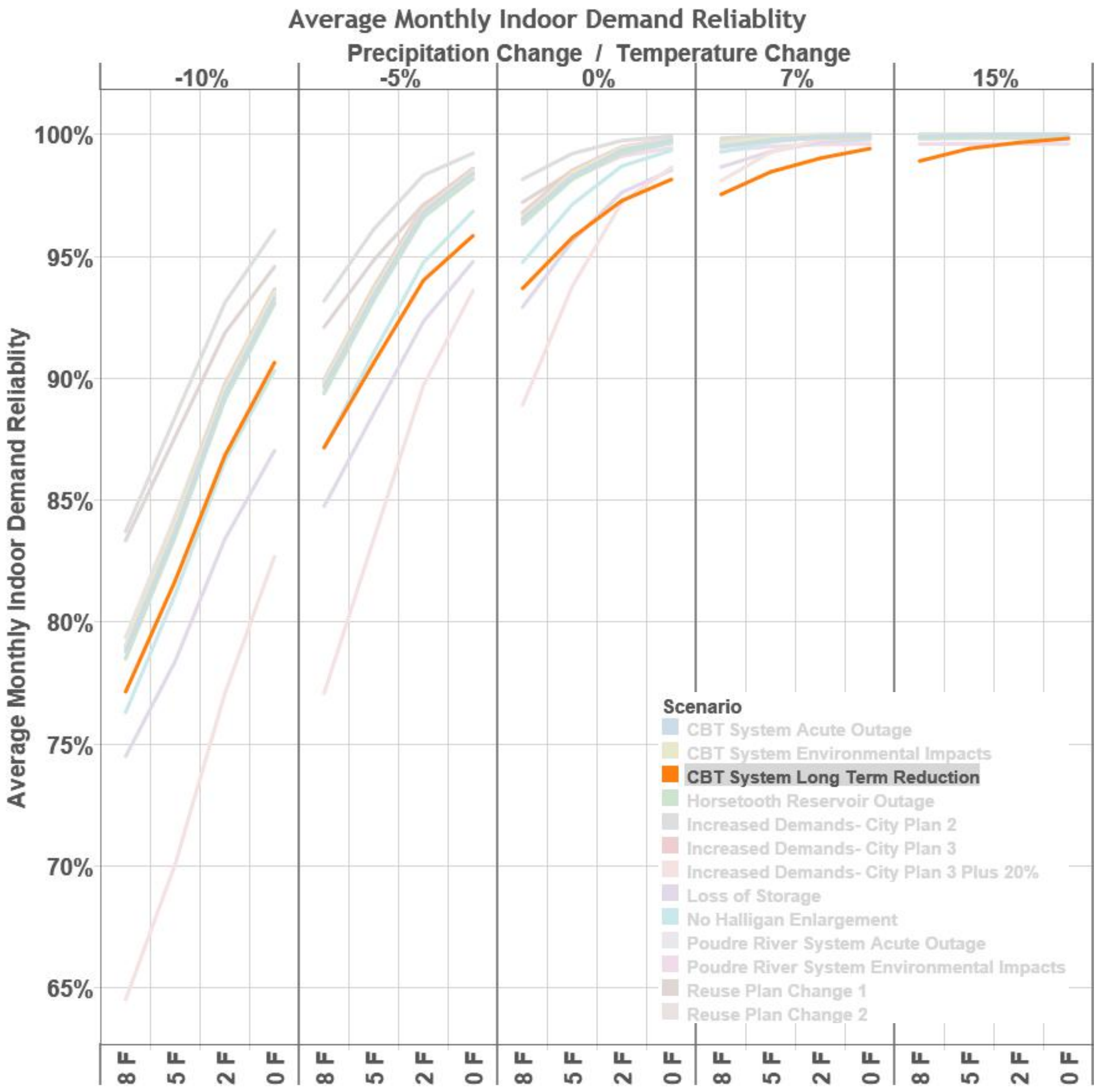


Figure 7-30 Indoor Demand Reliability Metric – C-BT Long Term Reduction Scenario

Note: Poorer performance indicated by lower reliability towards bottom of graph

7.5.5 Timing of Risk Scenario Impacts

Impacts of the risk scenarios are not evenly distributed throughout the year. Because demands vary seasonally and peak in the summer months, most risk scenarios affect the ability to meet the current water supply planning policy criteria in the fall and winter months when storage is depleted and streamflow yields have declined. To demonstrate this seasonal distribution of risk, histograms were prepared for the average number of months in which demand shortages occurred in simulations for the Loss of Storage Scenario (a long-term risk scenario) and the Poudre River System- Acute Outage Scenario (a short-term risk scenario) for City Plan 3 demand and selected climate conditions.

Figure 7-31 shows the average distribution of the occurrence of demand shortages for selected climates under the Poudre River System Acute Outage Scenario. The figure reflects the count of demand shortages only; SRF shortages are not reflected in the figure. More detailed descriptions of the risk scenarios can be found in Appendix F. The three climates selected are wetter with no temperature increase (T=0 and P=+7%), current climate conditions (T=0 and P=0) and the most severe hot and dry climate (T=8 and P=-10%). Under wetter conditions, when the system is not stressed by climate, most shortages occur in the summer months of July, August and September. Comparing the wetter climate to the current conditions climate, August and September still stand out with the most shortages, but more shortages appear in all months relatively uniformly. In the most severe climate, only months of peak streamflow yield experience few shortages. This shows that climate has the largest effect on shortages in the fall and winter months, while the short-term risk itself causes shortages in the summer months even under a wet climate.

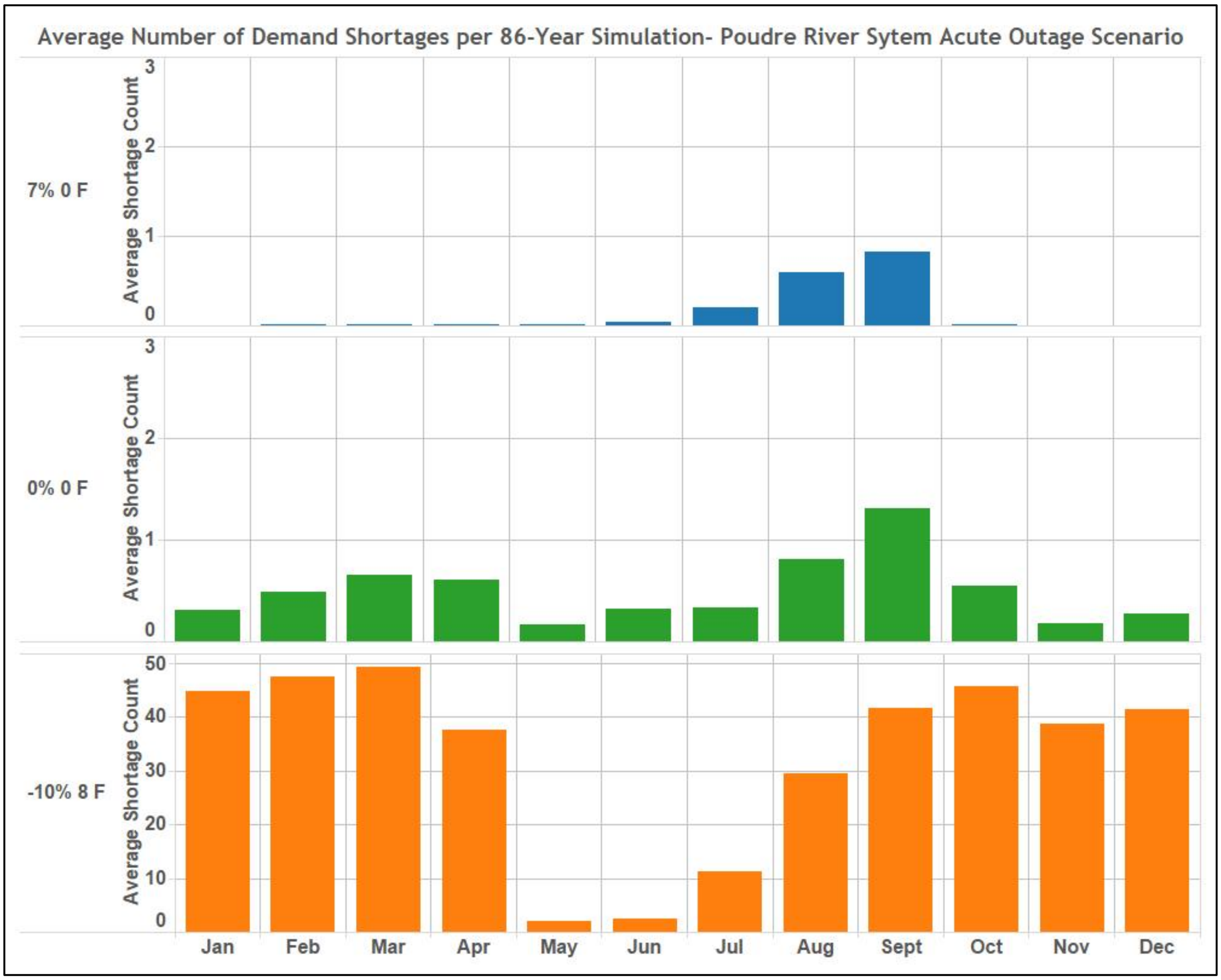


Figure 7-31 Average Monthly Distribution of Demand Shortages for Poudre River Acute Outage Scenario Under Selected Climates

Figure 7-32 shows the average distribution of the occurrence of demand shortages for selected climates under the Loss of Storage Scenario for the same three climates described above. The figure reflects the count of demand shortages only; SRF shortages are not reflected in the figure. The monthly distribution pattern is similar for the three climate conditions, with the direct runoff months of May and June being the only months when shortages rarely occur. More severe climates increase the number of shortages during the rest of the year but do not shift the seasonal occurrence of those shortages. This shows the extent of impact of not having sufficient storage to capture spring runoff for use until the next spring runoff occurs and show how that impact is more significant in warmer, drier climate conditions.

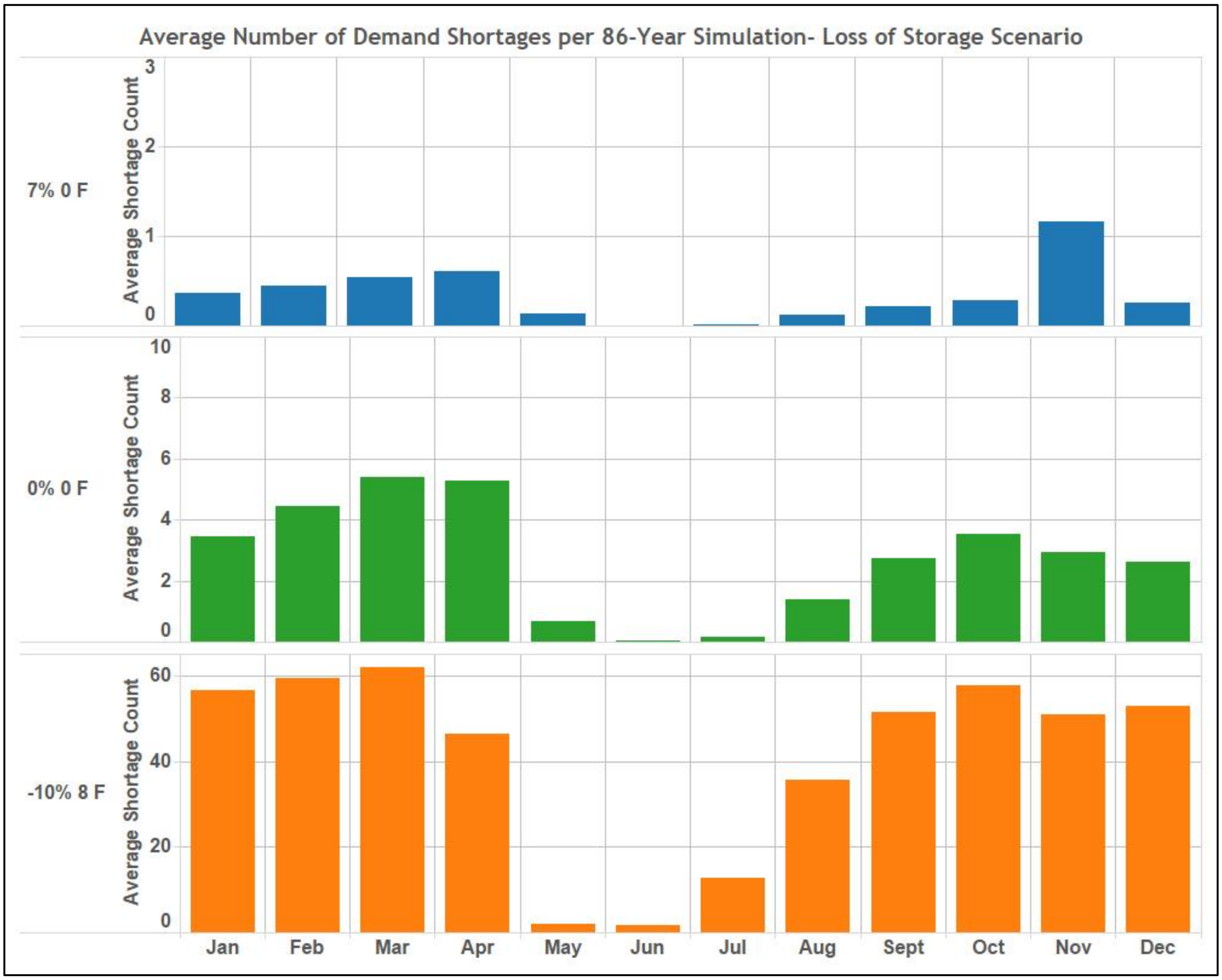


Figure 7-32 Average Monthly Distribution of Demand Shortages for Loss of Storage Scenario Under Selected Climates

7.5.6 Summary of Findings for Risk Scenarios

This section summarizes the primary findings from the analysis of the risk scenarios simulated for the WSVS.

- Climate is a critical driver for FCU system performance. Regardless of the scenario, future climate will have a dramatic effect on FCU system performance and the ability of FCU to meet all criteria of its current water supply planning policy. A hotter, drier climate would severely stress the current FCU water resources system with or without the occurrence of other system risks. It would reduce supply, increase demand, shift runoff earlier making existing reservoir storage less effective and trigger other potential environmental effects. In general, climate has a more significant effect on system performance than increased demand over the range of climate conditions and future demands simulated in the WSVS. The more severe climates may also have a more significant impact than any of the assumed risk scenarios at current climate conditions. As shown in **Figure 7-16**, the number of years with annual demand shortages ranges from 1 to 10 across all the risk scenarios at the current climate (T=0, P=0%); in contrast, the number of years with annual demand shortages ranges from 54 to 75 for the hottest, driest climate condition (T=8, P=-10%) and from 0 to 2 for the coolest, wettest climate condition (T=0, P=+15%). Thus, future climate conditions may be more impactful to FCU's ability to meet its water supply planning policy criteria than the occurrence of any particular infrastructure outage or environmental condition simulated in the WSVS risk scenarios.

- Water demands higher than those forecast in the City Plan 3 scenario represent a significant vulnerability to the current FCU system. This points out the importance of FCU maintaining its water conservation program and working with City Planning Department to closely monitor population and development density trends to see how they are tracking with City Plan assumptions. An increase in 2070 demands by 20% significantly increases shortages and incidence of failures to meet the water supply policy requiring 20% of average annual demand in storage at all times.

- The top risk scenarios representing vulnerabilities to the FCU system are:

    - **Elimination of the Reuse Plan**. Risks affecting viability of the reuse plan would reduce FCU's ability to make maximum use of its reusable water supplies, putting additional stress on local Poudre River water supplies and water from storage such that the system would be more susceptible to impacts of droughts and other reductions in supply.

    - **Loss of C-BT carryover storage and proposed Halligan Reservoir enlargement.** FCU has limited reservoir storage, so loss of these storage options would make it impossible for FCU to meet its current water supply planning policy criteria under most future climate and demand conditions. Storage is particularly important in meeting demands late in the year after runoff has declined, so loss of storage would increase the threat of fall and winter shortages.

- **Long-term reductions in C-BT imports due to shortages in the Colorado River system**. C-BT imports from the Colorado River Basin are a critical source of supply for FCU. A substantial reduction in the C-BT quota for 10 years would pose a significant threat to FCU's ability to meet its current water supply planning policy criteria. This risk is the most impactful to meeting indoor demands at wetter climates, indicating that even under less severe climate futures FCU is still vulnerable to long-term reductions in C-BT imports.

Based on the ranking of risks and uncertainties in Section 5.2 and 5.3, many of the most critical long-term or chronic risks were found to be unlikely; however, their impact was estimated to be significant. The WSVS risk scenario simulations validated that assumption.

The risk scenario simulations demonstrated the fundamental difference between long-term or chronic risks and short-term or acute risks. All the most impactful risks based on the metrics used in the WSVS are long-term risks. This is biased by the metrics themselves which, with the exception of the annual demand shortage metric, are always calculated over the entire 86-year simulation period. Thus, long-term risks that adversely affect system performance over the entire simulation period or for many years within the simulation period affect metric values more than short-term risks that occur for only a few months or years. Short-term risks such as an outage of the Poudre River pipelines or C-BT facilities can have extreme impacts on system performance for a short period but are masked by climate shifts that cause significant long-term impacts to performance. The effects of long-term risks are not as easily masked by the shifts in climate, as their impacts are also significant over several years or the entire simulation.

Figure 7-33 highlights the average annual shortage volume metric and **Figure 7-34** highlights the storage reserve metric for the five short-term risks simulated for the WSVS. These figures show that most of the short-term risk scenarios have very similar performance when measured by the WSVS metrics. This is particularly true for the 20% SRF metric. The two short-term Poudre River risk scenarios show a more pronounced response to wetter climate conditions for the average annual shortage metric than the other short-term risk scenarios. The frequency of shortages due to climate influence is reduced for wetter climates, and when shortages do occur for these risk scenarios their magnitude is quite large, resulting in a high average shortage volume metric value. In this case, instances of failure to satisfy the current water supply planning policy criteria would be brief but impacts could be significant without application of appropriate mitigation strategies.

Additional investigation may be warranted to develop different metrics that are useful in comparing performance of short-term risks to each other. Strategies for addressing short-term risks in a future water resources plan may differ from strategies addressing long-term risks; e.g., they may include short-term emergency operations that would be effective over a period of weeks or months but not for multiple years. Referring to the ranking of risks and uncertainties in Section 5.2 and 5.3, many of these short-term risks received relatively high composite scores (likelihood multiplied by impact), meaning they are of high concern to FCU staff and should be further assessed.

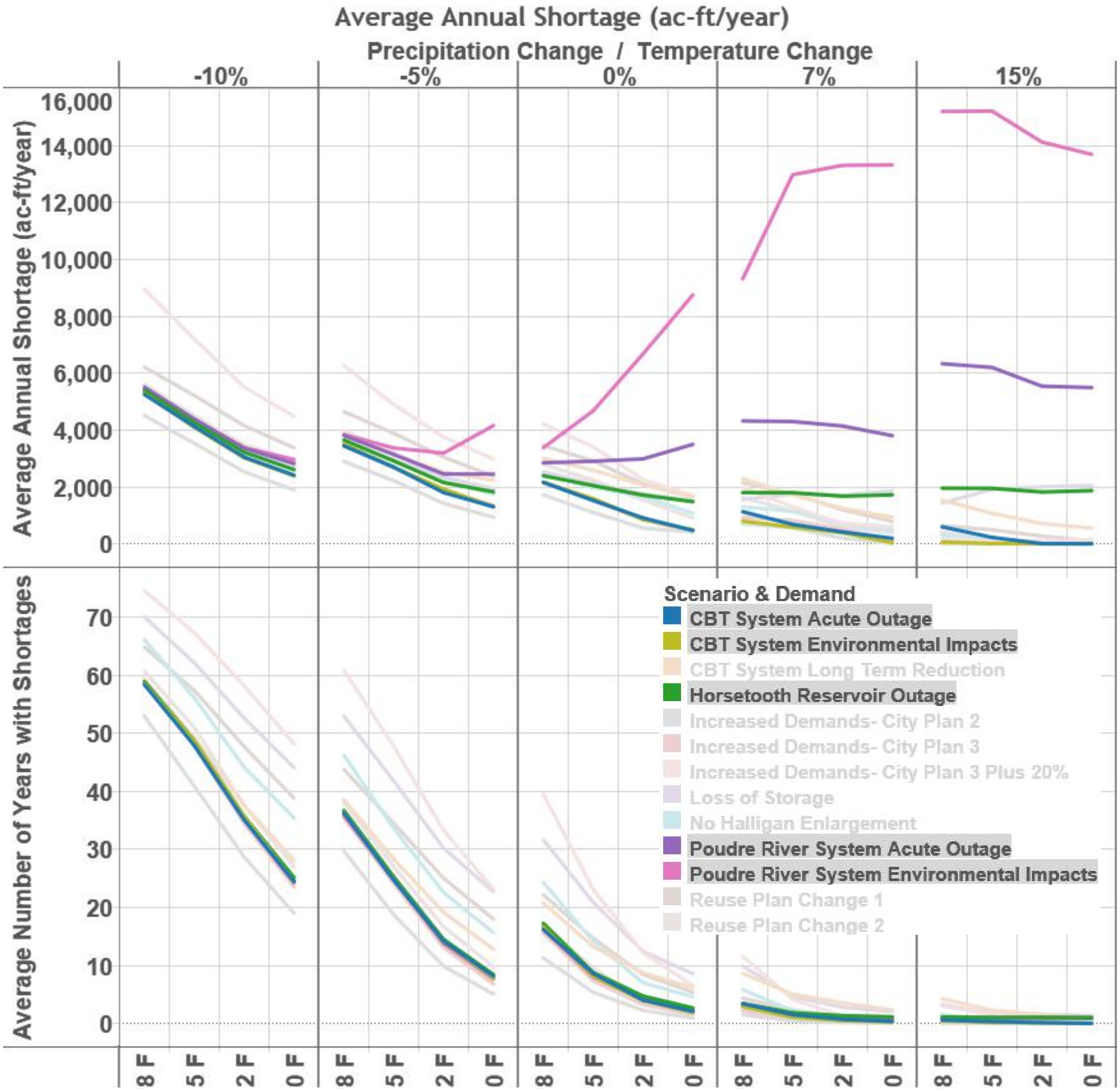


Figure 7-33 Average Annual Shortage Volume for Short Term Risks Compared to Long Term Risks

Note: Poorer performance indicated by greater shortage towards top of graph

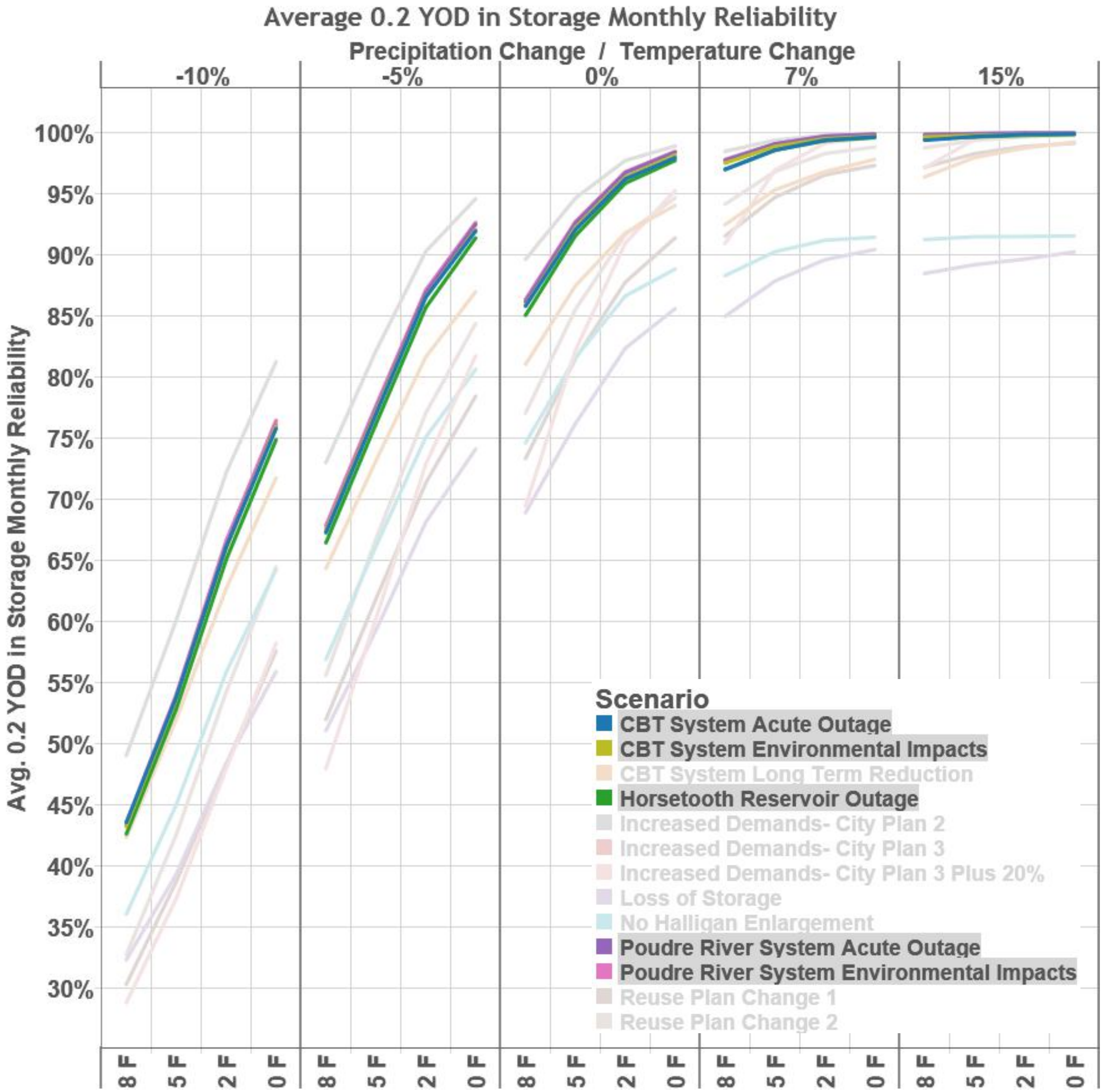


Figure 7-34 Reliability of Retaining 20% Storage Reserve for Short Term Risks Compared to Long Term Risks

Note: Poorer performance indicated by lower reliability towards bottom of graph

7.6 SUMMARY OF RISK SCENARIO RESULTS FOR SELECTED FUTURE CLIMATE CONDITION

FCU will use the results of the WSVS to update its Water Supply and Demand Management Policy. In the process of updating the policy, FCU may select a particular future climate condition or range of climate conditions to focus development of water supply alternatives. Mid-term planning could be based on a moderate climate future, such as T=5/P=0, while long-term planning may be based on a more severe climate future.

To show how the results of the WSVS could be used at that stage of water supply planning, results of the risk analysis are summarized below for the T=5/P=0 climate condition. These descriptions tie key metrics for this one possible climate condition to the current water supply planning policy.

- For the climate change risk alone (i.e., not combined with other risk scenarios), the chances of not meeting the 20% SRF would decrease from 84% of years to 67% of years when compared to current climate. Implementation of management measures such as water use restrictions would be required in about 33% of years compared to 16% of years for current climate conditions.
- For City Plan 2 and City Plan 3 demands in 2070, demand shortages would occur in about 8% of years; the 20% SRF would be met in 73% of years, and implementation of demand management or supply enhancement measures would be needed in about 27% of years. For City Plan 3 + 20% demands in 2070, shortages would occur in 27% of years; the 20% SRF target would be met in 50% of years; and implementation of demand management or supply enhancement measures would be needed in about 60% of years.
- Risk scenarios would reduce system performance such that shortages would occur in about 8% to 27% of years, depending on the risk scenario. The 20% SRF could be met between 1% and 76% of years over the range of risk scenarios. Most risk scenarios would force FCU to implement demand or supply management measures in the range of 25% to 36% of years. The Reuse Plan risk scenarios, scenarios involving loss of storage, and City Plan 3 + 20% demand scenarios cause higher risk of needing to implement management measures; water use restrictions or comparable options would be needed in 53% to 99% of years. Indoor demand shortages would occur in 6% to 21% of years across all risk scenarios, compared to 6% of years or less for the current climate across all risk scenarios.

Results indicate that even a moderate increase of 5 degrees in mean annual temperature with no change in mean annual precipitation has a significant adverse impact on the ability of FCU to meet customer demands as established in the water supply planning policy. At this climate, 2070 City Plan demands could be met in about 93% of years without implementing shortage management measures. Any of the system risks would require shortage management actions in anywhere from 29% of years to 99% of years based on the current water supply planning policy. Implementing water restrictions or other near-term strategies would probably not be enough to meet customers objectives under the current policy; new water supply projects would be needed to enhance supply.

8.0 CONCLUSIONS

The future is full of uncertainties. Fort Collins Utilities must make water supply planning decisions in the face of uncertain future water demand that is driven by complex demographic, economic and customer behavior factors; uncertain future hydrologic supply influenced by a climate that could be warmer and drier or warmer and wetter; and external risks to water supplies due to environmental influences and to infrastructure critical to the FCU water system. The WSVS provides FCU with an improved understanding of the most important risks and uncertainties to plan for in the future.

FCU's water system and water rights portfolio are well adapted to current climate conditions. With no change in average annual temperature or precipitation, the system performs well for the four metrics analyzed in this study (total demand shortage volume, reliability of maintaining a 20% storage reserve factor, reliability of not needing demand management measures like watering restrictions and reliability of meeting indoor demands).

However, once climate begins to shift towards hotter and drier conditions, the system performance begins to decline and the frequency with which FCU would have to implement demand management measures or access additional water supplies increases. Uncertain future hydrology is the most significant threat to FCU's future water supply, as global climate models have a wide range of predictions for the Poudre River and Upper Colorado River basins. Even the risk scenarios with the worst performance under current climate conditions perform better than a scenario with no system risks and an increase in temperature and decrease in precipitation. Thus, future climate conditions may be more impactful to FCU's ability to meet its water supply planning policy criteria than the occurrence of any particular infrastructure outage or environmental condition simulated in the WSVS risk scenarios.

Water demands higher than those forecast in the City Plan 3 scenario represent the next most significant vulnerability to the current FCU system. This points out the importance of FCU maintaining its water conservation program, and working with City Planning Department to closely monitor population and development density trends to see how they are tracking with City Plan assumptions. A 20% increase in the forecasted City Plan 3 demand due to increased population, large commercial users, expansion of the service territory, or other factors would stress supplies in all years and would be especially challenging in future hotter and drier climate conditions. The current FCU water supply would have to be enhanced or demand management measures would have to be implemented frequently to avoid shortages and to meet the 20% SRF goal.

Other risks found to have the largest impact on the FCU system performance are:

- Loss of storage, including no Halligan Reservoir enlargement; the FCU system is storage-limited so loss of any existing or proposed storage capacity has significant adverse effects.
- Reuse Plan changes, including elimination or 50% reduction in the amount of water incorporated in the Plan; the Reuse Plan is an efficient supply strategy that stretches current supplies, and losing all or part of it has compounding effects on FCU water supply.

- A long-term reduction in C-BT quotas due to C-BT supply or delivery infrastructure issues. C-BT supply is a critical part of FCU's water supply portfolio and reduction in that source over several years significantly impacts FCU's ability to meet its water supply planning policies.

Over the four metrics presented in this study, the above risks and risk scenarios show the poorest performance for current climate conditions and their performance is significantly reduced for the warmer and drier climates. These four risk scenarios create the greatest threats to meeting the current FCU water supply planning policy including frequent failures to meet total customer water demands, frequent failures to maintain the 20% storage reserve factor, and frequent years in which the current FCU water shortage response policy would call for implementation of water use restrictions or other emergency measures.

For most risk scenarios, shortages for climate conditions that are wetter than the current climate would occur most often in late summer and early fall. For warmer and drier climate conditions, shortages would occur throughout the year except in the peak runoff months of May and June. This shows the challenge of maintaining a resilient water resources system in the face of a warmer and drier climate with the limited amount of storage in the FCU raw water system.

Without the proposed Halligan Reservoir enlargement of 8,125 AF, FCU system performance would be significantly impacted and current water supply planning policy criteria could not be met under most future climate and demand conditions.

FCU may choose a moderate future climate condition as the focus for updating its water supply plan. If a future climate is chosen with 5-degree F warmer temperature and the same average annual precipitation, the following challenges would have to be addressed in meeting the current water supply planning policy.

- For City Plan 2 and City Plan 3 demands in 2070, demands shortages would occur in about 8% of years; the 20% SRF would be met in 73% of years, and implementation of demand management or supply enhancement measures would be needed in about 27% of years. For City Plan 3 + 20% demands in 2070, shortages would occur in 27% of years; the 20% SRF target would be met in 50% of years; and implementation of demand management or supply enhancement measures would be needed in about 60% of years.

- Most risk scenarios would force FCU to implement demand or supply management measures in the range of 25% to 36% of years. The Reuse Plan risk scenarios, scenarios involving loss of storage, and City Plan 3 + 20% demand scenarios cause higher risk of potentially needing to implement management measures; water use restrictions or comparable options would be needed in 53% to 99% of years.

- Indoor demand shortages would occur in 6% to 21% of years across all risk scenarios, compared to 6% of years or less for the current climate.

One approach to interpreting the WSVS results is to identify the risk scenarios that generate the greatest potential for failure to satisfy each of the current water supply planning policy criteria in 2070.

- **Total demand** (level of service target reliability = 100%). For warmer/drier climates, the most impactful risk scenarios are the City Plan + 20% demand and elimination of the Reuse Plan. For wetter climates, the most impactful risk scenarios are those that have short-term limitations on deliveries of Poudre River supplies.
- **20% storage reserve factor** (level of service target reliability = 100%). For warmer/drier climates, the most impactful risk scenarios are the City Plan + 20% demand and elimination of the Reuse Plan. For wetter climates, the most impactful risk scenarios are those that reduce storage, either through loss of C-BT carryover storage, loss of the ability to enlarge Halligan Reservoir as planned, or both. The FCU system has relatively little storage now, so loss of any current or proposed reservoir storage capacity significantly impacts the ability to meet this planning criteria.
- **Water use restrictions** (level of service target reliability = 100%; no restrictions or other emergency measures for the 1-in-50 drought). Loss of storage and elimination of the Reuse Plan are the most impactful risk scenarios in terms of creating conditions in which water use restrictions or some form of demand management or supply enhancement response would be required to prevent water shortages based on current water supply planning criteria.
- **Indoor demand shortages** (level of service target reliability = 100%). The City Plan 3 + 20% and Loss of Storage risk scenarios pose the greatest risk of not satisfying all indoor demands in 2070. For the warmest/driest climate, indoor demand reliability would be about 70% for these two risk scenarios; for current climate the indoor demand reliability for these scenarios would be about 90%; for the wettest climate the indoor demand reliability for these scenarios would be about 99.5%.

The risk scenario simulations demonstrated the fundamental difference between long-term or chronic risks and short-term or acute risks. Critical risks identified in the WSVS are long-term risks, impacting the FCU system for at least 10 years. However, many of the short-term risk scenarios may have a short-term, severe impact that was not fully captured in the metrics used in this study. The metrics are always calculated over the entire 86-year simulation period. Thus, long-term risks that adversely affect system performance over the entire simulation period or for many years within the simulation period affect metric values more than short-term risks that occur for only a few months or years. Short-term risks such as outage of the Poudre River pipelines or C-BT facilities can have extreme impacts on system performance for a short period, but this will not translate into a poor WSVS metric value when compared to the long-term risks in the study. Additional studies would be required to more closely analyze and rank the impacts of those short-term risks on the FCU water system.

FCU plans to use the results and conclusions of the WSVS as the foundation for updating its Water Supply and Demand Management Policy and its long-range water resources planning strategy. The following findings from the WSVS may be important as FCU contemplates the coming planning process.

- Climate change is the most important vulnerability faced by the FCU water supply system but it is the most difficult risk to track. Long-term trends are difficult to measure and are obscured by the natural variability in wet and dry years. Participating in or keeping informed of state and federal climate change studies will help FCU understand the trajectory of climate change in the region.

- Water demands higher than those forecast in the City Plan 3 scenario represent a significant vulnerability to the current FCU system. This points out the importance of FCU maintaining its water conservation program and working with City Planning Department to closely monitor population and development density trends to see how they are tracking with City Plan assumptions. Increased water demand is the risk over which FCU, in collaboration with City Planning, has the most control.
- The WSVS analysis was performed without simulating the effects of demand management measures that FCU could adopt under the City's current Water Supply Shortage Response Plan. Investigating benefits of the current shortage response policy should be a key aspect of the water supply plan update.
- The WSVS highlights the importance of storage in the FCU system and the significant vulnerability posed by the inability to implement the proposed Halligan Reservoir enlargement or a similar storage project as a strategy to mitigate effects of climate change and other risks.
- The WSVS validates that FCU is highly reliant on the C-BT system and is particularly susceptible to extended periods of low quotas and loss of the carryover storage program. FCU should monitor conditions that could trigger either of those risks.
- Results of the WSVS are biased toward long-term risks, but a number of short-term risks were identified that could severely impact FCU operations for a few weeks or months. These conditions will require further study and may involve a different management strategy in future water supply planning.
- FCU now has a water supply modeling tool that can be used to conduct more detailed analyses of the WSVS risk scenarios or explore a broader range of uncertainties or operating conditions if desired. It can also be used to measure and compare the effectiveness of alternative water supply system improvements.

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TECHNICAL APPENDICES

Appendix A LEVEL OF SERVICE GOALS AND METRICS TECHNICAL MEMORANDUM

Technical Memorandum

Level of Service Goals and Metrics

Date: June 12, 2018
From: Neil Stewart, Chip Paulson, Lisa Fardal
To: Fort Collins Utilities

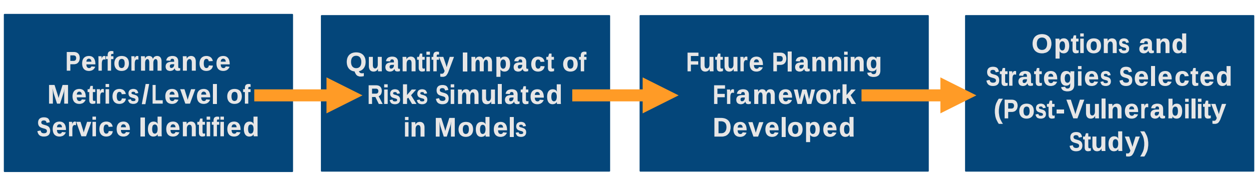
1.0 INTRODUCTION

The Fort Collins Utilities (FCU) Water Supply Vulnerability Study will explore a variety of future conditions related to climate, demands, and system risks with the goal of robustly assessing which of these future conditions present vulnerabilities for the FCU raw water system. The FCU water supply system model (FCM) will be used to simulate these many futures and is a key part of the study. As part of this process, the performance of the FCU system needs to be quantified using the FCM and then classified into satisfactory and unsatisfactory states. This will inform FCU on what future conditions create challenges for their water supply system.

There are two primary parameters needed to quantify satisfactory and unsatisfactory water supply system performance:

- *Performance Metrics* are specific measures characterizing the key features of a water supply system that are definable, measureable, representative, and unique. Examples of performance metrics could be maintaining a minimum volume of water in storage in July, years without customer restrictions, or use of Colorado-Big Thompson (CBT) supplies.
- *Level of Service (LOS)* goals are thresholds used to separate key performance metrics into satisfactory and unsatisfactory states. Examples of level of service goals could be triggering customer watering restrictions 5% of the time, or maintaining a volume of water equivalent to 1 year of demand in storage in 90% of Aprils.

The figure below shows how these performance metrics and level of service goals will be used in the Water Supply Vulnerability Study. First, they will be used to assess the impact of risks and uncertainties detailed in the *Risk Identification Technical Memorandum*. The outcome of that step will be identification of the risks and uncertainties to which the FCU system is most vulnerable. Then, these key risks and uncertainties will be used to develop future scenarios for use in the future planning framework. This future planning framework will then be used in a post-Vulnerability Study effort to evaluate options and develop future water supply strategies.



Ultimately, these performance metrics and LOS goals will be used to justify the conclusions of the Water Supply Vulnerability Study as well as the recommended options and strategies to FCU leadership and the public. Therefore, it is critical they capture how FCU assesses their own performance internally, as well as how external stakeholders and customers asses FCU's performance. This technical memorandum proposes the performance metrics and LOS goals for FCU's water supply system for these purposes.

2.0 BACKGROUND

The FCU Water Supply Vulnerability Study is a risk-based process using simulations of the FCU water resources system to evaluate system performance. In this type of plan, the definition of successful performance of the system is not pre-set (e.g. full demands are always met), but rather the model is allowed to operate the system freely and the results are used to inform what level of risk FCU is willing to take on in the future. In order to understand this risk, performance metrics and level of service goals must be established.

Prior water supply plans for FCU and throughout the water industry justified recommendations using the concept of firm yield, which assumes demands are met 100% of the time for a single future condition (e.g., one set of hydrology and one demand forecast). By moving away from firm yield and employing a suite of performance metrics, a risk-based approach can be used to develop recommendations around different hydrologic conditions, water demand, infrastructure reliability, and other factors. It also allows for multiple portfolios of water projects to be investigated to find those that are most effective across the widest variety of possible future conditions. In essence, this approach better answers the question "What level of performance can or should we afford?" by exploring the tradeoff between performance and cost of water supply improvements.

2.1 DEFINITIONS

As previously stated, there are two components to measuring system performance: performance metrics and LOS goals. Performance metrics are specific measures characterizing performance of key water supply system features (e.g. total storage, flow through a pipeline, yields from a watershed). Performance metrics are definable, measureable, representative, and unique within the FCM. Most importantly, performance metrics reflect how FCU staff measures and assesses water supply system performance.

Performance metrics are traditionally presented using the terms reliability, resilience, and vulnerability (RRV) but can also be calculated using statistical measures such as the mean, median, maximum, or minimum. The formal definitions of reliability, resilience, and vulnerability are:

- *Reliability* is the probability that the water supply system feature is in a satisfactory state, answering the question "how often".
- *Resilience* is the probability that a time period when the water supply system feature is in an unsatisfactory state is followed by a time period when the water supply system feature is in the satisfactory state, answering the question "how long".
- *Vulnerability* is the severity or magnitude of the unsatisfactory state for the water supply system feature, answering the question "how severe".

LOS goals separate values of key performance metrics into satisfactory and unsatisfactory states, ultimately justifying conclusions and/or recommendations from a water supply study. LOS goals are most effective when they reflect how water supply system performance is communicated to management and are in alignment with governing policy.

2.2 EXISTING MEASURES OF PERFORMANCE

Prior to this analysis, any current measures of water supply system performance adopted by Fort Collins Utilities were identified. The Water Supply and Demand Management Policy Report 2012 Update listed governing policy for various aspects of the FCU water system such as climate, water supply, conservation, and water quality. Of these, one was applicable to water supply reliability. This existing water supply reliability criterion has three components:

1. FCU will meet a planning level demand of 150 gpcd;
2. during at least a 1-in-50 year drought;
3. while maintaining 20% of annual demand in storage.

These components represent a current level of service goal, as futures that do not meet this condition are considered unsatisfactory. FCU has set policies around other aspects of water system operation as well, such as water use efficiency, water quality, and regional cooperation that could be considered when developing LOS goals and performance metrics.

3.0 PERFORMANCE METRICS

Performance metrics were identified during a workshop conducted with FCU staff and the consulting team. **Table 3.1** lists the identified performance metrics for the FCU water supply system that will be used for the Water Supply Vulnerability Study.

Table 3.1 - Identified performance metrics

	ID	Performance Metric	Description
Meeting Customer Demands	1	Minimum Met Annual Demand	The minimum annual demand met in acre-ft/year across a simulation
	2	Meeting Indoor Demands	The RRV of meeting indoor demands across a simulation
	3	Meeting Reduced Demands	The RRV of meeting demands after they have been reduced by restrictions
	4	Annual Response Level 1 Restrictions	The R&R of when customers are in Response Level 1 restrictions across a simulation
	5	Annual Response Level 2 Restrictions	The R&R of when customers are in Response Level 2 restrictions across a simulation
	6	Annual Response Level 3 Restrictions	The R&R of when customers are in Response Level 3 restrictions across a simulation
	7	Annual Response Level 4 Restrictions	The R&R of when customers are in Response Level 4 restrictions across a simulation
Maintaining Supply in Storage	8	0.1-Year of Demand in System Storage	The RRV of maintaining 0.1-Year of Demand in Storage at all times during a simulation
	9	0.2-Year of Demand in System Storage	The RRV of maintaining 0.2-Year of Demand in Storage at all times during a simulation
	10	0.3-Year of Demand in System Storage	The RRV of maintaining 0.3-Year of Demand in Storage at all times during a simulation
	11	0.4 Year of Demand in System Storage	The RRV of maintaining 0.4-Year of Demand in Storage at all times during a simulation
	12	0.5 Year of Demand in System Storage	The RRV of maintaining 0.5-Year of Demand in Storage at all times during a simulation
	13	0.6 Year of Demand in System Storage	The RRV of maintaining 0.6-Year of Demand in Storage at all times during a simulation
	14	0.7 Year of Demand in System Storage	The RRV of maintaining 0.7-Year of Demand in Storage at all times during a simulation
	15	0.8 Year of Demand in System Storage	The RRV of maintaining 0.8-Year of Demand in Storage at all times during a simulation
	16	0.9 Year of Demand in System Storage	The RRV of maintaining 0.9-Year of Demand in Storage at all times during a simulation
	17	1.0 Year of Demand in System Storage	The RRV of maintaining 1.0-Year of Demand in Storage at all times during a simulation
	18	Minimum Storage – YOD	Minimum YOD storage volume during a simulation
	19	Minimum Storage – acre-feet	Minimum acre-foot storage volume during a simulation
Operational	20	Lost Water Due to Water Quality Requirement	Statistical quantifications (average, max, count) of annual volume of water lost due to water quality blending requirements
	21	Lost Water Due to Insufficient Storage	Statistical quantifications (average, max, count) of annual volume of useable water lost due to insufficient storage capacity
	22	Meeting Reusable Demands	The RRV of meeting reusable demands

R&R is Reliability and Resilience
RRV is Reliability, Resilience, and Vulnerability

Seven performance metrics were identified that capture the ability of the water supply system to meet customer demands. FCU has an adopted Water Supply Shortage Response Plan that specifies how FCU will restrict customer water use during periods of water shortage, typically observed during droughts. This Water Supply Shortage Response Plan specifies four response levels, summarized in **Table 3.2**, that are determined based on water supply shortage. Water supply shortage, for this purpose, is the difference between forecasted demand and forecasted supply prior to runoff season. A performance metric was specified for the reliability and resilience of each of these response levels. The RRV of meeting demands after they have been reduced by restrictions will also be a performance metric. The RRV of always meeting FCU indoor demands is another demand-based performance metric, as inability to meet all indoor customer demands represents a critical system failure. Finally, the minimum met annual demand was identified as a performance metric as FCU governing policy specifies a minimum gallons per-capita-day demand that must be met by the water supply system.

Table 3.2 - Water Supply Shortage Response Plan elements

Response Level One	Enacted when water supply shortage is less than 10%. Outdoor irrigation allowed only two days per week.
Response Level Two	Enacted when water supply shortage is between 11% and 20%. Outdoor irrigation allowed only one day per week.
Response Level Three	Enacted when water supply shortage is between 21% and 30%. Outdoor irrigation allowed only one day per week with a 2-hour time limit on watering.
Response Level Four	Enacted when water supply shortage is greater than 30%. No outdoor irrigation allowed

Twelve performance metrics were identified related to water supply system storage. These performance metrics quantify the RRV of maintaining a certain volume of water in storage at all times, with storage volumes represented as percentages of years of annual demand (YOD). Quantifying the RRV of maintaining increasing volumes of storage in the water supply system is important as storage is the primary way FCU can reduce the risk of major customer impacts during emergency conditions (e.g. natural disasters, unplanned outages, wildfires). Storage volumes from 10% to 100% of annual demand in 10% increments will be quantified using RRV performance metrics. Additionally, the minimum storage across a simulation (reported out both in acre-feet values and YOD) will be tracked to ensure governing policy is met.

Three performance metrics were identified that capture operational goals. The first quantifies statistically the volume of water lost due to water quality blending requirements. FCU's current system is operated by blending water supply sources to meet a minimum level of water quality prior to treatment. This operational requirement occasionally results in water that cannot be used because there is insufficient high-quality water to blend with and the treatment plants do not have the ability to treat water from the available sources. Another quantifies statistically the volume of water lost due to demands being less than supply and available storage being insufficient to make up the difference. The final metric quantifies the RRV that FCU's water supply system can meet the reusable demands as laid out in the Reuse Plan. If FCU is unable to meet these demands, it could result in violation of this contract and a reduction of supplies available to FCU.

Overall, 20 performance metrics were identified by FCU staff that capture a variety of features of the water supply system. These performance metrics will be calculated for every simulation completed per the process described in Section 5.0.

4.0 LEVEL OF SERVICE GOALS

The performance metrics described in Section 3.0 were evaluated to determine which are applicable as level of service goals and what the thresholds for level of service are. Seven performance metrics were included as level of service goals, which are shown in **Table 4.1**. Level of service goals were selected to align with FCU governing policy.

The selected level service goals are primarily customer-facing, such that futures that significantly impact customers will be considered unsatisfactory. Any future for which indoor demands are not always met will be unsatisfactory. FCU accepts future conditions where customers are in any type of water restriction every 1 in 10 years (90% reliability) with more impactful restraints occurring less frequently. To comply with governing policy, at least 20% of annual demand must be maintained in storage at all times for a future to be considered satisfactory. Finally, all reusable demands must be met 100% of the time[1].

Table 4.1 - Selected Level of Service Goals

ID	Performance Metric	Level of Service Goal	Justification
2	Meeting Indoor Demands	100% Reliability	Governing policy, greatest customers impact
4	Annual Response Level 1 Restrictions	1 in 10 Years (90% Reliability)	Perceived customer risk tolerance
5	Annual Response Level 2 Restrictions	1 in 25 Years (96% Reliability)	Perceived customer risk tolerance
6	Annual Response Level 3 Restrictions	1 in 100 Years (99% Reliability)	Perceived customer risk tolerance
7	Annual Response Level 4 Restrictions	1 in 500 Years (99.8% Reliability)	Perceived customer risk tolerance
9	0.2-Year of Demand in System Storage	100% Reliability	Governing policy
20	Meeting Reusable Demands[1]	100% Reliability	Reuse Plan Agreement

These LOS goals will be used in the Water Vulnerability Study to separate futures for which water supply system performance is satisfactory from those for which it is unsatisfactory. However, these LOS goals are a policy decision, and one potential water resources strategy is to change the LOS goals or thresholds to take on more risk. For example, FCU could lower the storage requirement from 0.2 to 0.1 years of demand in storage with 100% reliability, thereby improving performance (relative to the relaxed objective) but increasing the risk that sufficient water would not be available during an emergency. This question will be addressed as part of a later study.

[1] The reuseable demand level of service goal is still in development, this TM will be updated accordingly when this level of service goal is determined.

5.0 MODELING IMPLEMENTATION

The identified performance metrics from Section 3.0 will be incorporated into the FCM data management system (DMS). Each simulation completed will have the corresponding performance metrics automatically calculated, tracked, and stored in the central database. **Table 5.1** summarizes the procedure for calculating these performance metrics. With the exception of the Minimum Storage metric, all performance metrics will be calculated monthly but reported annually. An example of this, using the “0.5 YOD in System Storage” metric, the total system storage will be calculated at the end of each month during a simulation. If any months during a water year have total system storage below 0.5 YOD, then the water year will be noted as a failure. The resulting performance metric value will be the percent of simulated water years in which any month had total system storage below 0.5 YOD. The “Lost Water Due to Water Quality Requirement” performance metric will sum the lost water across a water year, then apply the corresponding statistical measure.

Table 5.1 - Implementation of Metrics in FCM and DMS

ID	Performance Metric	Calculation(s)	Representative FCM Object
1	Minimum Met Annual Demand	Minimum	CityDem, LCUsu, LCUwc
2	Meeting Indoor Demands	RRV	LCUsu, LCUwc +Pre-processing for CityDem or change in model to reflect indoor + outdoor split
3	Meeting Reduced Demands	R&R	LCUsu, LCUwc, CityDem
4	Annual Response Level 1 Restrictions	R&R	0-10% shortage (projected + shortage reserve factor, triggers for time period. What is quota today (yield/shares), snowpack today (streamflow today) – maybe look at future inflow over next 6 months.
5	Annual Response Level 2 Restrictions	R&R	Same as 4, but for 10-20% shortage
6	Annual Response Level 3 Restrictions	R&R	Same as 4, but for 20-30% shortage
7	Annual Response Level 4 Restrictions	R&R	Same as 4, but for >30% shortage
8	0.1-Year of Demand in System Storage	RRV	Carryover StoRight (only if carryover is on), Horsetooth StoRight, Halligan StoRight, JoeWright StoRight
9	0.2-Year of Demand in System Storage	RRV	
10	0.3-Year of Demand in System Storage	RRV	
11	0.4 Year of Demand in System Storage	RRV	
12	0.5 Year of Demand in System Storage	RRV	
13	0.6 Year of Demand in System Storage	RRV	
14	0.7 Year of Demand in System Storage	RRV	
15	0.8 Year of Demand in System Storage	RRV	
16	0.9 Year of Demand in System Storage	RRV	
17	1.0 Year of Demand in System Storage	RRV	
18/19	Minimum Storage (acre-feet and YOD)	Minimum	
20	Lost Water Due to Water Quality Requirement	Non-zero Average, Frequency, Maximum	Poudre Avail – HT used – Reuse Plan Reqts, limited to max of HT used + Reuse Plan. Post processing calculation
21	Lost Water Due to Insufficient Storage	Non-zero Average, Frequency, Maximum	In Development
22/23	Meeting Reusable Demands	RRV	LCUwc[2]

R&R is Reliability and Resilience

RRV is Reliability, Resilience, and Vulnerability

[2] The reuseable demand FCM implementation is still in development, this TM will be updated accordingly when this FCM implementation is determined.

6.0 SUMMARY

As part of the FCU Water Supply Vulnerability study, performance metrics and LOS goals were identified for implementation in the FCM and DMS. FCU staff identified 20 performance metrics that capture a variety of demand, storage, and operational measures. Of these 20, eight performance metrics were identified for use as LOS goals. These LOS goals and performance metrics will be used to both asses the vulnerability of the water supply system to future conditions as well as ultimately compare different potential options or strategies for addressing the vulnerabilities.

Appendix B WATER SUPPLY SYSTEM RISKS IDENTIFICATION TECHNICAL MEMORANDUM

Technical Memorandum

Water Vulnerability Study

Water Supply System Risks Identification

Date: May 8, 2018

From: Neil Stewart, Chip Paulson, Lisa Fardal

To: Fort Collins Utilities

1.0 INTRODUCTION

The Fort Collins Utilities (FCU) water supply system spans many watersheds and is comprised of a variety of infrastructure components, some owned and operated by FCU and some owned and operated by other entities. In this past, aspects of this system have been compromised by various events or conditions that impacted FCU's ability to meet customer needs. These events and conditions that have occurred before, as well as emerging ones, will continue to threaten FCU's water supply system in the future.

As part of the Fort Collins Water Vulnerability Study, a future planning framework is being developed that FCU will use to develop a robust plan to meet level of service goals in an uncertain future. This framework will include planning for events and conditions that could negatively impact Fort Collins' water supply system and its ability to meet customer needs.

Therefore, a key element of the Water Vulnerability Study is identification of future risks and uncertainties to be included in FCU's overall water supply planning process. The figure below shows how the information presented in this technical memorandum (TM) fits within the larger Water Vulnerability Study. The TM summarizes the identified risks and uncertainties, the process used to prioritize them, and how the prioritized risks were simulated in the Fort Collins water resources modeling system. Later analysis will develop the future planning framework and a separate study will be conducted to evaluate these options and strategies.

The purpose of the risk and uncertainty assessment was to look out 50 years and forecast events that could adversely affect FCU water supplies or infrastructure. The 50-year timeframe is the period adopted for the Water Vulnerability Study. It is recognized that anticipating conditions that may exist 50 years in the future is highly speculative. However, for purposes of the Water Vulnerability Study it is appropriate to investigate a broad range of possible future conditions to determine which conditions would stress the performance of the current water supply system.

The areal scope of the Water Vulnerability Study includes source water areas and infrastructure upstream of the FCU water treatment plant. In addition to local Poudre River Basin supplies, the scope includes supply derived from the Colorado-Big Thompson (C-BT) Project, operated by the U.S. Bureau of Reclamation (Bureau) and the Northern Colorado Water Conservancy District (Northern). Therefore risks and uncertainties were identified by both FCU staff and Northern staff. These were two separate processes, as described later in this TM.

Identified risks and uncertainties were organized in the following categories that span the various aspects of the FCU water supply system:

- ***Climate and Hydrology*** risks relate to weather variability and other hydrologic factors, both short- and long-term, that can impact the potential yields from a watershed.
- ***Watershed*** risks relate to physical watershed conditions that can impact the yields available to FCU.
- ***Operational and Infrastructure*** risks relate to how FCU delivers physically and legally available water to its treatment facilities.
- ***Administrative and Legal*** risks relate to conditions, regulations, or policies that could impact the legal allocation or availability of water supplies.
- ***Demand*** risks relate to changes in required volume, timing, and quality of water that will need to be delivered to water treatment facilities to meet customer needs

These identified risks were then scored as part of the prioritization process. Individual risks were scored by assigning a 1-5 score for likelihood (possibility of the risk or uncertainty occurring) and impact (consequences to the FCU/C-BT water supply system if the risk or uncertainty were to occur) according to the definitions below. The composite score (likelihood times impact) was then used to help prioritize risks.

Score	Likelihood Definition	Impact Definition
1	***Rare*** – the risk will only occur in exceptional circumstances.	***Insignificant*** – If the risk occurs the impact to the water supply system would be negligible.
2	***Unlikely*** – the risk will occur in occasional circumstances.	***Minor*** – If the risk occurs the impact to the water supply system would be minimal.
3	***Possible*** – the risk will occur in some circumstances.	***Moderate*** – If the risk occurs there would be a noticeable impact to the water supply system.
4	***Likely*** – the risk will occur in a majority of circumstances.	***Major*** – If the risk occurs there would be substantial impact to the water supply system.
5	***Almost Certain*** – the risk will occur in almost all circumstances or is imminent.	***Extreme*** – If the risk occurs there would be extensive or catastrophic impact to the water supply system or customers.

2.0 FORT COLLINS UTILITIES' WATER SUPPLY SYSTEM RISKS

Risks and uncertainties to the FCU water supply system were identified by staff members representing a variety of groups within the organization during a half-day workshop. Workshop attendees included representatives from water supply, water treatment, demand and conservation, watershed management, legal, and water operations groups. These same staff members scored the risks as a group using the rubric described in Section 1.0 based on their perceptions and professional judgment. The adopted score was the consensus of the workshop participants. Therefore, results of the scoring process are presented as a *perceived* threat to the water supply system, as the actual impact to the water supply system will be quantified using simulation later in the Water Vulnerability Study. This section summarizes all risks and uncertainties identified and then describes how these identified risks and uncertainties were prioritized for simulation.

2.1 SUMMARY OF ALL RISKS

Identified risks and uncertainties are summarized around five categories that represent different aspects of a water supply system: Climate and Hydrology, Watershed, Operations and Infrastructure, Legal and Administrative, and Demand.

2.1.1 Climate and Hydrology Risks

Table 2.1 lists the five risks and uncertainties associated with the climate and hydrology in the watersheds contributing to the FCU water supply system. For purposes of this evaluation, climate change assumptions in the Fort Collins region and water source areas were based on general findings of past climate change studies for Colorado and the Front Range region. These studies suggest future climate will be characterized by increased temperature; however, the impact on precipitation is unclear as it may increase or decrease.

- C1 - Longer duration droughts (e.g. multiple years with below average yields or back-to-back severe droughts) are perceived as the biggest threat to FCU's water supply system as these types of droughts can occur under the current climate, but would also be exacerbated under climate change or conditions of increased climate variability as seen in paleohydrology data pre-dating the period of observed records.

- C2 - Change in runoff timing (peak runoff occurring earlier and/or over a shorter period of time) is predicted by climate change studies for Colorado, and was perceived as a high threat due to a combination of limited storage in FCU's system, capacities of diversion systems, and highly specific timing of certain decreed water rights. Less runoff would be captured when higher peaks occur because more flow would exceed the diversion structure capacity and bypass the diversion. Limited storage space makes it more difficult to meet demands late in the season during dry years when runoff has subsided earlier than historically. Finally, certain water right decrees for FCU only allow diversions within fixed periods early in the runoff season, and these decrees would yield less water in the future than they do currently if runoff begins earlier and occurs outside of the allowable diversion window.

- C3 - One anticipated impact of warmer temperatures due to climate change in the study area would be a shift in precipitation type to more rainfall and less snow. A change in precipitation type was perceived as a high threat as the “snowpack reservoir” would be reduced and FCU would be unable to compensate for that in their system due to a lack of storage.

- C4 – Another anticipated impact of climate change in the study area is a change in the frequency and magnitude of precipitation events. Precipitation events could be less frequent, but more intense when they do occur, such as the September 2013 event. This increases the risk of flooding.

- C5 - A longer growing season due to warmer temperatures was not perceived as a significant threat from a hydrology perspective because agricultural users in the Poudre River Basin already use their full decreed water rights. Additionally, research shows a warming climate may actually reduce agricultural productivity (and hence water use) due to increased heat stress on plants. An analysis conducted by FCU concluded that their system is not sensitive to changing agricultural demands.

Table 2.1 – Identified Climate and Hydrology Risks and Uncertainties

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score
C1	Longer duration droughts	Multi-year and/or more severe droughts occur in the future that are not captured in the observed record.	5	4	20
C2	Changes in runoff timing	Early higher runoff and lower late-season baseflow reduces yield from volumetric decrees that list specific diversion dates.	4	4	16
C3	Change in precipitation type	More precipitation falls as rain instead of snow during the Fall and Spring.	4	4	16
C4	Changes in frequency/ magnitude of precipitation events	Precipitation events, particularly summer rainstorms, become less frequent and more intense.	4	4	16
C5	Longer growing season	Warmer climate increases growing season in Spring and Fall, changing potential water rights calls and increasing irrigation demand.	4	2	8

2.1.2 Watershed Risks

Table 2.2 lists the seven risks and uncertainties identified that would impact the watershed aspect (i.e., source water areas) of the FCU water supply system.

- W1 - Wildfires were perceived as the most significant threat to watersheds due to their broad impacts and increased likelihood in a warmer climate. In the short term wildfires have significant water quality impacts that could render yields from a particular watershed untreatable, and could cause an increase in sediment loads that would impact diversions or other conveyance systems. In the longer-term, water quality impacts would persist and may require upgrades to water treatment plants, and hydrograph changes would be persistent until the vegetation recovers.

- W2 - Forest health degradation was also perceived as a high threat to watersheds. In the future, one of the primary causes of forest health degradation is expected to be pine beetle kill and impacts of other similar pests as warmer temperatures allow for infestations to impact broader areas of forest. Other potential causes could be warmer temperatures and more frequent droughts which would stress vegetation more significantly. Regardless of the cause, reduced forest health would cause changes to the hydrograph, increased sedimentation, and lower water quality. These impacts would occur slowly over many years; however, their impacts would be difficult to effectively mitigate. Additionally, degraded forest health would increase the risk of wildfires. The uncertainty of the impact of forest health on FCU water supplies is amplified by the fact that 90% of forests in source watersheds are managed by the Federal Government and thus, are outside Fort Collins' control.

- W3 - Development in watersheds such as expanded communities, denser development, oil and gas development, mining, and new road construction was perceived as a moderate threat to watersheds. These activities could cause both long-term impacts, such as reduced water quality due to road traffic and more septic systems, and short-term impacts, such as contamination events due to spills or vehicle accidents. The pressure for these kinds of development in the FCU contributing watersheds is currently relatively modest, largely because there is limited land available for development and most of the watershed is owned and managed by natural resource agencies as described above.

- W4 - Increased atmospheric deposition of particulates and pollutants within FCU watersheds is a possible outcome of a drier climate due to changes in vegetation land cover in the Western U.S. This trend has already been observed in Colorado's mountains. Increased atmospheric deposition was perceived as a moderate threat due to the potential for the emergence of new water quality issues in previously pristine high-alpine bodies of water and streams, such as algal blooms or long-term diminished water quality.

The remaining risks and uncertainties listed in **Table 2.2** were not perceived as significant threats to the water supply derived from the FCU source water watersheds.

Table 2.2 - Identified Watershed Risks and Uncertainties

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score
W1	Wildfires	Wildfires occur, causing a variety of impacts on water quality, runoff, and threats to infrastructure.	5	4	20
W2	Forest Health Degradation	Forested area health decreases due to beetle kill, pollution, warming climate, etc.	4	4	16
W3	Development in Watersheds	Land development in watersheds (recreation, residential, O&G, mining) increases risk of water quality contamination.	4	3	12
W4	Atmospheric Deposition	Increased levels of contaminants in bodies of water and forests lead to new water quality issues.	5	2	10
W5	Deficiencies in Federal land Management	Federally owned land, which comprises nearly all of the watersheds, is poorly managed against wildfires or to promote forest health.	2	3	6
W6	Abandoned Mine Runoff	Runoff from abandoned mines leads to decreased water quality. Few mines exist in FCU watersheds.	1	4	4
W7	Privatization of Public Lands	Lands owned by the federal government are transferred to private entities, increasing development potential.	1	4	4

2.1.3 Operations and Infrastructure Risks

Table 2.3 lists the 16 risks and uncertainties identified that would impact the operations and infrastructure aspect of the FCU water supply system.

- O1 and O2 - An outage of either the 24-inch or 27-inch raw water delivery pipelines from the Poudre River were perceived as an extreme threat to the water supply system. Without one of these pipelines, FCU would have limited capacity to convey Poudre River supply to its Soldier Canyon water treatment plant. The pipelines are in high risk zones for landslides and some sections are underneath the river, which in the event of a major flood could expose the pipelines or fill them with sediment. Some pipeline segments are extremely hard to access, making repairs costly and time-intensive.

- O3 - Algal blooms were also perceived as a significant threat to the water supply system. FCU has experienced problems with algal blooms in its source water in the past, and a warmer future climate would increase the likelihood of these events. Algae outbreaks could have a minor impact of causing maintenance issues in impacted reservoirs or river reaches, potentially affecting operations. More significantly, large algal blooms in reservoirs could have severe impacts to water quality that FCU's water treatment plant would currently be unable to treat. Therefore, in these events, FCU would be unable to use the impacted supply during high risk months (approximately June to October). Horsetooth Reservoir is the most vulnerable storage facility, supplying water to the FCU system, to this type of algal bloom impact.

- O4, O5, and O6 - Three infrastructure outages were perceived as high threats to the water supply system: Michigan Ditch, Horsetooth Reservoir Intake, and Chambers Reservoir. Without Michigan Ditch, FCU cannot convey transmountain supply to its Front Range collection system. Without the Horsetooth Reservoir intake, FCU cannot utilize its Colorado-Big Thompson (CBT) shares stored in Horsetooth Reservoir. There is currently no system redundancy for delivering FCU water from Horsetooth Reservoir. Finally, most FCU water supplies are generated above Chambers Reservoir but must pass through the reservoir before reaching FCU's diversion facilities. Chambers Reservoir is not owned by FCU and is at a higher risk of failure due to the potential for underfunded maintenance which may result in sudden operational changes that impact FCU.

The remaining risks were not perceived as significant threats. However, some of the remaining risks are low likelihood (score of 1 or 2) and high impact (score of 4 or 5). These risks, which could have significant impact if they were to occur, were further evaluated when risks were prioritized; this is discussed in Section 2.2.

Table 2.3 - Identified Operations and Infrastructure Risks and Uncertainties

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score
O1	Outage - 24 Pipeline	Short term outage due to flooding, landslides, wildfire, etc.	5	5	25
O2	Outage - 27 Pipeline	Short term outage due to flooding, landslides, wildfire, etc.	5	5	25
O3	Algal Blooms	Algal blooms in storage reservoirs and rivers increases water quality issues and potential treatment problems.	5	4	20
O4	Outage - Michigan Ditch	Short term outage due to flooding, landslides, wildfire, etc.	5	3	15
O5	Outage - Horsetooth Reservoir Outlet	Short term outage of reservoir outlet and intake to WTP; higher risk due to lack of redundancy.	3	5	15
O6	Outage - Chambers Reservoir	Short term outage due to flooding, landslides, wildfire, etc.	3	4	12
O7	Outage - Munroe Canal	Short term outage due to flooding, landslides, wildfire, etc.	3	3	9
O8	Outage - Joe Wright Reservoir	Short term outage due to flooding, landslides, wildfire, etc.	2	4	8
O9	Shared infrastructure - Chambers Reservoir	Lack of control of operations could lead to issues with delivering water.	2	4	8
O10	Outage - Meadow Creek Reservoir	Short term outage due to flooding, landslides, wildfire, etc.	3	2	6
O11	Outage - Pleasant Valley Pipeline	Short term outage due to flooding, landslides, wildfire, etc.	1	4	4
O12	Shared infrastructure - Munroe Canal	Lack of control of operations could lead to issues with delivering water.	1	4	4
O13	Shared infrastructure - Pleasant Valley Pipeline	Lack of control of operations could lead to issues with delivering water.	1	4	4
O14	Sediment Loading - Reservoirs	Loss of capacity in reservoirs due to increased sediment loads.	3	1	3
O15	Freeze/Thaw Cycles	Initial freezing stages impact water quality, ice coming down the river could impact operations.	3	1	3
O16	Shared infrastructure - Meadow Creek Reservoir	Lack of control of operations could lead to issues with delivering water.	1	1	1

2.1.4 Legal and Administrative Risks

Table 2.4 lists the eight risks and uncertainties identified that would be associated with the legal and administrative aspects of the FCU water supply system.

- A1 - New regulations, including both water quality and environmental regulations, were perceived as a significant risk. New or more stringent water quality standards or environmental permitting requirements could affect FCU water resources in several different ways. For example, new environmental regulations calling for increases or changes to environmental flows in the Poudre River watershed would need to be made up from existing water uses, which could impact the yields available to FCU. New water quality regulations could preclude use of existing water sources without additional treatment and may limit FCU's ability to blend Poudre River water with CBT water, impacting operations. More stringent permitting requirements could make it more difficult to develop new water supplies, including transfer of agricultural water rights.

- A2 - Increased demands by other water users in the Poudre River basin were perceived as a high threat to the water supply system. Regional water demands could increase either through new urban development or through changes in agricultural crop selection or irrigation practices. This risk could be manifested both as an increase in competition for new water rights and supplies as well as increasing use of existing water rights which could impact the yields available to FCU. Also, since FCU shares much of its water collection and storage infrastructure with other entities, other users may have conflicting operational objectives which may impact yields to FCU.

- A4 - Another potential future condition perceived as a significant risk to the water supply system was a change in state administration of water rights. Since water rights are based on an assumed hydrology, and that hydrology may change in response to climate variability, the way Colorado administers water rights under the prior appropriation doctrine could change. For example, assumed shrink values for conveying water through specific river reaches may increase to account for greater losses, resulting in lower yields for FCU. Also, when water rights are transferred, the adjudicated yield from those rights may be reduced by the state, impacting the yield FCU receives from future water rights.

- A9 – The Reuse Plan, which results in FCU receiving 1,900 acre-feet of firm supply, relies on the continued operation of the Rawhide Energy Station, owned and operated by Platter River Power Authority (PRPA). In the future if PRPA no longer requires Rawhide Energy Station and takes it offline, this will end the Reuse Plan and remove the corresponding 1,900 acre-feet of firm supply from FCU's water supply portfolio. Also in multi-year drought events, the yields from the Reuse Plan are reduced and or eliminated, impacting FCU's water supply portfolio.

- A3 - Since FCU receives a significant amount of yield from the CBT project and the operation of its system is designed around how Northern operates this system, changes to that operation are perceived as a risk to FCU. One possible trigger for this change would be a continuation of the recent trend of a toward more municipal CBT ownership and less agricultural ownership. This could affect the Northern Board's process for setting the annual CBT quota, which determines how much CBT water is available to FCU and other CBT allottees. Additionally, the current Carryover Program or Regional Pool Program, which offers more flexibility to municipal CTP share owners in how they manage their water resources, could change or be eliminated by future Northern Boards. Any of these CBT changes could impact FCU operations.

The remaining risks and uncertainties in **Table 2.4** were not perceived as being a significant threat to FCU water supply system.

Table 2.4 - Identified Legal and Administrative Risks and Uncertainties

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score
A1	New Regulations - water quality and environmental	New regulations (either federal or state) impact availability of yields from existing water rights.	5	4	20
A2	Increased Basin Demands	Higher demands across the entire Poudre River basin (due to climate change/population growth) impact use of water rights.	5	3	15
A4	Changing state administration	Policies around state water administration change, impacting yields from water rights.	5	3	15
A9	Elimination or Interruption of Reuse Plan	Platte River Power Authority decommissions Rawhide Energy Station, effectively eliminating the need for the Reuse Plan. In multi-year droughts, water from the Reuse Plan is reduced or unavailable.	4	3	12
A3	Changes to Northern Water CBT Operations	Allocation of CBT water through setting of the quota, and ways in which CBT water can be managed, changes in the future.	4	3	12
A5	Water Court Risks to existing decrees	Existing water rights are challenged in court, potentially changing their availability.	5	2	10
A6	New Regulations - Endangered Species	New regulations impact availability of yields from existing water rights and ability to permit new projects. Mostly impacts new projects.	3	3	9
A7	Public Trust Doctrine	Colorado water law is fundamentally changed, eliminating the prior appropriation system.	1	5	5
A8	Yields reduced in future change cases	Less water is realized from future water rights as assumed yields are greater than actual. FCU doesn't anticipate acquiring many new water rights so risk is low.	4	1	4

2.1.5 Demand Risks

Table 2.5 lists the eight risks and uncertainties identified that are related to demands on the water supply system.

Three demand-related risks and uncertainties were perceived as being a high threat to the water supply system.

- D1 - There is currently significant development pressure in the north Front Range region driving growth in and around Fort Collins. While the current FCU service area is mostly built-out, additional growth within or expansion of that service area could increase demands and change operations.
- D2 - Over the last 15 years, per capita water use in Fort Collins has steadily declined due to a variety of factors such as increased indoor fixture efficiency, changes to outdoor landscaping and irrigation, and an effective City water conservation program. This has created a new relationship between demand increases and population growth. The same trend has been experienced throughout Colorado and the Western U.S. How long this trend will continue is unknown. Reduced per capita demand has the benefit of stretching existing water supplies, although it has adverse impacts on utility revenue. Lower per capita demands could potentially reduce the demand savings achievable from future water use restrictions during droughts or water shortage emergencies. This phenomenon is also known as demand hardening, and could affect how Fort Collins plans for future water shortages.
- D3 - New development could be considerably different than past development. Residential development could have greater density and less landscaped area if current trends persist. Significant future development could consist of redevelopment in high-income areas. This includes higher densities, mixed uses within a single building, and different outdoor space uses. This would change how future demand is tied to residential population and commercial activity, leading to greater uncertainty in predicting the impact of population and economic growth on water use.

Three uncertainties tied to how climate change may impact demands were also perceived as being moderately impactful to the water supply system.

- D6, D8, and D9 - Overall temperature increases would increase peak summer demands and extend high demand periods further into the spring and fall. This could be coupled with increased precipitation in the form of rain, which may also change demand patterns. These demand increases would occur both for FCU and for other water providers in the region, stressing water supplies. Finally, if summer precipitation events become less frequent but more intense, this may lead to an overall increase in demand as customers need to irrigate more frequently.

The remaining risks and uncertainties in **Table 2.5** were not perceived as being a significant threat to FCU's water supply system.

Table 2.5 - Identified Demand Risks and Uncertainties

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score
D1	Service area growth and Regionalization	Ft. Collins expands its service area or enters into agreements to provide water to regional entities.	3	5	15
D2	Water use changes	Decrease in per capita use continues and how water is used (e.g. indoor vs. outdoor) changes.	5	3	15
D3	Development Uncertainty	The composition of development in service area (e.g. density, type, outdoor area) is different that past.	5	3	15
D6	Hotter summer changes irrigation	A warmer climate increases the length of the irrigation season and hotter days increase demand during the summer.	4	3	12
D8	Change in precipitation type	More precipitation falls as rain instead of snow during the Fall and Spring.	4	3	12
D9	Changes in frequency/ magnitude of precipitation events	Precipitation events become less frequent and more intense.	4	3	12
D4	Landscape Changes	Changes in outdoor landscaping (e.g. xeriscape) change demands from past.	3	3	9
D5	Decreased water restriction effectiveness	Watering restrictions become less effective at temporarily reducing demands.	3	3	9
D7	New Large Users	A new, non-regional water user is brought on in the service area.	3	2	6
D10	Changes to Existing Obligations	Existing large water contracts change or end.	3	1	3

2.2 PRIORITIZED RISKS

Figure 2.1 plots all risks and uncertainties identified by FCU as a circle on a grid corresponding to their likelihood and impact scores, with the impact score as columns and the likelihood score as rows. The color of the circle corresponds to the category the risk or uncertainty originates from and the label is the ID of the risk or uncertainty. In total, 46 risks and uncertainties were identified by FCU.

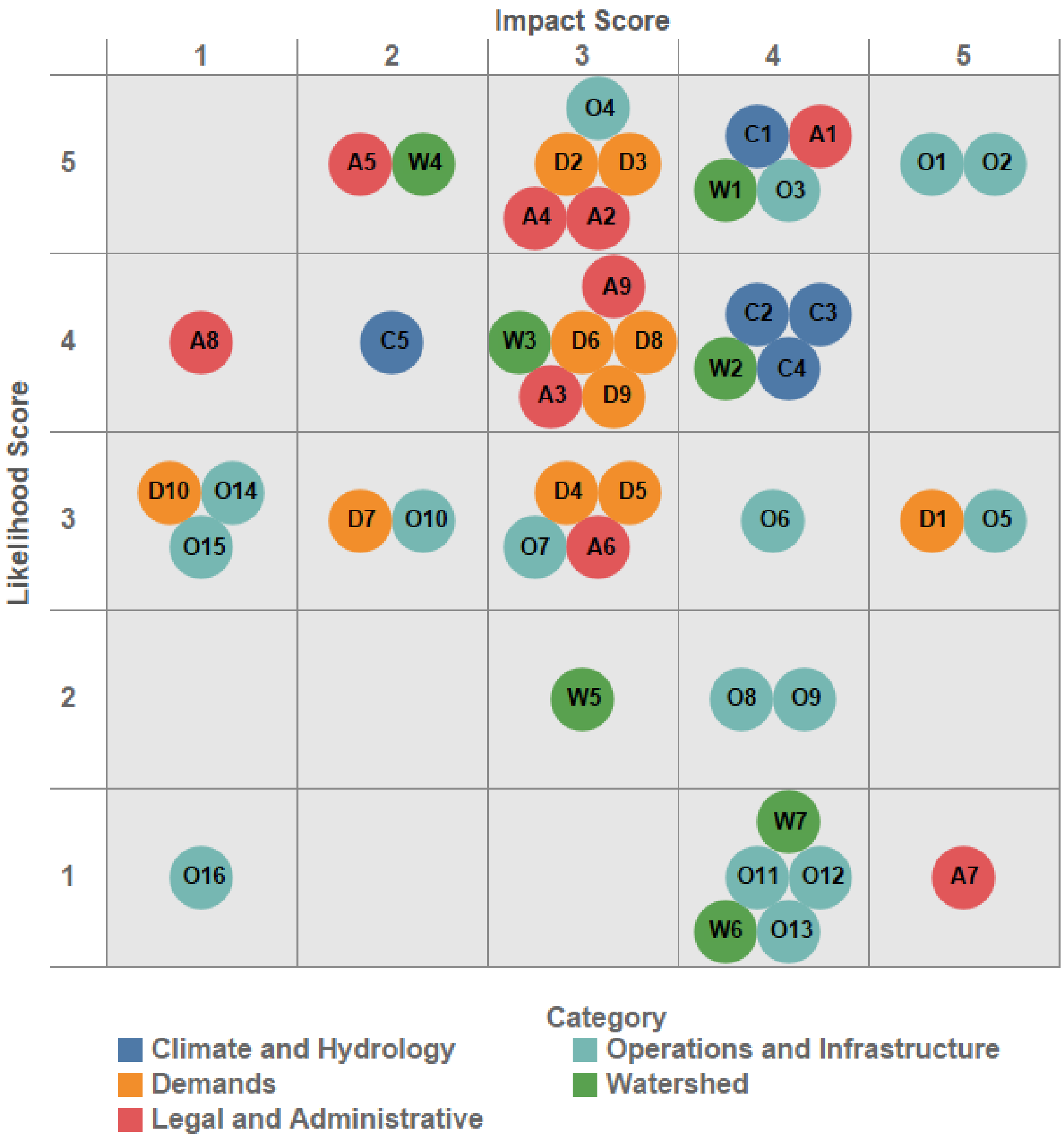
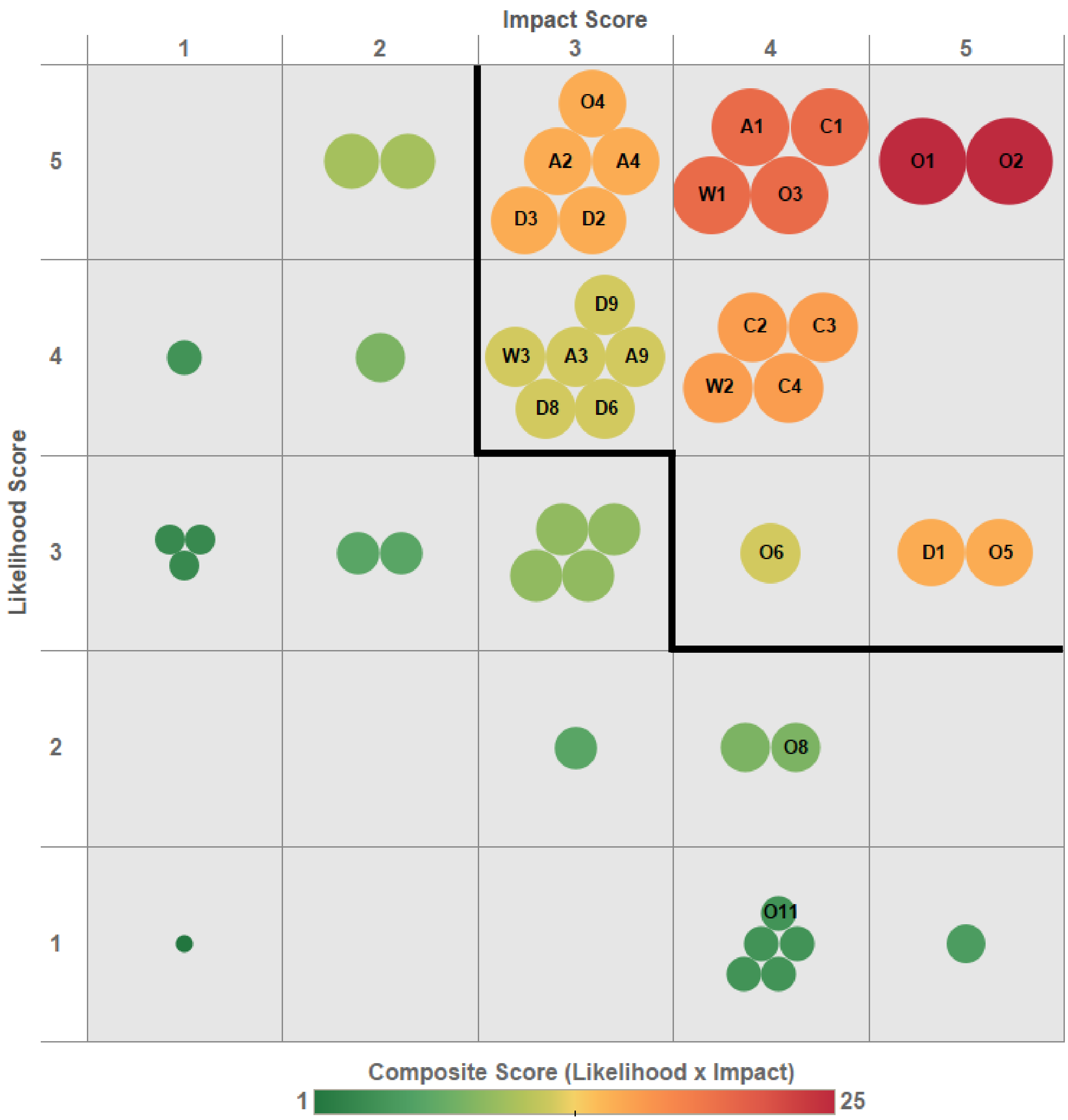


Figure 2.1 – Risks and uncertainties identified by FCU

As part of the future planning framework development, the key identified risks and uncertainties will be simulated to quantify their potential impact on FCU water supply system. However, not every risk and uncertainty can be, or needs to be simulated. Therefore, the previously identified risks and uncertainties were prioritized, identifying those that would be simulated to quantify impacts.

The first step to prioritize risks was to select all risks with a composite score of 12 or above (out of a possible 25). FCU felt these risks were impactful enough to warrant their further examination and potential simulation. Next, all risks that received an impact score of 4 or 5 where further examined (regardless of their composite score) as these risks could be significantly impactful even if their likelihood of occurring was low. Of these highly impactful risks, an outage of Joe Wright Reservoir (O8) and an outage of the Pleasant Valley Pipeline (O11) were identified for further analysis.

Figure 2.2 highlights prioritized risks and uncertainties. The color and size of the circles correspond to their composite scores, with larger and redder circles as the risks and uncertainties with greater perceived significance to FCU's water supply system. Labeled risks and uncertainties are those that were prioritized for further analysis, with the black line separating the region with composite scores of 12 and above from the region with scores less than 12. Note the two low likelihood/high impact risks selected that fall outside this boundary.



Note: larger and redder circles indicate a higher composite score. Prioritized risk IDs are labeled with the black line separating the composite scores used for prioritizing

Figure 2.2 – Summary of likelihood and impact scores of identified risks and uncertainties.

The prioritized risks and uncertainties identified above were summarized around five major threat groups that span the various categories: climate change, demands, critical outages, enhanced environmental stressors, and shared infrastructure (i.e. risks or uncertainties due to lack of ownership by FCU in infrastructure). **Table 2.6** lists all the key risks and uncertainties prioritized for simulation and their threat group.

Table 2.6 - List of Key Risks and Uncertainties Prioritized for Simulation

ID	Risk or Uncertainty Name	Threat Group	Likelihood Score	Impact Score	Composite Score
O1	Outage - 24 Pipeline	CO	5	5	25
O2	Outage - 27 Pipeline	CO	5	5	25
O3	Algal Blooms	EES	5	4	20
C1	Longer duration droughts	CC	5	4	20
A1	New Regulations	EES	5	4	20
W1	Wildfires	EES	5	4	20
C3	Change in precipitation type - Hydrology	CC	4	4	16
C4	Changes in frequency/ magnitude of precip events - Hydrology	CC	4	4	16
C2	Changes in runoff timing	CC	4	4	16
W2	Forest Health Degradation	EES	4	4	16
A4	Changing state administration	CC	5	3	15
D3	Development Uncertainty	D	5	3	15
A2	Increased Basin Demands	D	5	3	15
O5	Outage - Horsetooth Reservoir Intake	CO	3	5	15
O4	Outage - Michigan Ditch	CO	5	3	15
D2	Water Use Changes	D	5	3	15
D1	Service area growth and Regionalization	D	3	5	15
A9	Elimination or Interruption of Reuse Plan	SI	4	3	12
D8	Change in precipitation type - Demands	CC	4	3	12
D9	Changes in frequency/ magnitude of precip events - Demands	CC	4	3	12
A3	Changes to Northern Water CBT Operations	SI	4	3	12
W3	Development in Watersheds	EES	4	3	12
D6	Hotter summer changes irrigation	D	4	3	12
O6	Outage - Chambers Reservoir	CO	3	4	12
O8	Outage - Joe Wright Reservoir	CO	2	4	8
O11	Outage - Pleasant Valley Pipeline	CO	1	4	4

Key: CC = Climate Change, CO = Critical Outages, D = Demands, EES = Enhanced Environmental Stressors, SI = Shared Infrastructure

Figure 2.3 summarizes these threats, averaging the likelihood and impact scores across the individual risks and uncertainties for each threat group, with the size of circle and number corresponding to the number of risks and uncertainties within the threat group. The threats associated with climate change, demands, and enhanced environmental stressors are perceived as being highly likely with a significant impact. The critical outage threats are perceived as being moderately likely with a severe impact on the system.

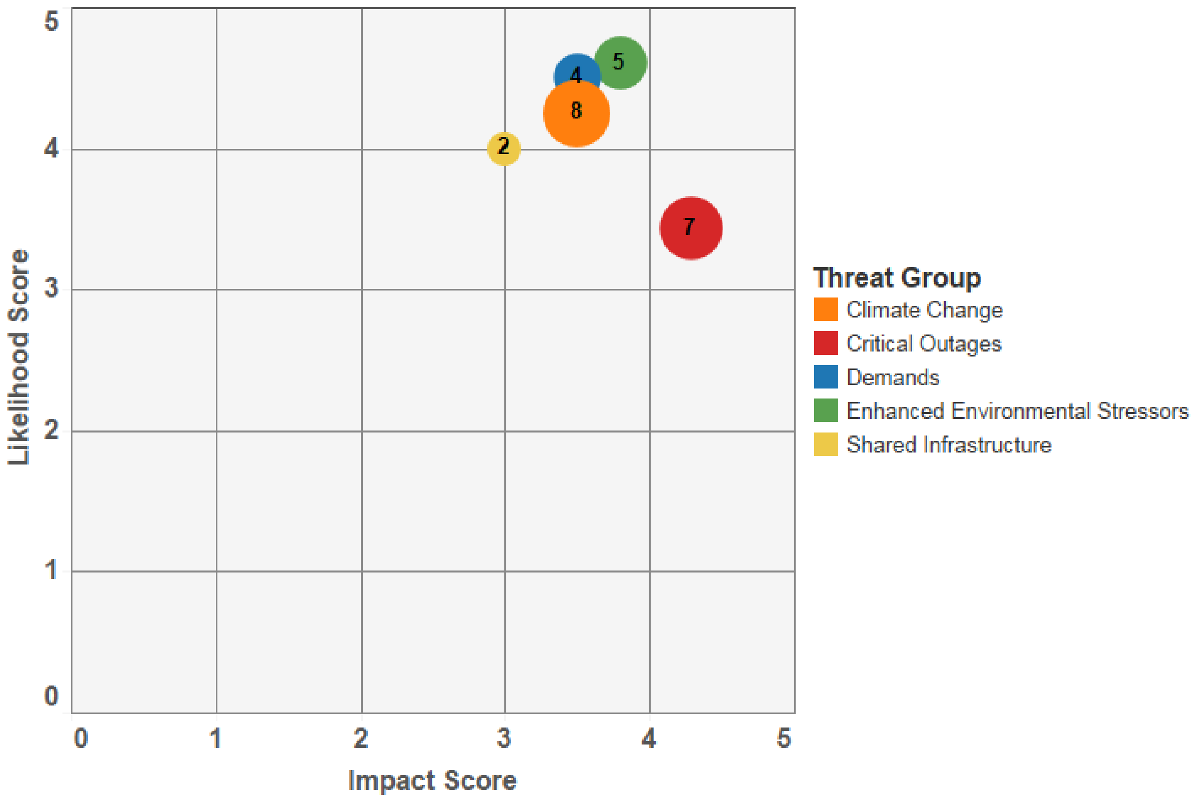


Figure 2.3 – Summary of prioritized risks and uncertainties within each threat group

3.0 C-BT PROJECT WATER SUPPLY SYSTEM RISKS

A significant component of the FCU water supply system is water received from the C-BT Project, owned and operated by Reclamation and Northern. Therefore, as part of the Water Vulnerability Study, risks and uncertainties to the C-BT system were identified by Northern.

Risks and uncertainties to the C-BT Project were identified by staff members from Northern during a half-day workshop. Staff from Northern represented at the workshop included experts in water supply, watershed management, water quality, and operations. FCU staff also participated in the workshop. While the primary goal was to generate risks around the C-BT system that would impact FCU, Northern generated risks across their entire C-BT collection and storage system. These same staff members then scored the identified risks using the rubric described in Section 1.0 based on their perceptions and professional judgment. Therefore, scoring is presented as a *perceived* threat to the water supply system; the actual impact to the water supply system will be quantified for selected key risks using the FCU water resources simulation models.

The scope of the Northern risk and uncertainty evaluation included the C-BT source watersheds, collection system, and storage reservoirs. Risks to the delivery and distribution system were only considered insofar as they could affect deliveries to FCU. As with the Fort Collins risk assessment process, the planning horizon was 50 years.

This section summarizes all risks and uncertainties identified in the Northern workshop and then describes how these identified risks and uncertainties were prioritized for simulation.

3.1 SUMMARY OF ALL RISKS

Identified risks and uncertainties are summarized around five categories that represent different aspects of a water supply system: Climate and Hydrology, Watershed, Operations and Infrastructure, Legal and Administrative, and Demand.

3.1.1 Climate and Hydrology Risks

Table 3.1 lists the six risks and uncertainties associated with the climate and hydrology in the watersheds contributing to the FCU water supply system. For purposes of this evaluation, climate change assumptions in the C-BT source areas were based on general findings of past climate change studies for Colorado and the Front Range region. These studies suggest future climate will be characterized by increased temperature, however the impact on precipitation is unclear as it may increase or decrease.

- CN1 - Longer duration droughts due to increased climate variability or climate change were perceived as a significant threat to the C-BT Project. With respect to the C-BT Project supply, during the first few years of a drought, quota allocations would be set high since allottees use C-BT as a supplemental water supply. If a drought persisted longer than about three years, the C-BT system would become supply-limited and quotas would be set based on the supply available and not the need within the region. It is these types of droughts that last three or more years that would be most impactful to the C-BT system. While not in the observed record, these types of droughts could occur under the current climate, but would also be more frequent and serve under climate change.

- CN2 - An increase in frequency of extremely dry years (e.g., 2002 or 2012) was perceived as a high threat to the C-BT Project. The threat is more pronounced for the Windy Gap system as the C-BT system has sufficient storage to manage through a severe single-year drought. However, if these severe droughts become more frequent, without sufficient recovery, the C-BT system would be impacted.

- CN3 - Reduction in runoff volume due to a warmer, drier climate is perceived as a moderate threat. For example, in 2002 and 2012, warm spring temperatures quickly reduced snowpack without contributing to runoff. With a warmer overall climate projected, those types of spring conditions may be more common. An overall reduction in runoff would eventually translate to less supply available for the C-BT system.

The remaining risks in **Table 3.1** are perceived as less impactful to the C-BT Project water supply system.

Table 3.1 - Identified Northern Water Climate and Hydrology Risks and Uncertainties

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score
CN1	Longer Duration Droughts	Long-term droughts that have longer durations than occurred in past.	4	5	20
CN2	Increased frequency of extreme dry years	Years like 2002 and 2012 become more frequent	4	4	16
CN3	Changes in runoff volume	Long-term reductions in runoff volume due to hotter, drier climate reduce overall yield	3	4	12
CN4	Changes in runoff timing	Runoff volumes shift earlier in the Spring/Summer with peak runoff occurring earlier. Northern has sufficient storage to capture this and its water rights are not specific in time.	5	2	10
CN5	Increased Evaporation in Reservoirs	Temperature increase results in increased evaporation losses from reservoirs. Overall this would be minimal.	5	2	10
CN6	More precipitation as rain	More precipitation falls as rain instead of snow. The impacts on yields and runoff are uncertain due to complex watershed processes.	5	2	10

3.1.2 Watershed Risks

Table 3.2 lists the nine risks and uncertainties identified that would impact the watershed aspect (i.e. source water areas) of the C-BT Project system.

- WN1 - Changes in wildfire characteristics are perceived as a significant threat to the C-BT system. The likelihood of wildfires in the forested areas that comprise the C-BT watersheds is increasing due to a warmer climate, lack of a recent wildfires, and insufficient forest management in some places. If wildfires were to occur, they could burn longer across a wider area and could also burn hotter, increasing the occurrence of hydrophobic soils. This would amplify many of the negative impacts from wildfires such as decreased water quality, major shifts in the hydrograph, and increased sediment loads. The way in which these secondary impacts affect the C-BT system specifically were considered in separate risks.

- WN2 - A wildfire upstream of Grand Lake and Shadow Mountain Reservoir is perceived as being a highly impactful risk to the C-BT system. Because of the forest characteristics in this area, a fire would result in significant short term and potentially longer term impacts to the operations of Grand Lake and Shadow Mountain Reservoir such as increased sedimentation and decreased water quality. However, these impacts could be mitigated to reduce their impact. The long-term impacts would be changes to the hydrograph and sedimentation issues, which would need to be mitigated after major rainfall events.

- WN3 - Forest health degradation in the C-BT source water watersheds is also perceived as being a highly impactful risk. Factors that could affect forest health were described in Section 2.1.2. The majority of all tributary watersheds to C-BT facilities consist of forested areas managed by federal resource agencies, so Northern is dependent on their forest management programs to maintain the health of its source water areas.

- WN4 - Wildfires on the East Slope of the Continental Divide, specifically in the Big Thompson watershed, are perceived as a moderately impactful risk. Transmountain water is conveyed through a section of the Big Thompson River. If a wildfire in the Big Thompson watershed were to occur, the Big Thompson River may be unable to convey C-BT project water due to water quality issues. However, Northern does have alternative delivery methods that would mitigate the impact of this risk. Additionally, this may impact the ability of allottees to use C-BT Project water due to water quality issues. For example, in the summer and early fall of 2017, there were times when the City of Loveland was unable to utilize its native water rights or C-BT water because of water quality issues in the Big Thompson River as well as an outage on the C-BT system.

- WN5 - Increased sediment loading (resulting from fires, flooding, etc.) in reservoirs and open conveyance systems is perceived as a moderately impactful risk. Shadow Mountain Reservoir is the facility with the most potential to be impacted by sedimentation, especially from a water quality perspective due to its very shallow depth. Other Northern reservoir and conveyance facilities could be more easily managed after major sedimentation events, however there would be short-term operational impacts.

The remaining risks and uncertainties in **Table 3.2** are perceived as being less impactful to the C-BT Project collection water system.

Table 3.2 - Identified C-BT Project Watershed Risks and Uncertainties

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score
WN1	Changes in wildfire characteristics	Increase in extent and severity of wildfires in high elevation forests degrades water quality, increases sediment loads and changes runoff characteristics	5	4	20
WN2	Wildfires - Upstream of Grand Lake/Shadow Mountain	Increased occurrence of wildfire leads to short term reduced capacity and ability to use Grand Lake/Shadow Mountain Reservoir. Long term channel and sediment changes.	4	4	16
WN3	Watershed forest health degradation	Poorer forest health leads to increase in wildfire risk, water quality impacts, hydrology impacts and increased sediment load.	5	3	15
WN4	Wildfires - East Slope	Increased occurrence of wildfires in Big Thompson River basin degrades water quality and may prevent ability to use Big Thompson River to move C-BT water. Watershed above Lake Estes has lower wildfire impact risk but higher likelihood.	4	3	12
WN5	Increased sediment loading	Increased sediment loading from several causes reduces reservoir or conveyance capacity and affects water quality.	4	3	12
WN6	Flooding	Major flooding events cause mostly short term impacts during which water cannot be used due to compromised water quality.	5	2	10
WN7	Development in Fraser Valley	Residential development increases water quality risks due to urban runoff, return flows and more septic systems.	4	1	4
WN8	Wildfires - East Slope Reservoirs	Wildfires in East Slope reservoir watersheds (e.g., Horsetooth Reservoir watershed) affects water quality, sediment loading and runoff characteristics for drainage into the reservoirs.	4	1	4
WN9	Development above Lake Granby	Residential development increases water quality risks in Lake Granby and Tri-Lakes system.	3	1	3

3.1.3 Operations and Infrastructure Risks

Table 3.3 lists the 22 risks and uncertainties identified that would impact the operations and infrastructure aspect of the C-BT Project water system.

- ON1 - The Green Mountain Reservoir Replacement Pool is operated for Northern to make releases to the Colorado River system in order to offset out-of-priority diversions by the C-BT collection system. These out-of-priority diversions are important to maximizing the yields and benefits of the C-BT Project. If the size of the Green Mountain Reservoir Replacement Pool is inadequate under future hydrologic conditions because of changing hydrographs and river calls, Northern may not be able to use this replacement pool to divert out-of-priority water as efficiently as it has in the past. This would diminish its ability to mitigate a variety of future risks to its water diversions.

- ON2, ON3, ON4 - Three infrastructure outages are perceived as being moderately impactful to C-BT Project supply system. An outage of Unit Number 3 of the Flatiron Facility would restrict pumping into Carter Lake and limit the ability of Northern to deliver C-BT water to southern allottees. An outage of the Power Arm facility would also prevent moving water into Carter Lake and limit the ability of Northern to deliver C-BT water to southern allottees. Finally, an outage of the Southern Water Supply Project, which could occur due to failures or problems with any of the associated pipelines or canals, would prevent water being delivered to southern allottees. None of these three conditions would impact deliveries of C-BT or Windy Gap water to FCU.

The remaining identified risks or uncertainties in **Table 3.3** are perceived as being less impactful to the C-BT Project water system. Many of these can be easily mitigated if they were to occur or there is sufficient redundancy in the system, diminishing their impact. There are several highly impactful risks that will be evaluated further (see Section 3.2), however Northern has a robust asset management and maintenance program that makes the likelihood of these risks very low.

Table 3.3 - Identified C-BT Project Operations and Maintenance Risks and Uncertainties

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score
ON1	Green Mountain Replacement Pool Inadequacy	With changing hydrology, the 52,000 acre-ft replacement pool may be inadequate to mitigate against a variety of future risks This could reduce Northern's ability to divert out-of-priority water.	4	4	16
ON2	Unit No3 of Flatiron Facility Outage	Failure of Unit 3 in the Flatiron Pump Station prevents pumping water into Carter Lake	4	3	12
ON3	Power Arm Outage	Failure of Power Arm prevents moving water into Carter Lake	4	3	12
ON4	Southern Water Supply Project Outage	Failure of Southern Water Supply Project prevents delivering water to southern allottees	3	4	12
ON5	EPA Transfer Rule	New EPA policy on transbasin diversions makes all existing and future C-BT/Windy Gap subject to discharge requirements	2	5	10
ON6	East Slope Water Rights Uncertainty	Runoff timing changes or increased basin demands impact Northern's yields from East Slope rights and change operation of reservoirs.	3	3	9
ON7	Power Transmission Lines Outages	Wildfire or other emergency causes outage in transmission lines providing power to C-BT/Windy Gap pump stations.	3	3	9
ON8	Algal Blooms	Increased nutrients and temperatures cause algal blooms in reservoirs, impacting suitability of water supply for potable uses	4	2	8
ON9	Aquatic Plants	Increased nutrients and invasive plants grow in reservoirs and canals, impacting operations and potentially increasing treatment requirements	4	2	8
ON10	Invasive Species - Mussels	Mussels clog inlet/outlet pipelines which combined with lack of redundancy may cause short term outages.	2	4	8
ON11	Grand Lake Clarity	Managing to meet clarity requirements leads to less operational flexibility in the system.	4	2	8
ON12	Conveyance Systems to Horsetooth Outage	Variety of events could cause outages or reduced in deliveries in conveyance system components to Horsetooth Reservoir	2	4	8

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score
ON13	Power Generation vs. Water Delivery Operations	Power generation may be given preference over delivering water in C-BT operations	2	4	8
ON14	Grand River Ditch Breach	Failure of the ditch brings sediment into Shadow Mountain/Grand Lake that causes operational changes.	2	3	6
ON15	Conveyance Systems from Carter Lake Outage	Variety of events could cause outages or reduced deliveries from Carter Lake	2	3	6
ON16	Boulder Reservoir Shared Operations	Increased constraints due to Boulder operations impacts ability to deliver water to southern allottees.	2	3	6
ON17	Farr Pump Plant Outage	Pump station failure prevents moving water from Lake Granby to Grand Lake and Adams Tunnel.	1	5	5
ON18	Adams Tunnel Outage	Tunnel failure prevents moving all C-BT/Windy Gap water to East Slope.	1	5	5
ON19	Lake Granby Dam/Dike System Outage	Reduced capacity due to safety reduction or other outage issue limits ability to move water to Grand Lake and Adams Tunnel	1	5	5
ON20	Windy Gap Plant Outage	Pump station failure prevents transfer of Windy Gap water into the C-BT delivery system	1	4	4
ON21	Power Arm and Dille Tunnel Failure (Concurrent)	Concurrent failure of both conveyance facilities would prevent delivering water to Horsetooth Reservoir.	1	4	4
ON22	Willow Creek Pump Plant Outage	Pump station failure prevents pumping C-BT water into Lake Granby and reduces system yield	1	3	3

3.1.4 Legal and Administrative Risks

Table 3.4 lists the four risks and uncertainties identified that would impact the legal and administrative aspect of the C-BT Project water system.

- AN1 - New environmental regulations or changes to existing regulations are perceived as being a moderate threat to the C-BT Project water system. These could result in additional water being required for environmental purposes, which could reduce the C-BT yield and hence the quota set for allottees. Additionally, new infrastructure or improvements to existing infrastructure would be more difficult to permit if new species were added to federal and state lists of protected species or mitigation requirements were expanded.

- AN2 - Colorado River Hydrologic Uncertainty / Major Outage of C-BT Project. Colorado River flows for 2000-2017 represent a significant drought event when compared to both relatively recent recorded data and flow records reconstructed from tree-ring records that go back over one thousand years. The 10 year rolling average of actual flows in the Colorado River below Lake Powell is currently approximately 91 million acre feet. It is not possible to predict if or when actual flows in the Colorado River below Lake Powell will fall below 75 million acre feet on a 10 year rolling average, how long actual flows in the Colorado River below Lake Powell could be below 75 million acre feet on a 10 year rolling average, or whether and how such flows would, under the Colorado River Compact or Upper Colorado River Compact, affect Colorado-Big Thompson Project diversions. Given these uncertainties, the modeled scenarios include a scenario with no diversions by the C-BT Project and a scenario with an extended period of reduced diversions by the C-BT Project, which is represented in the Green Mountain Pool scenario. These scenarios are intended to assess the impact of outages or reduced diversions caused by reduced flows in the Colorado River that are not dependent on currently unknown future hydrology or legal requirements.

The remaining risks and uncertainties in **Table 3.4** are perceived as being less impactful than those described above.

Table 3.4 - Identified C-BT Project Legal and Administrative Risks and Uncertainties

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score
AN1	Environmental Regulations (changes, new, compliance)	New regulations or changes in federal permitting compliance may lead to more water used for environmental mitigation/flows.	**3**	**4**	**12**
AN2	Colorado River Hydrologic Uncertainty / Major Outage of C-BT Project	Possible changes in C-BT operations based on hydrologic uncertainties and a large C-BT Project outage.	**2**	**5**	**10**
AN3	Windy Gap renegotiation	When current 40-year contract limit expires, a renegotiated contract gives less yield (due to increased shrink for example)	**5**	**2**	**10**
AN4	Federal law requires modification of Project Operations.	Federal law requires changes in how the C-BT Project is operated (e.g. for endangered species), reducing C-BT/Windy Gap yield	**2**	**4**	**8**

3.1.5 Demand Risks

Table 3.5 lists the five risks and uncertainties identified that would impact demand aspect of the C-BT Project water system.

Northern is a raw water supplier with a fixed amount of supply available to allocate each year. In that sense its operations are not directly driven by changes in the demands of its allottees. While allottee demands may indirectly impact Northern, the district has a fixed number of units and its quota system allows it to control the amount of water distributed annually to its allottees. Therefore, none of the demand risks or uncertainties are perceived as being significantly impactful to the C-BT Project water system.

Table 3.5 - Identified Northern Water Demand Risks and Uncertainties

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score
DN1	Longer Growing Season	Hotter, drier climate lengthens the growing season for agricultural and M&I allottees, increasing their demands and changing when they need C-BT/Windy Gap water	5	2	10
DN2	Changes in C-BT Users	Continued shift in C-BT ownership to M&I users, who would want quotas set differently than agricultural users.	5	1	5
DN3	Uncertainty of Setting Quota	Change in ownership and Board membership changes the process by which quota is set. May be narrower range to satisfy M&I allottees.	3	1	3
DN4	Increase in quota use	Quotas are not set as high, but as time goes on actual water use is closer to the quota amount.	4	1	4
DN5	Northern Water Management Program Changes	Changes to the Annual Carryover Storage program or Regional Pool program occur, making water management for M&I allottees less flexible.	3	1	3

3.2 PRIORITIZED RISKS

Figure 3.1 plots all risks and uncertainties identified by Northern as a circle on a grid corresponding to their likelihood and impact scores, with the impact score as columns and the likelihood score as rows. The color of the circle corresponds to the category the risk or uncertainty originates from and the label is the ID of the risk or uncertainty. In total, 45 risks and uncertainties were identified by Northern.

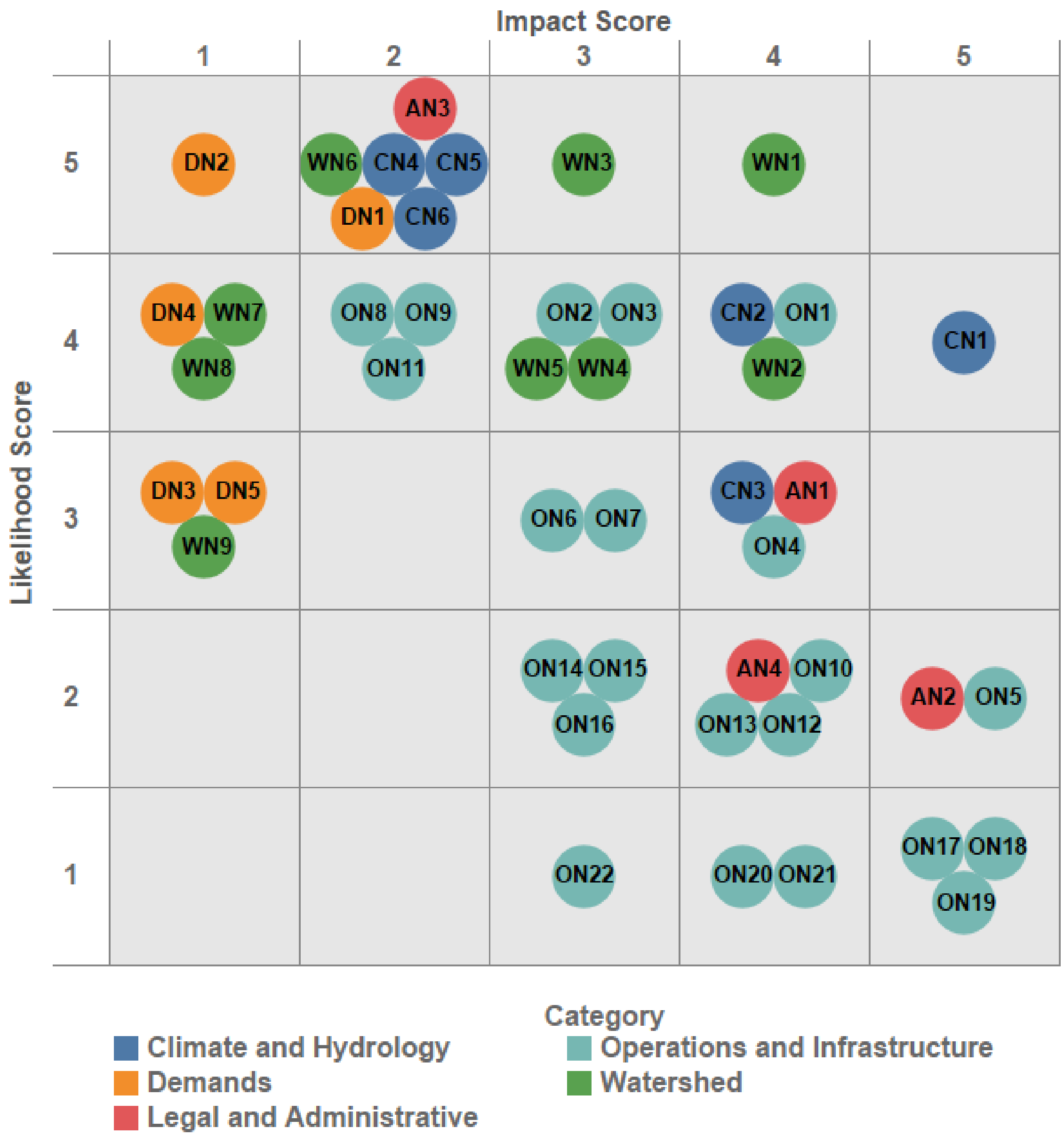


Figure 3.1 - Risks and uncertainties identified by Northern.

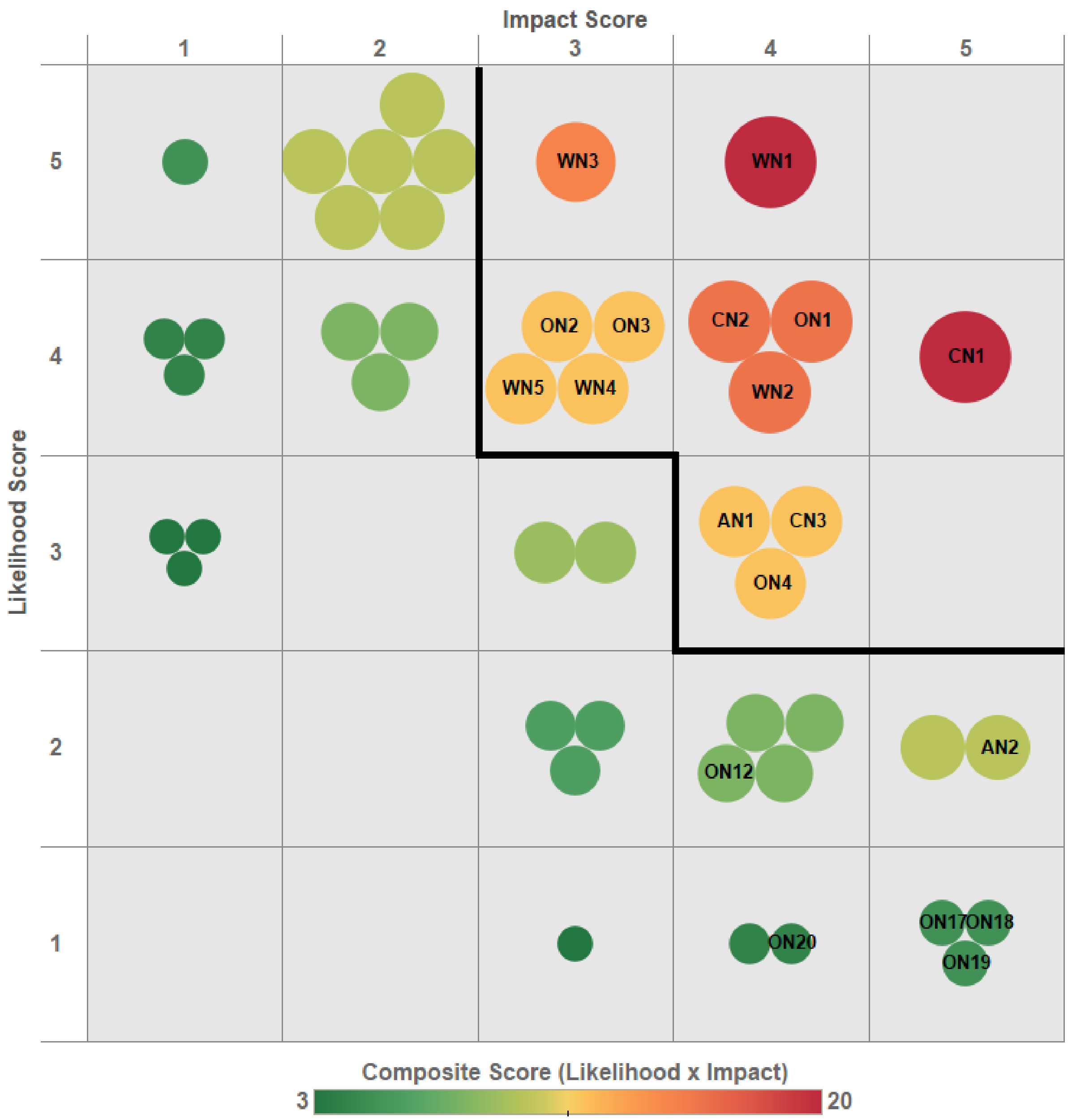
As part of the larger FCU Water Vulnerability Study, the risks and uncertainties identified by Northern need to be translated to C-BT quota impacts because C-BT deliveries comprise a significant portion of FCU water supply. The annual C-BT yield based on the quota is an important input to the FCU water resources model. The process used by the Northern Board to set the annual C-BT quota is based on a number of factors including supplemental regional need, hydrology, amount of water in storage, and past Board experience. Northern has a model that estimates a C-BT quota depending on West Slope and East Slope hydrology and operations of their major reservoirs. This model will be used to estimate the effect of risks and uncertainties on the C-BT quota. However, not every risk and uncertainty needs to be simulated. Therefore, the previously identified risks and uncertainties were prioritized, identifying those that would be simulated in the C-BT quota model.

Similar to the process used by FCU, the first step to prioritize risks was to include all risks with a composite score of 12 or above (out of a possible 25). Northern and FCU felt these risks were impactful enough to warrant further examination and potential simulation. Additionally, all risks that received an impact score of 4 or 5 were further examined (regardless of their composite score) as these risks could be significantly impactful even if their likelihood of occurring was low. Of these highly impactful risks, those prioritized were:

- Conveyance system to Horsetooth Reservoir Outage (ON12)
- Adams Tunnel Outage (ON18)
- Farr Pump Plant Outage (ON17)
- Lake Granby Dam/Dike System Outage (ON19)
- Colorado River Hydrologic Uncertainty / Major Outage of C-BT Project (AN2)
- Windy Gap Plant Outage (ON20)

Note: larger and redder circles indicate a higher composite score. Prioritized risk IDs are labeled with the black line separating the composite scores used for prioritizing

Figure 3.2 plots all identified risks and uncertainties as a circle on a grid corresponding to their likelihood and impact scores, with the impact score as columns and the likelihood score as rows. The color and size of the circles correspond to their composite scores, with larger and redder circles indicating the risks and uncertainties perceived as being more impactful to the C-BT Project water system. Labeled risks and uncertainties are those that were prioritized for further analysis, with the black line separating the region with composite scores of 12 and above from the region with scores less than 12.



Note: larger and redder circles indicate a higher composite score. Prioritized risk IDs are labeled with the black line separating the composite scores used for prioritizing

Figure 3.2 - Summary of likelihood and impact scores of Northern Water identified risks and uncertainties.

The prioritized risks and uncertainties identified above were then summarized around the same five major threat groups used by FCU: climate change, demands, critical outages, enhanced environmental stressors, and shared infrastructure. **Table 3.6** lists the key risks and uncertainties prioritized for simulation and their threat group.

Table 3.6 - List of Northern Water Prioritized Risks and Uncertainties

ID	Name	Threat Group	Likelihood Score	Impact Score	Composite Score
CN1	Longer Duration Droughts	CC	4	5	20
WN1	Changes in wildfire characteristics	EES	5	4	20
CN2	Increased frequency of extreme dry years	CC	4	4	16
ON1	Green Mountain Replacement Pool Inadequacy	D	4	4	16
WN2	Wildfires - Upstream of Grand Lake/Shadow Mountain	EES	4	4	16
WN3	Watershed forest health degradation	EES	5	3	15
AN1	Environmental Regulations (changes, new, compliance)	EES	3	4	12
CN3	Changes in runoff volume	CC	3	4	12
ON3	Power Arm Outage	CO	4	3	12
ON4	Southern Water Supply Project Outage	CO	3	4	12
ON2	Unit No3 of Flatiron Facility Outage	CO	4	3	12
WN5	Increased sediment loading	EES	4	3	12
WN4	Wildfires - East Slope	EES	4	3	12
AN2	Colorado River Hydrologic Uncertainty / Major Outage of C-BT Project	CC/CO	2	5	10
ON12	Conveyance Systems to Horsetooth Outage	CO	2	4	8
ON18	Adams Tunnel Outage	CO	1	5	5
ON17	Farr Pump Plant Outage	CO	1	5	5
ON19	Lake Granby Dam/Dike System Outage	CO	1	5	5
ON20	Windy Gap Plant Outage	CO	1	4	4

Key: CC = Climate Change, CO = Critical Outages, D = Demands, EES = Enhanced Environmental Stressors, SI = Shared Infrastructure

Figure 3.3 summarizes these threats, averaging the likelihood and impact scores across the individual risks and uncertainties for each threat, with the size of circle and number corresponding to the number of risks and uncertainties within the threat group. Shared infrastructure risks were not identified as threats. Critical outages are perceived to be unlikely to occur, but are significantly impactful if they do. Climate change is perceived as being both likely to occur and significantly impactful.

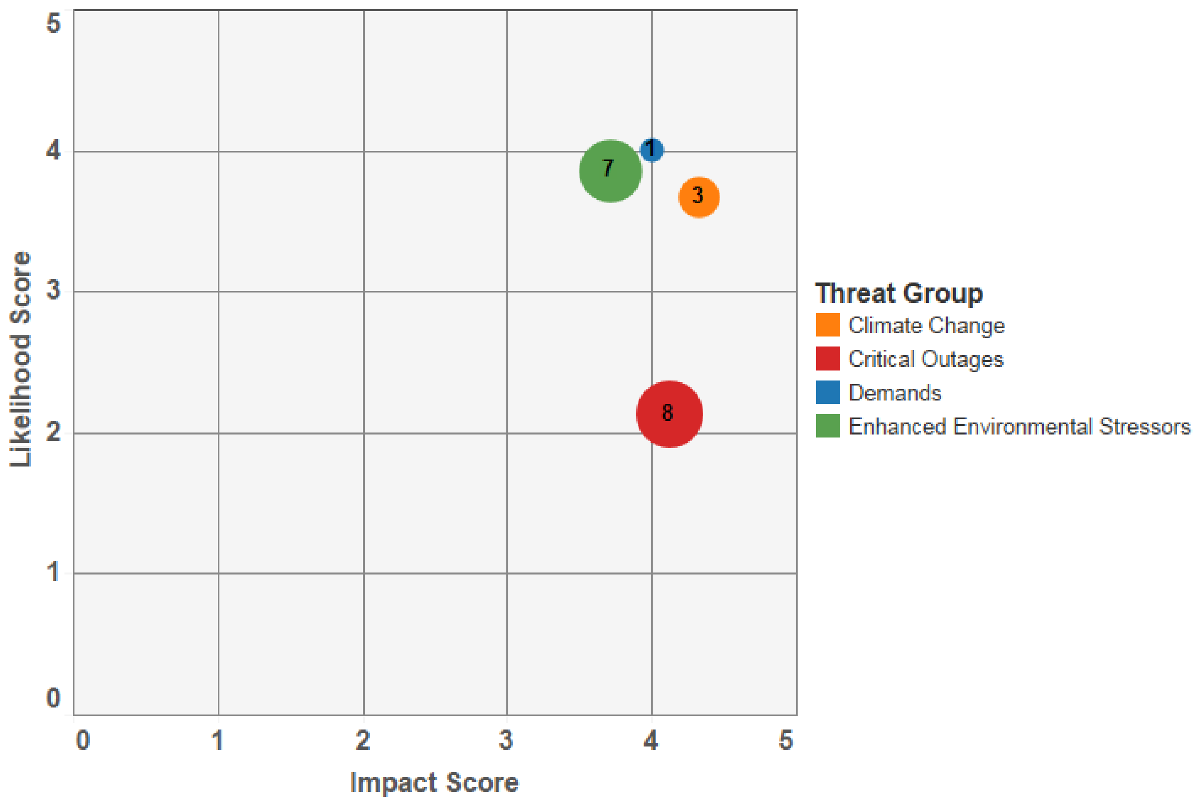


Figure 3.3 - Summary of Northern Water prioritized risks and uncertainties within each threat group

4.0 SIMULATION APPROACH FOR SELECTED RISKS

To develop the future planning framework for the Fort Collins Water Vulnerability Study, the impacts of the identified risks and uncertainties on the water supply system need to be quantified. The Fort Collins and Northern water resources models will be used to simulate these impacts, providing objective information about which risks and uncertainties are a significant threat.

Therefore, a simulation approach for the prioritized risks and uncertainties identified by FCU for its water supply system in Section 2 and the prioritized risks and uncertainties identified by Northern for the C-BT Project in Section 3 was developed. This approach is described in this section.

4.1 GENERAL SIMULATION APPROACH

The risk and uncertainty simulation process requires a reasonable estimate of the water supply feature being impacted by each key risk/uncertainty, the duration of the impact, and determination of the models that should be used to simulate its effects. Some risks or uncertainties, though prioritized, will not be explicitly simulated in the models though their specific impacts will be qualitatively described.

There are three models that represent FCU's water supply system, described below. How the simulation approach will be specifically applied to each model is described in more detail in Section 4.2, Section 4.3, and Section 4.4. Risks related to the Reuse Plan are not finalized at this time but will be added to the documentation when they are.

- The Fort Collins System Model (FCM) simulates the operation of infrastructure used to deliver yields from sources to FCU's water treatment plant.
- The Poudre Basin Network (PBN) model simulates the water allocation and storage for water users in the Poudre River basin.
- The C-BT Quota model (CBTQ) simulates the anticipated quota for C-BT allottees based on hydrology, operations of the major reservoirs in the C-BT system, and other factors.

Table 4.1 presents the proposed simulation approach for the prioritized risks and uncertainties related to the FCU water supply system described in Section 2.2. For risks with a simulation approach that is applied for a fixed period of time (e.g., June-October, 5 years), the simulated year that risk occurs will be fixed (e.g. year 10 of the simulation) across all three models. Because different hydrology are being developed for these models, risks occurring the same simulated year will occur across a variety of hydrologic conditions (e.g. short droughts, multi-year droughts, wet periods, drought recovery).

Table 4.1 – Simulation approach for FCU water supply system risks and uncertainties

ID	Risk or Uncertainty Name	Model for Simulation	Simulation Approach
O1	Outage – 24" Pipeline	FCM	100% outage between October and March, when impact would be most severe to operations. Will be combined with 27" Pipeline Outage in model.
O2	Outage – 27" Pipeline	FCM	100% outage between October and March, when impact would be most severe to operations. Will be combined with 24" Pipeline Outage in model.
O3	Algal Blooms	FCM	C-BT water use will be reduced by a fixed percent between June-October.
C1	Longer duration droughts	All	Incorporated into new stochastic hydrology
A1	New Regulations- Water quality and environmental	Not Simulated	
W1	Wildfires	FCM	Outage of non-C-BT supply between June-September, followed by 10-year, 20% reduction in non C-BT-supply.
C3	Change in precipitation type - Hydrology	All	Incorporated into new stochastic hydrology
C4	Changes in frequency/magnitude of precipitation events - Hydrology	All	Incorporated into new stochastic hydrology
C2	Changes in runoff timing	All	Incorporated into new stochastic hydrology
W2	Forest Health Degradation	Not Simulated	
A4	Changing state water rights administration	Not Simulated	
D3	Development Uncertainty	FCM/PBN	Captured in demand scenario modeling
A2	Increased Basin Demands	Not Simulated	A separate sensitivity analysis around this was completed by FCU and found no significant impact on water availability.
O5	Outage - Horsetooth Reservoir Outlet	FCM	Horsetooth empties in October, then 100% storage capacity reduction for 9 months, though water can still flow through the reservoir.
O4	Outage - Michigan Ditch	FCM	100% reduction for 24 months
D2	Water Use Changes	FCM	Captured in demand scenario modeling

ID	Risk or Uncertainty Name	Model for Simulation	Simulation Approach
D1	Service area growth and regionalization	FCM	Apply a percent increase to demands in new demand model based on how much demands may increase.
D8	Change in precipitation type - Demands	FCM	Captured in demand scenario modeling
D9	Changes in frequency/magnitude of precipitation events - Demands	FCM	Captured in demand scenario modeling
A3	Changes to Northern Water C-BT Operations	FCM/PBN	Simulate various quota assumption scenarios (e.g. fixed 50% quota). Scenarios to be developed.
W3	Development in Watersheds	Not Simulated	
D6	Hotter summer changes irrigation	FCM	Captured in demand scenario modeling
O6	Outage - Chambers Reservoir	Not Simulated	
O8	Outage - Joe Wright Reservoir	FCM	100% reduction in capacity for 24 months starting in November. All inflows bypassed.
O11	Outage - Pleasant Valley Pipeline	FCM	100% reduction from April-October
A9	Elimination or Interruption of Reuse Plan	FCM	In development

Table 4.2 presents the simulation approach for the prioritized risks and uncertainties related to the C-BT water supply system described in Section 3.2.

Table 4.2 - Simulation approach for the C-BT Project water system risks and uncertainties

ID	Name	Model for Simulation	Simulation Approach
CN1	Longer Duration Droughts	CBTQ	Incorporated into new hydrology.
WN1	Changes in wildfire characteristics	Not Simulated	
CN2	Increased frequency of extreme dry years	CBTQ	Incorporated into new stochastic hydrology.
ON1	Green Mountain Replacement Pool Inadequacy	CBTQ	Reduce inflows into model to account for loss of out-of-priority diversions.
WN2	Wildfires - Upstream of Grand Lake/Shadow Mountain	Not simulated	Potential quota changes captured in other risks.
WN3	Watershed forest health degradation	Not simulated	
AN1	Environmental Regulations (changes, new, compliance)	CBTQ	Reduce inflows into model to account for loss due to increased environmental flows.
CN3	Changes in runoff volume	CBTQ	Incorporated into new stochastic hydrology.
ON3	Power Arm Outage	Not simulated	Doesn't impact quota setting or deliveries of C-BT supply to FCU
ON4	Southern Water Supply Project Outage	Not simulated	Doesn't impact quota setting or deliveries of C-BT supply to FCU

ON2	Unit No3 of Flatiron Facility Outage	Not simulated	Doesn't impact quota setting or deliveries of C-BT supply to FCU
WN5	Increased sediment loading	Not Simulated	Shadow Mountain Reservoir is mostly a pass through reservoir, so may not be greatly affected by reduced capacity.
WN4	Wildfires - East Slope	CBTQ	Reduction in Big Thompson-captured inflows. No delivery of C-BT water to certain water users (e.g. Greeley) through Big Thompson River.
ON12	Conveyance Systems to Horsetooth Outage	FCM	Doesn't impact quota setting. 100% reduction in C-BT delivery to Horsetooth Reservoir from January – June. Existing water in Horsetooth Reservoir still useable.
ON18	Adams Tunnel Outage	FCM/PBN	100% reduction in West Slope yields for a single year. Anticipated quota scenario will be developed.
ON17	Farr Pump Plant Outage	FCM/PBN	60% reduction in West Slope yields for a single year. Anticipated quota scenario will be developed.
ON19	Lake Granby Dam/Dike System Outage	FCM/PBN	100% reduction in West Slope yields for a single year. Anticipated quota scenario will be developed.
AN2	Colorado River Hydrologic Uncertainty / Major Outage of C-BT Project	CBTQ	A reactive response that is a 100% reduction in West Slope inflows for 5 years.
ON20	Windy Gap Plant Outage	CBTQ	100% reduction in West Slope yields for a single year.

4.2 FORT COLLINS SYSTEM MODEL

Many of the risks presented in Table 4.1 will be simulated by adjusting specific links and/or nodes in the FCM model. Others will be captured by altering the demand inputs or the hydrology inputs to the model.

Table 4.4 details how the risk will be initiated, how long the risk will last and which nodes or links will be adjusted in the FCM model to simulate the modeled risks. Table 4.5 lists the risks that are not modeled by adjusting a link or node setting, but rather by altering the demand inputs or hydrology inputs to the FCM model.

Table 4.3- Simulation method for risks and uncertainties affecting the Fort Collins System Model

ID	Risk or Uncertainty Name	Risk Initiation	Reduction Factor	Duration (timesteps)	FCM Nodes/Links
O1	Outage – 24” Pipeline	Random, starting in October	100	12	Pipecap link will be split into three links (multilink). Only one of the three links will be affected.
O2	Outage – 27” Pipeline	Random, starting in October	100	12	Pipecap link will be split into three links (multilink). Only one of the three links will be affected.
O3	Algal Blooms	Annual Canyon Mountain Naturalized Flow. Bin into three bins based off current hydrology. Select a random year from within the dry bin.	Blending construct	5	Simulated in new blending construct
W1	Wildfires	Hydrology-based	Year 1: 100% Years 2-10: 25%	Year 1: June-September Years 2-10: April-October	Pipecap link will be split into three links (multilink). Which link or links will be affected?
O5	Outage - Horsetooth Reservoir Outlet	Random, starting in October	100	9	Horsetooth_StoRight node target and capacity
O4	Outage - Michigan Ditch	Random, starting in June	100	24	MD link
O8	Outage - Joe Wright Reservoir	Random, starting in November	100	24	JoeWright_StoRight node
O11	Outage - Pleasant Valley Pipeline	Random, starting in April	100	12	Pipecap link will be split into three links (multilink). Which link or links will be affected?
A9	Reuse Plan Gone				Developed as part of Reuse Plan simulation
A9	Reuse Plan Interrupted				Developed as part of Reuse Plan simulation
ON12	Conveyance Systems to Horsetooth Outage	Random, starting in April	100	January-June	cbtin link

Table 4.4- Summary of risks and uncertainties reflected in demand or hydrology inputs to the Fort Collins System Model

ID	Risk or Uncertainty Name	Simulation Approach
C1	Longer duration droughts	Incorporated into new stochastic hydrology
C2	Changes in runoff timing	Incorporated into new stochastic hydrology
C3	Change in precipitation type - Hydrology	Incorporated into new stochastic hydrology
C4	Changes in frequency/magnitude of precipitation events - Hydrology	Incorporated into new stochastic hydrology
D1	Service area growth and regionalization	Apply a percent increase to demands in new demand model based on how much demands may increase.
D2	Water Use Changes	Captured in demand scenario modeling
D3	Development Uncertainty	Captured in demand scenario modeling
D6	Hotter summer changes irrigation	Captured in demand scenario modeling
D8	Change in precipitation type - Demands	Captured in demand scenario modeling
D9	Changes in frequency/magnitude of precipitation events - Demands	Captured in demand scenario modeling

4.3 POUDRE BASIN NETWORK MODEL

PBN model output serves as hydrology input to the FCM model, so only hydrology-based risks will be simulated in the PBN model. By altering PBN inputs based on the risks, the PBN output will reflect the simulated risks, which will be used as input to the FCM model. Table 4.6 lists the risks that are simulated in the PBN model.

Table 4.5- Summary of risks and uncertainties reflected in hydrology inputs to the PBN Model

ID	Risk or Uncertainty Name	Simulation Approach
C1	Longer duration droughts	Incorporated into new stochastic hydrology
C2	Changes in runoff timing	Incorporated into new stochastic hydrology
C3	Change in precipitation type - Hydrology	Incorporated into new stochastic hydrology
C4	Changes in frequency/magnitude of precipitation events - Hydrology	Incorporated into new stochastic hydrology

4.4 NORTHERN WATER QUOTA MODEL

The CBTQ model output will be used as input to both the PBN model and the FCM model. The risks identified by Northern in Table 4.2 will alter how the quota is set; and thus, will need be simulated in the CBTQ model. The quotas produced will be used as inputs to the PBN and FCM models, and will reflect the simulated risk.

Table 4.7 details how specific model objects in the CBTQ model are adjusted to simulate the identified risks. Table 4.8 lists the risks that are modeled by altering the hydrologic inputs to the CBTQ model.

Table 4.6- Simulation method for risks and uncertainties affecting the CBTQ Model

ID	Risk or Uncertainty Name	Duration	CBTQ Model Objects	Model Object Setting
WN4	Wildfires - East Slope	3 years	Timeseries Sheet: column “East Slope Wildfires”	1 in year of the fire and following 2 years
			Model Control Sheet: Cell B49	100
ON20	Windy Gap Plant Outage	1 year	Timeseries Sheet: column “Windy Gap Pump Outage”	1 in year(s) of pump outage

Because of the operation of the C-BT Project by which allottees are delivered water via a quota that is set each year, risks and uncertainties interact with the C-BT and FCU water supply systems differently. Some risks and uncertainties impact how the quota is set while others impact how the water committed under the quota is delivered. The CBTQ model captures how risks and uncertainties to hydrology and reservoirs would impact how the quota is set. However risks and uncertainties that impact how the water committed under the quota is delivered are not captured in the CBTQ model. Therefore for the Water Vulnerability Study, quota scenarios, in addition to those simulated in the CBTQ model, will be developed for risks and uncertainties that are not captured in the CBTQ model and applied to the PBN and FCM models. **Table 4.3** summarizes the quota scenarios developed and the risks and uncertainties they capture.

Table 4.7 - Quota Scenarios for the FCM and PBN Models

Scenario Name	Description	Risks and Uncertainties Captured
Adams Tunnel Outage	Quota is set to 25% in the three years following the outage for all Horsetooth storage levels.	Adams Tunnel Outage (ON18)
Farr Pump Plant Outage	Quota is set to 39% in the three years following the outage for all Horsetooth storage levels.	Farr Pump Plant Outage (ON17)
Lake Granby Dam/Dike System	Quota is set to 40% in the three years following the outage for all Horsetooth storage levels.	Lake Granby Dam/Dike System Outage (ON9)

Table 4.8- Summary of risks and uncertainties reflected in hydrology inputs to the CBTQ Model

ID	Risk or Uncertainty Name	Simulation Approach
CN1	Longer Duration Droughts	Incorporated into new hydrology.
CN2	Increased frequency of extreme dry years	Incorporated into new stochastic hydrology.
CN3	Changes in runoff volume	Incorporated into new stochastic hydrology.
ON1	Green Mountain Replacement Pool Inadequacy	Incorporated into new hydrology
AN1	Environmental Regulations (changes, new, compliance)	Incorporated into new hydrology
AN2	Colorado River Hydrologic Uncertainty / Major Outage of C-BT Project- Reactive Response	Incorporated into new hydrology

5.0 SUMMARY AND CONCLUSIONS

As part of the Fort Collins Water Vulnerability Study, a future planning framework to evaluate the need for new water supply strategies is being developed. A key part of this framework will be incorporating risks and uncertainties that could negatively impact FCU's ability to deliver water to its customers. Therefore, risks and uncertainties to the FCU water supply system were identified and prioritized. Because FCU gets a significant portion of its supply from the C-BT Project, risks and uncertainties to the C-BT project were also identified by Northern.

In total, 46 risks and uncertainties were identified for the FCU water supply system and 53 risks and uncertainties were identified for the C-BT system. Each of these were assigned a likelihood score and an impact score by staff from each agency based on their professional judgment. These risks and uncertainties were then prioritized for simulation using the composite score (likelihood score x risk score). 25 risks and uncertainties related to the FCU water supply system were prioritized for simulation and 24 risks and uncertainties related to the C-BT system were prioritized for simulation.

For each of these key prioritized risks and uncertainties, a simulation approach was developed to capture their potential impact in one of models used to simulate the FCU water supply system and the C-BT annual quota. These individual risks and uncertainties will then be combined into various scenarios and simulated in the water resources models, using performance metrics and level of service goals to determine which risks and uncertainties should be included in the future planning framework.

APPENDIX A – FORT COLLINS UTILITIES RISK AND UNCERTAINTY TABLES

A.1 Climate and Hydrology

The following table presents the climate and hydrology risks and uncertainties identified by FCU and their associated scores and additional notes.

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score	Notes
C1	Longer duration droughts	Multi-year and/or more severe droughts occur in the future that are not captured in the observed record.	**5**	**4**	**20**	Could be caused by natural climate variability or climate change. Longer periods of low streamflow and reduced yields from water rights.
C2	Changes in runoff timing	Early higher runoff and lower late-season baseflow reduces yield from volumetric decrees that list specific diversion dates.	**4**	**4**	**16**	Earlier runoff is already occurring compared to historical averages. Fort Collins system is vulnerable due to limited storage. Water rights have highly specific timing of decreed water which may reduce yields if there is changes in runoff timing.
C3	Change in precipitation type	More precipitation falls as rain instead of snow during the Fall and Spring.	**4**	**4**	**16**	This is occurring now relative to historical averages. Reduces benefits of "snowpack reservoir." Fort Collins system is vulnerable due to limited storage.
C4	Changes in frequency/ magnitude of precipitation events	Precipitation events, particularly summer rainstorms, become less frequent and more intense.	**4**	**4**	**16**	More intense storms could cause flooding, damaging infrastructure. More storms like September 2013.
C5	Longer growing season	Warmer climate increases growing season in Spring and Fall, changing potential water rights calls and increasing irrigation demand.	**4**	**2**	**8**	Increased agricultural diversions in Spring and Fall could affect yield from Fort Collins rights. However, many ag users already use most of their decreed supply and there is research that shows that longer growing seasons may reduce water-intensive crops.

A.2 Watershed

The following table presents the watershed risks and uncertainties identified by FCU and their associated scores and additional notes.

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score	Notes
W1	Wildfires	Wildfires occur, causing a variety of impacts on water quality, runoff, and threats to infrastructure.	5	4	20	Climate change leading to hotter, drier climate would increase risk of wildfire. High Park Fire demonstrated wildfire threat. Water quality has short term and long term effects that make Poudre River water untreatable. Wildfire itself and sediment loads from runoff after the fire could affect diversions and conveyance systems in the FCU system.
W2	Forest Health Degradation	Forested area health decreases due to beetle kill, pollution, warming climate, etc.	4	4	16	Declining forest health could affect streamflow magnitude and timing (higher peak, earlier runoff) and degrade water quality. Also, increases risk of wildfire.
W3	Development in Watersheds	Land development in watersheds (recreation, residential, O&G, mining) increases risk of water quality contamination.	4	3	12	Long-term water quality degradation due to increased road traffic and septic systems and increased risk of acute contamination events due to spills or vehicle accidents.
W4	Atmospheric Deposition	Increased levels of contaminants in bodies of water and forests lead to new water quality issues	5	2	10	Deposition of nutrients in pristine high-altitude bodies of water increases risk of algal blooms or other water quality issues that could impact water quality and availability.
W5	Deficiencies in Federal land Management	Federally owned land, which comprises nearly all of the watersheds, is poorly managed against wildfires or to promote forest health	2	3	6	Over 90% of Fort Collins water supply yield is derived from land owned and managed by the Federal government. Challenges with proactive forest management increase frequency and/or severity of wildfires. Limited rehabilitation of forests after a wildfire increase risk to water quality contamination, sedimentation, and runoff timing changes.
W6	Abandoned Mine Runoff	Runoff from abandoned mines leads to decreased water quality in FCU watersheds.	1	4	4	Abandoned mines could release metals and other toxic chemicals. Few mines in the Fort Collins source watersheds so low likelihood of problems.
W7	Privatization of Public Lands	Lands owned by the federal government are transferred to private entities, increasing development potential	1	4	4	More area for development and more development intensity would increase risk of impacts of development as described above.

A.3 Operations and Infrastructure

The following table presents the operations and infrastructure risks and uncertainties identified by FCU and their associated scores and notes

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score	Notes
O1	Outage - 24 Pipeline	Short term outage due to flooding, landslides, wildfire, etc.	5	5	25	Inability to convey Poudre River supply to WTP without pipeline. High risk of landslides, full alignment uncertain, in river stretches increases risk of filling with sediment if it fails. Sections very difficult to access.
O2	Outage - 27 Pipeline	Short term outage due to flooding, landslides, wildfire, etc.	5	5	25	Inability to convey Poudre River supply to WTP. High risk of landslides, hard to access in event of failure.
O3	Algal Blooms	Algal blooms in storage reservoirs and rivers increases water quality issues and potential treatment problems	5	4	20	Due to variety of factors, increased risk of algal blooms in Fort Collins storage facilities. Current WTP unable to treat water with algal contaminants; could potentially significantly restrict available water in late summer/fall months.
O4	Outage - Michigan Ditch	Short term outage due to flooding, landslides, wildfire, etc.	5	3	15	Inability to convey transmountain supply to WTP. Variety of factors could lead to outage.
O5	Outage - Horsetooth Reservoir Outlet	Short term outage of reservoir outlet and intake to WTP; higher risk due to lack of redundancy	3	5	15	Inability to convey CBT supply from Horsetooth Reservoir to WTP. Outage of the Horsetooth Reservoir intake recently occurred, validating this risk.
O6	Outage - Chambers Reservoir	Short term outage due to flooding, landslides, wildfire, etc.	3	4	12	Maintenance is underfunded, increasing risk of failures. Fort Collins has minimal influence or control over reservoir.
O7	Outage - Munroe Canal	Short term outage due to flooding, landslides, wildfire, etc.	3	3	9	Inability to convey NPIC shares to City WTP.
O8	Outage - Joe Wright Reservoir	Short term outage due to flooding, landslides, wildfire, etc.	2	4	8	Inability to access water from storage in Joe Wright Reservoir. There is currently an active landslide in reservoir footprint. Fort Collins owns minimal land around reservoir, increasing risk due to wildfires and their impacts.
O9	Shared infrastructure - Chambers Reservoir	Lack of control of operations could lead to issues with delivering water	2	4	8	City cannot control movement of its water to its system, so may not have access to supply when needed

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score	Notes
O10	Outage - Meadow Creek Reservoir	Short term outage due to flooding, landslides, wildfire, etc.	3	2	6	Impact could be significantly higher if outage occurs during drought event as it was Fort Collins sole source of water during 2002 drought.
O11	Outage - Pleasant Valley Pipeline	Short term outage due to flooding, landslides, wildfire, etc.	1	4	4	Inability to use PVP to convey Poudre River supply to WTP. Shared ownership with Northern, low exposure risk.
O12	Shared infrastructure - Munroe Canal	Lack of control of operations could lead to issues with delivering water	1	4	4	City cannot control movement of its water to its system due to NPIC decisions, so may not have access to supply when needed
O13	Shared infrastructure - Pleasant Valley Pipeline	Lack of control of operations could lead to issues with delivering water	1	4	4	City cannot control movement of its water to its system due to the PVP participant decisions (Greeley, TriDistricts), so may not have access to supply when needed.
O14	Sediment Loading - Reservoirs	Loss of capacity in reservoirs due to increased sediment loads	3	1	3	Long term reduction in available storage.
O15	Freeze/Thaw Cycles	Initial freezing stages impact water quality, ice coming down the river could impact operations	3	1	3	More frequent degraded water quality. Potential damage to diversion structures could limit ability to access Poudre River supply.
O16	Shared infrastructure - Meadow Creek Reservoir	Lack of control of operations could lead to issues with delivering water	1	1	1	City cannot control movement of its water to its system due to decisions by others, so may not have access to supply when needed.

A.4 Legal and Administrative

The following table presents the legal and administrative risks and uncertainties identified by FCU and their associated scores and additional notes.

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score	Notes
A1	New Regulations - Water Quality	New regulations (either federal or state) impact availability of yields from existing water rights	5	4	20	Existing supplies may not meet standards without additional treatment. Could affect ability to blend Poudre water and CBT water.
A2	Increased Basin Demands	Higher demands across the entire Poudre River basin (due to climate change/population growth) impact use of water rights	5	3	15	Could increase annual demands and extend irrigation period. Magnitude of impact is uncertain without modeling of system performance.
A3	Changes to Northern Water CBT Operations	Allocation of CBT water through setting of the quota, and ways in which CBT water can be managed, changes in the future	4	3	12	Northern Water sets annual quota. Method of setting quota could change, especially with transition to more municipal ownership.
A4	Changing state administration	Policies around state water administration change, impacting yields from water rights	5	3	15	Policy changes could affect shrink applied to conveyance, water rights transfers, etc. in ways that would reduce yield from the City's existing rights or reduce yield from future acquisitions.
A5	Water Court Risks to existing decrees	Existing water rights are challenged in court, potentially changing their availability	5	2	10	More of a concern in the future as competition for scare water resources increases.
A6	New Regulations - Endangered Species	New regulations impact availability of yields from existing water rights and ability to permit new projects	3	3	9	Primary concern would be ability to permit new water projects.
A7	Public Trust Doctrine	Colorado water law is fundamentally changed, eliminating the prior appropriation system	1	5	5	Yield from all current City water rights and rights of other water users in the basin would suddenly be uncertain.
A8	Yields reduced in future change cases	Less water is realized from future water rights as assumed yields are greater than actual. FCU doesn't anticipate acquiring new water rights so risk is low.	4	1	4	Fort Collins has already done most of their change cases and expects a minimal amount in the future.
A9	Elimination or Interruption of Reuse Plan	Platte River Power Authority decommissions Rawhide Energy Station, effectively eliminating the need for the Reuse Plan. In multi-year droughts, water from the Reuse Plan is reduced or unavailable.	4	3	12	Current response to Reuse Plan being developed by FCU.

A.5 Demands

The following table presents the demand risks and uncertainties identified by FCU and their associated scores and additional notes.

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score	Notes
D1	Service area growth and Regionalization	Ft. Collins expands its service area or enters into agreements to provide water to regional entities.	3	5	15	Increased water demands must be met and service connections extended.
D2	Water use changes	Decrease in per capita use continues and how water is used (e.g. indoor vs. outdoor) changes	5	3	15	Continuation of recent trends in less per capita residential use and less outdoor use relative to indoor use.
D3	Development Uncertainty	The composition of development in service area (e.g. density, type, outdoor area) is different that past.	5	3	15	Increased density is anticipated with redevelopment in some areas and higher land values.
D6	Hotter summer changes irrigation	A warmer climate increases the length of the irrigation season and hotter days increase demand during the summer.	4	3	12	Affects City demand and demand by other users in the basin.
D8	Change in precipitation type	More precipitation falls as rain instead of snow during the Fall and Spring.	4	3	12	Affects irrigation demand in City service area and in region.
D9	Changes in frequency/ magnitude of precipitation events	Precipitation events become less frequent and more intense	4	3	12	Higher summer rainfall could affect demand patterns.
D4	Landscape Changes	Changes in outdoor landscaping (e.g. xeriscape) change demands from past	3	3	9	Reduction in outdoor use and irrigation season demand.
D5	Decreased water restriction effectiveness	Watering restrictions become less effective at temporarily reducing demands.	3	3	9	Demand hardening with less outdoor demand and other non-critical demands.
D7	New Large Users	A new, non-regional water user is brought on in the service area.	3	2	6	New commercial or industrial user similar to AB or HP.
D10	Changes to Existing Obligations	Existing large water contracts change or end	3	1	3	Major industrial user moves out of town, or converts to raw water rather than potable water.

APPENDIX B – NORTHERN WATER RISK AND UNCERTAINTY TABLES

B.1 Climate and Hydrology

The following table presents the climate and hydrology risks and uncertainties identified by Northern and their associated scores and additional notes

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score	Notes
CN1	Longer Duration Droughts	Long-term droughts that have longer durations than occurred in past.	4	5	20	Quotas would be set high for first few years to meet allottee requests, but in later dry years they would be lower than requested based on limited water availability. The third year of a drought will be hardest to meet with quota system. Anticipated that allottees will adjust their own water use to account for long duration drought.
CN2	Increased frequency of extreme dry years	Years like 2002 and 2011 become more frequent	4	4	16	Single extreme dry years will be more impactful on Windy Gap than C-BT. System can absorb 1-2 years of these types of drought years without impacting quotas due to large amount of storage in C-BT.
CN3	Changes in runoff volume	Long-term reductions in runoff volume due to hotter, drier climate reduce overall yield. Northern has sufficient storage to capture this and its water rights are not specific in time.	3	4	12	Historical examples in 2002 and 2012 had lower runoff due to sublimation of snowpack in a hot Spring. Climate models suggest hotter future in Upper Colorado River basin.
CN4	Changes in runoff timing	Runoff volumes shift earlier in the Spring/Summer with peak runoff occurring earlier.	5	2	10	This situation is already occurring compared to historical records. C-BT and Windy Gap West Slope water rights are not dependent on timing of runoff. However, East Slope water rights may yield less water due to earlier filling of storage facilities.
CN5	Increased Evaporation in Reservoirs	Temperature increase results in increased evaporation losses from reservoirs.	5	2	10	Most facilities are at higher altitudes with low evaporation losses, so even large percentage increases in evaporation rate would not result in significant reductions in yield.
CN6	More precipitation as rain	More precipitation falls as rain instead of snow. The impacts on yields and runoff are uncertain due to complex watershed processes.	5	2	10	Willow Creek Reservoir on West Slope is at risk of spilling due to flashy rain events.

B.2 Watersheds

The following table presents the watershed risks and uncertainties identified by Northern and their associated scores and additional notes.

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score	Notes
WN1	Changes in wildfire characteristics	Increase in extent and severity of wildfires in high elevation forests degrades water quality, increases sediment loads and changes runoff characteristics	5	4	20	Lake Granby more vulnerable to O&M impacts; Grand Lake and Shadow Mountain Reservoir more vulnerable to WQ impacts. Lack of recent fire in area increases potential negative impacts. Hot burns creating hydrophobic soils are most problematic.
WN2	Wildfires - Upstream of Grand Lake/Shadow Mountain	Increased occurrence of wildfire leads to short term reduced capacity and ability to use Grand Lake/Shadow Mountain Reservoir. Long term channel and sediment changes.	4	4	16	Increased sediment loads, water quality issues, debris flows.
WN3	Watershed forest health degradation	Poorer forest health leads to increase in wildfire risk, water quality impacts, hydrology impacts and increased sediment load.	5	3	15	Already occurring due to hotter climate and bark beetle infestation. Degraded forest affects runoff quality, generates more sediment, and increases total volume and accelerates timing of runoff.
WN4	Wildfires - East Slope	Increased occurrence of wildfires in Big Thompson River basin degrades water quality and may prevent ability to use Big T to move C-BT water. Watershed above Lake Estes has lower wildfire impact risk but higher likelihood.	4	3	12	Loveland in 2017 wasn't able to utilize their C-BT water due to water quality issues in Big Thompson. Some impacts can be bypassed using Power Arm.
WN5	Increased sediment loading	Increased sediment loading from several causes reduces reservoir or conveyance capacity and affects water quality.	4	3	12	Shadow Mountain has highest water quality risk. East Slope facilities have lower risk and can be more easily mitigated. Sediment accumulation impacts water deliveries from reservoirs less than canals.
WN6	Flooding	Major flooding events cause mostly short term impacts during which water cannot be used due to compromised water quality.	5	2	10	September 2013 is a recent example of impacts. Most facilities are robust against flooding and have redundancy in the system.
WN7	Development in Fraser Valley	Residential development increases water quality risks due to urban runoff, return flows and more septic systems.	4	1	4	Potential for urban development in Fraser Valley is greater than around Lake Granby, Shadow Mountain and Grand Lake. Fraser River is tributary to Upper Colorado upstream of the C-BT and Windy Gap pumping plants that pump water into Granby and ultimately Adams Tunnel.
WN8	Wildfires - East Slope Reservoirs	Wildfires in East Slope reservoir watersheds (e.g., Horsetooth Reservoir watershed) affects water quality, sediment loading and runoff characteristics for drainage into the reservoirs.	4	1	4	Past events in the Horsetooth Reservoir watershed and others have had low impact on water quality or sediment due to ability to implement mitigation measures.
WN9	Development above Lake Granby	Residential development increases water quality risks in Lake Granby and Tri-Lakes system.	3	1	3	Minimal space is available for new development to occur, which reduces impact of risk.

B.3 Operations and Infrastructure

The following table presents the operations and infrastructure risks and uncertainties identified by Northern and their associated scores and notes.

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score	Notes
ON1	Green Mountain Replacement Pool Inadequacy	With changing hydrology the 52,000 acre-ft replacement pool may be inadequate to mitigate against a variety of future risks.	4	4	16	Due to hydrologic uncertainty in the Colorado River, the efficiency of the 52,000 acre-ft pool to replace C-BT system out of priority depletions could be affected. Key element of Northern's West Slope operations.
ON2	Unit No3 of Flatiron Facility Outage	Failure of Unit 3 in the Flatiron Pump Station prevents pumping water into Carter Lake	4	3	12	
ON3	Power Arm Outage	Failure of Power Arm prevents moving water into Carter Lake	4	3	12	
ON4	Southern Water Supply Project Outage	Failure of Southern Water Supply Project prevents delivering water to southern allottees	3	4	12	This affects distribution pipes and canals but not C-BT or Windy Gap yield.
ON5	EPA Transfer Rule	New EPA policy on transbasin diversions makes all existing and future C-BT/Windy Gap subject to discharge requirements	2	5	10	Would require new/increased treatment to meet discharge standards and could reduce yields of water quality requirements could not be met.
ON6	East Slope Water Rights Uncertainty	Runoff timing changes or increased basin demands impact Northern's yields from East Slope rights and change operation of reservoirs.	3	3	9	
ON7	Power Transmission Lines Outages	Wildfire or other emergency causes outage in transmission lines providing power to C-BT/Windy Gap pump stations.	3	3	9	Would take affected pump stations offline for a short period of time (< 1 year)
ON8	Algal Blooms	Increased nutrients and temperatures cause algal blooms in reservoirs, impacting suitability of water supply for potable uses	4	2	8	Potential effects include cyanobacteria and taste/odor issues.
ON9	Aquatic Plants	Increased nutrients and invasive plants grow in reservoirs and canals, impacting operations and potentially increasing treatment requirements	4	2	8	Potential effects include increased treatment requirements, decreased canal capacity, changes in operations. Requires drawdowns of reservoirs for maintenance, restricting operations.
ON10	Invasive Species - Mussels	Mussels clog inlet/outlet pipelines which combined with lack of redundancy may cause short term outages.	2	4	8	Once species invade they cannot be removed. Water providers in other parts of state have successfully managed or mitigated this issue.
ON11	Grand Lake Clarity	Managing to meet clarity requirements leads to less operational flexibility in the system.	4	2	8	May lead to fewer days of diverting through Adams Tunnel, increasing spills from West Slope reservoirs and lowering overall yield.

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score	Notes
ON12	Conveyance Systems to Horsetooth Outage	Variety of events could cause outages or reduced in deliveries in conveyance system components to Horsetooth Reservoir	2	4	8	
ON13	Power Generation vs. Water Delivery Operations	Power generation may be given preference over delivering water in C-BT operations	2	4	8	Current priority is for water delivery with incidental power generation, but that could change in the future.
ON14	Grand River Ditch Breach	Failure of the ditch brings sediment into Shadow Mountain/Grand Lake that causes operational changes.	2	3	6	Linked to Grand Lake Clarity issues.
ON15	Conveyance Systems from Carter Lake Outage	Variety of events could cause outages or reduced deliveries from Carter Lake	2	3	6	This is a delivery system problem. No effect on C-BT/Windy Gap yield.
ON16	Boulder Reservoir Shared Operations	Increased constraints due to Boulder operations impacts ability to deliver water to southern allottees.	2	3	6	
ON17	Farr Pump Plant Outage	Pump station failure prevents moving water from Lake Granby to Grand Lake and Adams Tunnel.	1	5	5	
ON18	Adams Tunnel Outage	Tunnel failure prevents moving all C-BT/Windy Gap water to East Slope.	1	5	5	The Adams Tunnel is the only way for NCWCD to access their West Slope Supplies. However, it is well maintained and unlikely to experience and outage (other than planned). If an outage were to occur this would be catastrophic with no alternative.
ON19	Lake Granby Dam/Dike System Outage	Reduced capacity due to safety reduction or other outage issue limits ability to move water to Grand Lake and Adams Tunnel	1	5	5	
ON20	Windy Gap Plant Outage	Pump station failure prevents transfer of Windy Gap water into the C-BT system	1	4	4	
ON21	Power Arm and Dille Tunnel Failure (Concurrent)	Concurrent failure of both conveyance facilities would prevent delivering water to Horsetooth.	1	4	4	Would need to occur in combination to completely prevent delivering water to Horsetooth Reservoir.
ON22	Willow Creek Pump Plant Outage	Pump station failure prevents pumping C-BT water into Lake Granby and reduce system yield	1	3	3	

B.1 Legal and Administrative

The following table presents the legal and administrative risks and uncertainties identified by Northern and their associated scores and notes

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score	Notes
AN1	Environmental Regulations (changes, new, compliance)	New regulations or changes in federal permitting compliance may lead to more water used for environmental mitigation/flows.	3	4	12	Combination of Federal Permitting Compliance (NEPA, ESA Section 7, USACE 404) and New Endangered Species risks. Critical habitat for listed threatened/endangered species designated within watersheds. This could lead to additional water being unavailable to meet environmental flow needs--or for replacement infrastructure to be inaccessible.
AN2	Colorado River Hydrologic Uncertainty / Major Outage of C-BT Project	Possible changes in C-BT operations based on hydrologic uncertainties and a large C-BT Project outage	2	5	10	Combination of several possible conditions resulting in decreased deliveries from C-BT Project water to allottees. These scenarios are intended to assess the impact of outages of major C-BT delivery systems or reduced diversions caused by reduced flows in the Colorado River that are not dependent on currently unknown future hydrology or legal requirements.
AN3	Windy Gap renegotiation	When current 40-year contract limit expires, a renegotiated contract gives less yield (due to increased shrink for example)	5	2	10	
AN4	Federal law requires modification of Project Operations	Federal law requires changes in how the C-BT Project is operated (e.g. for endangered species, power), reducing C-BT/Windy Gap yield	2	4	8	

B.1 Demands

The following table presents the demand risks and uncertainties identified by Northern and their associated scores and additional notes.

ID	Risk or Uncertainty Name	Description	Likelihood Score	Impact Score	Composite Score	Notes
DN1	Longer Growing Season	Hotter, drier climate lengthens the growing season for agricultural and M&I allottees, increasing their demands and changing when they need C-BT/Windy Gap water	5	2	10	This is already occurring. Allottees not directly connected can only take water from April 1 - November 1. That's a policy that could be changed. May change how quotas are used and increase overall basin demand.
DN2	Changes in C-BT Users	Continued shift in C-BT ownership to M&I users, who would want quotas set differently than agricultural users.	5	1	5	M&I allottees emphasize use as a reliable water supply which would lead to increased carryover in system and desire for overall lower quota. Ag allottees emphasize higher use in drier years as a supplemental water supply as originally intended.
DN3	Uncertainty of Setting Quota	Change in ownership and Board membership changes the process by which quota is set. May be narrower range to satisfy M&I allottees.	3	1	3	May need to explore different quota policies since the nature and direction of changes is uncertain.
DN4	Increase in quota use	Quotas are not set as high, but as time goes on actual water use is closer to the quota amount.	4	1	4	This is already occurring.
DN5	Northern Water Management Program Changes	Changes to the Annual Carryover Storage program or Regional Pool program occur, making water management for M&I allottees less flexible.	3	1	3	Would only occur due to West Slope interests or Federal operations change. M&I allottees prefer more flexibility so any changes are likely to have minimal effect.

Appendix C WATER DEMAND FORECASTING TOOL TECHNICAL MEMORANDUM

Water Vulnerability Study

Technical Memorandum

Demand Estimation Documentation

Date: March 8, 2019 (Revised May 13, 2019)

From: Zelalem Mekonnen, Jason Polly and Enrique Triana
RTI International

To: City of Fort Collins Utilities

1 Introduction

This technical memorandum documents the main aspects of the demand estimation tool developed as part of the Water Supply Vulnerability Study for the City of Fort Collins Utilities (FCU). The development of the demand estimation tool incorporates the variables and computation algorithm used in the demand model, which was developed by FCU staff with data provided by RTI. The demand model consists of individual linear regression models developed for the main water customer users, i.e., single family and duplex, multifamily, commercial small, commercial medium and commercial large. The models were developed with processed water use from 2001-2016, which corresponds to the set of available years with complete water user data. The underlying data for the tool is derived from spatial processing of GIS layers and groupings of the variables by areas and sectors matching the demand models.

2 Data Processing Summary

2.1 Raw Data Source

Raw water use data from 2001 to 2016 provided by FCU was processed spatially using GIS premise (customer) points overlaid with parcels, and linking it to features associated with both the parcels and the premises, for example, building characteristics, irrigated areas, service areas, water districts. The spatial process resulted in a GIS summary table—the "Master Table"—that is imported into the water use database and is used by the demand estimation tool.

2.2 Water Use Database

The water use data was compiled into a water use database for this project. The water use database is maintained on the FCU server and it was used for data processing and data storage, as well as to develop the demand estimation tool. Table 1 provides general information about the database. This database includes imports of the raw use data, imports of the GIS Master Table, and preferences and scenarios of the demand models.

Table 1 – Water Use Database Information

SQL SERVER	10.100.0.87\DEV16
DATABASE NAME	FCU_WaterUseProcessing

2.3 GIS Master Table

The Master Table combines the spatial characteristics related to water use and demand estimation variables at a parcel resolution. It was developed to support the demand estimation tool and provides improved flexibility in calculating the elements of the demand. This table is composed of rows that represent polygons with unique water use characteristics.

2.3.1 Master Table Development

The Master Table refers to a single table resulting from a series of spatial and tabular process steps. The process was designed to relate water demand information to City of Fort Collins parcels. The development of the Master Table was performed in a GIS environment as most data inputs were spatial in nature and were not available within a pre-existing relational database.

2.3.1.1 Background

To construct the Master Table, RTI acquired pre-existing GIS layers from the City of Fort Collins. A demand model GIS database was developed to store raw data and resulting outputs. A GIS model was developed to process the raw data and produce the processed Master Table with related information.

2.3.1.2 Data Inputs

Table 2 lists the raw data used as base GIS layers.

Table 2 – Input Raw GIS Layers

LAYER ID	LAYER DESCRIPTION
1	Buildings
2	City Limits
3	Fort Collins Service Area
4	Growth Management Area (GMA)
5	Hydro
6	Natural Areas
7	Parcels
8	Water Districts
9	Zoning
10	Future Land Use Zoning
11	Meters
12	Traffic Analysis Zones (NRFMPO TAZ)

2.3.1.3 Development Framework

The framework used for developing the Master Table involved ESRI ArcGIS desktop software version 10.5. Within the software, an ESRI geodatabase was designed and populated with the raw data inputs. Feature datasets were used to separate data by source and type. ModelBuilder was then used to develop geoprocessing steps needed to relate layers under specific environments.

2.3.1.4 Model Steps and Results

Within ModelBuilder, a series of geoprocessing steps was constructed as outlined in Table 3.

Table 3 – High-Level Overview of Processing Steps Used in the Model

STEP ORDER	DESCRIPTION
1	Join Zoning to Parcels
2	Select Parcels by GMA
3	Dissolve on Shape
4	Add Unique Parcel ID
5	Tabulate Building Area for Parcel
6	Tabulate Meter Count for Parcel
7	Join Density Assumption Min/Max Values
8	Join Meter Premise ID
9	Join Future Land Use
10	Join Water Body Area
11	Join NFRMPO TAZ Populations
12	Calculate Demand DU
13	Calculate Demand Population
14	Join Fort Collins SA
15	Join City Limits
16	Join GMA

The final output GIS layer contains related information based off each tabular and spatial step. The polygons represented in the Master Table and the Growth Management Area (GMA) boundary are shown in Figure 1. The final GIS layer attribute table, or Master Table, was imported into the water use database in the ***MasterTableGISExport*** table. The Master Table plays an important role in the demand estimation method providing information about current densities in planning zones for future predictions of water use in undeveloped areas. Also, the Master Table allows grouping of current use and estimated water use by planning zones and areas of the city, such as FCU service areas, city limits, and GMA. Some of the main assumptions in the Master Table data and processing are:

- The planning zones are taken from the current data and areas without current planning zone classification are assigned with the future planning zone estimate.
- The GIS layers are current and complete.

The attribute table was then exported to be used within the demand analysis.

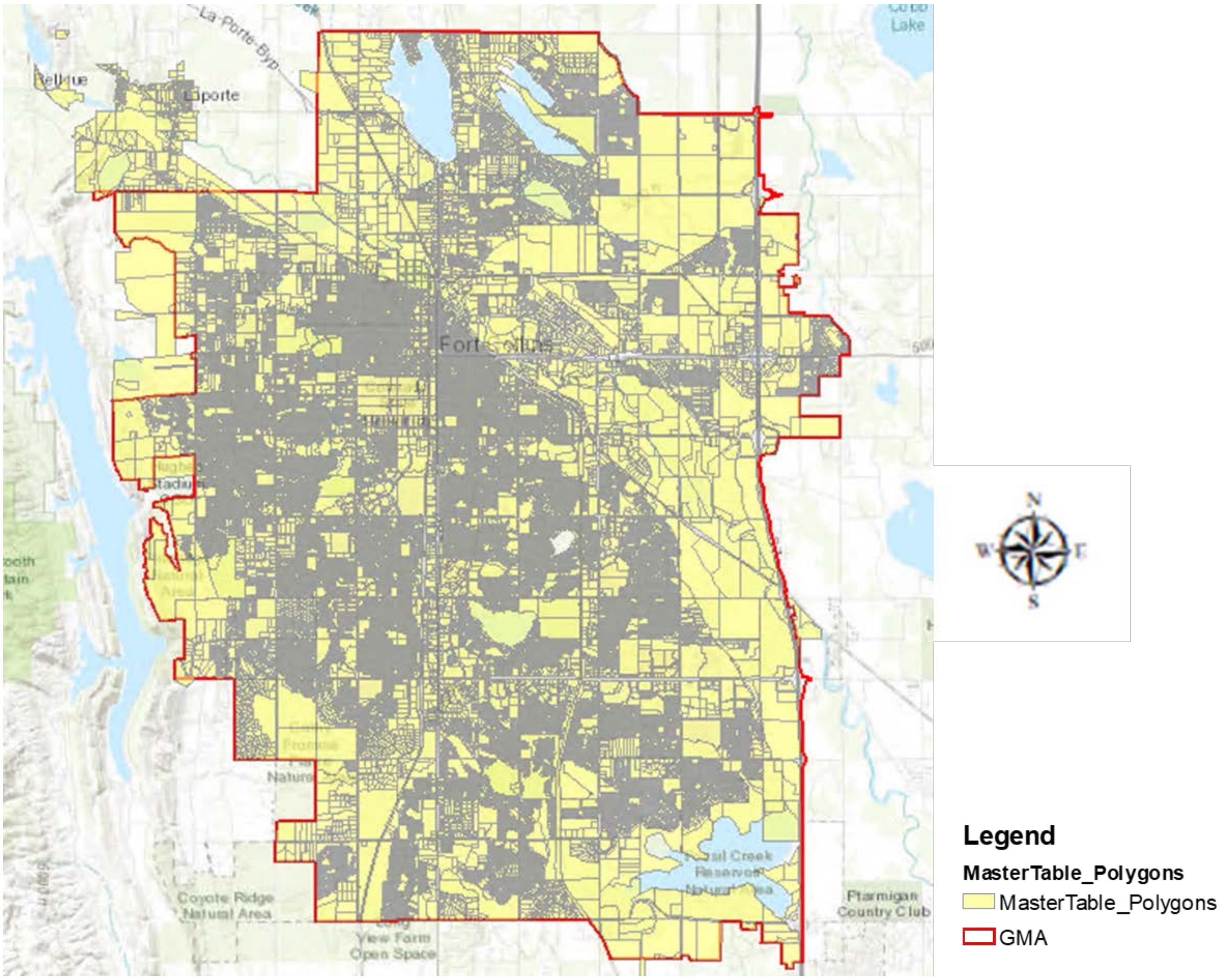


Figure 1 - Master Table Polygon Extent

Table 4 lists the fields and the different sources for each polygon in the Master Table.[1] Although not all the fields included in the current Master Table are used in the demand estimation model, the information in the table was left there for future reference and analyses.

[1] Polygons in the Master Table refer to parcel polygons from the city and county, identified by a unique parcel number.

Table 4 – Master Table Fields

FIELD	SOURCE	UNITS (if applicable)	DESCRIPTION
ZONE	City Current and Future Zoning	Zone Type	Spatial join of zone layers to parcel (current method for this field, only uses the current city zoning layer) values are null for nonzoned locations. Null values are filled with future zones from the Planning Department.
PARCEL_ID	Unique Parcel ID (RTI)	ID	RTI calculates a unique parcel ID for general tracking.
AREA	City Building	Sq ft	Area of building (footprint) within parcel using City building layer.
PERCENTAGE	Building Percentage	Percentage	Percentage of parcel covered by building (footprint).
PNT_COUNT	Count of premises, per parcel	Count	Tabular summary of premises within a parcel. Note, parcels with no premise are set to 1.
ZONE_DISTR	Source 2017 re-development worksheet		A residual field from the planning density table (used for join on zone type), not of use.
VACANT_AC	Source 2017 re-development worksheet		A residual field from the planning density table (used for join on zone type), not of use.
REDEV_ACRE	Source 2017 re-development worksheet		A residual field from the planning density table (used for join on zone type), not of use.
RES_LUM	Source 2017 re-development worksheet		Residential Land Use Mix – represents the percent of area in the zone that is residential. This parameter is used in the calculation of DEMAND_DU in the Master Table.
NONRES_LUM	Source 2017 re-development worksheet		A residual field from the planning density table (used for join on zone type), not of use.
AVG_DEN_DU	Source 2017 re-development worksheet		A field from the planning density table (used for join on zone type). Provides density values per zone.
AVG_DEN__F	Source 2017 re-development worksheet		A residual field from the planning density table (used for join on zone type), not of use.
DWEL_UNIT_	Source 2017 re-development worksheet		A residual field from the planning density table (used for join on zone type), not of use.
DWEL_UNIT1	Source 2017 re-development worksheet		A residual field from the planning density table (used for join on zone type), not of use.
NONCAP	Source 2017 re-development worksheet		A residual field from the planning density table (used for join on zone type), not of use.
NONCAP_SQ_	Source 2017 re-development worksheet		A residual field from the planning density table (used for join on zone type), not of use.
SDP	Premise (Meters) GIS layer		Spatial join (Premise-Parcel) using City (Meter/Premise) layer.
PREMISE	Premise (Meters) GIS layer	ID	Spatial join (Premise-Parcel) using City (Meter/Premise) layer.
SERVICETYP	Premise (Meters) GIS layer		Spatial join (Premise-Parcel) using City (Meter/Premise) layer.
SERVICECOD	Premise (Meters) GIS layer		Spatial join (Premise-Parcel) using City (Meter/Premise) layer.

FIELD	SOURCE	UNITS (if applicable)	DESCRIPTION
ADDRESS	Premise (Meters) GIS layer		Spatial join (Premise-Parcel) using City (Meter/Premise) layer.
CUSTOMERCO	Premise (Meters) GIS layer		Spatial join (Premise-Parcel) using City (Meter/Premise) layer.
STATUS	Premise (Meters) GIS layer		Spatial join (Premise-Parcel) using City (Meter/Premise) layer.
GMA	City GMA Layer		Spatial join (GMA-Parcel) (Null if outside) using City GMA layer.
SERVICEARE[2]	City Service Layer		Spatial join (Service Area-Parcel) (Null if outside) uses City Service Layer).
CLIMITS	City Limits Layer		Spatial join (City Limits-Parcel) (Null if outside) uses City Limits Layer.
PARCEL_ACR		acres	GIS area calculation (Parcel).
DEMAND_DU	Dwelling Unit Calculation		Used for checking the number of dwelling units for demand calculation ([Acres] * [Res_LUM]) * [Avg_Den_du_a].
DEMAND_POP	Population Calculation	Count	(([Acres] * [Res_LUM]) * [Avg_Den_du_a] * 2.37) / [PNT_COUNT].
HYDRO	Water Bodies GIS Layer		Spatial join, identifies parcels with a water body.
F_LU	City Future Zoning GIS Layer	Zone Type	Spatial join on future layers to parcel (Current method for this field, only uses the future zoning layer).
EMPDEN_12	NFRMPO_TAZ_12to40		Employment density (Assumed SqMi).
EMPDEN_15	NFRMPO_TAZ_12to40		Employment density (Assumed SqMi).
EMPDEN_20	NFRMPO_TAZ_12to40		Employment density (Assumed SqMi).
EMPDEN_25	NFRMPO_TAZ_12to40		Employment density (Assumed SqMi).
EMPDEN_30	NFRMPO_TAZ_12to40		Employment density (Assumed SqMi).
EMPDEN_35	NFRMPO_TAZ_12to40		Employment density (Assumed SqMi).
EMPDEN_40	NFRMPO_TAZ_12to40		Employment density (Assumed SqMi).
IRR_ACRES	WV2 imagery and LiDAR data	acres	Outdoor irrigation classification.

2.4 Water Use Processing

2.4.1 Water Use Process

The customer water use data used for the Vulnerability Study was provided by FCU, and initially processed by a group at Colorado State University (CSU) as part of a parallel effort. The residential single-family, multi-family, and commercial datasets for the FCU service area were provided in three different batches and imported into the ***RawWaterUseResidential***, ***RawWaterUseMultiFam***, and

[2] This attribute in the current Master Table was generated from the original service area map and was not updated with a revised service area provided in 2018. This attribute is used to group the parcels by utility service area and will need to be updated in the future with revised service area map.

RawWaterUseCommercial tables of the database. The modeling management system includes a processing algorithm with a user interface (Figure 2).

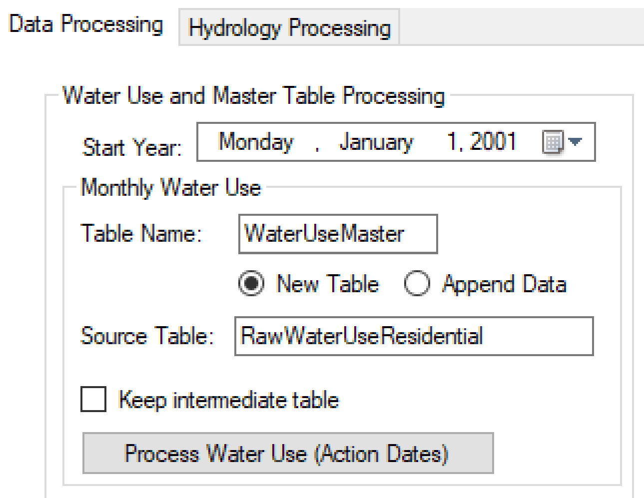


Figure 2 – Water Use Processing Algorithm User Interface

Each entry of the raw water use data includes an action date and days of service (DOS). Missing action dates were filled using the CSU-processed dataset. The water use meter readings for a customer, or premise, are typically around a month apart. However, in some cases, the reading includes multiple months in the DOS. RTI developed an algorithm to process the water use data to generate an approximation of the monthly water use per premise. The algorithm was implemented using SQL queries and VB.NET code. The main steps of the water use processing algorithm are:

1) For each record of water use in the imported data, the '***previous date***' is calculated as the action date minus the DOS.

2) Average water use per day is computed by dividing the consumption in gallons (i.e., **Consumption** field in the raw data table) by the DOS.

3) The number of days in the action month (i.e., the number of days from the beginning of the month to the action date), is multiplied by the average water use per day found in step 2 to calculate the partial water use in the action month.

4) Water use from the previous month or months to the action month, included in the DOS, are computed based on the average daily consumption calculated in step 2 and the number of days from the 'previous date' to the end of the month, or months if more than one is included in the DOS.

5) The monthly water use is estimated by aggregating the water use estimates for each portion of the month between readings.

The results of the water use data processing are stored in the water use database in the ***WaterUseMaster*** table. Some multifamily complexes are coded as single commercial users in the water use dataset; therefore, the processing of the water use data included recoding the rate code of multi-family premises that have a rate code as commercial in the raw water use dataset. The list of commercial premises that were converted to multifamily rate code (i.e., W260) for the demand calculation are included in Appendix 1. This change was performed in the ***WaterUseMaster*** table. The list of premises was compiled and provided by FCU and includes information about the type of use (e.g., irrigation, club, indoors). Note that the revenue from the raw water use data is also processed into the ***WaterUseMaster*** table, summarized by month.

2.4.2 Commercial Customer Groups

The size of the taps associated with the rate code were used to group the commercial water use as Commercial Small (CM_Sm), Commercial Medium (CM_Md), or Commercial Large (CM_Lg). Table 5 shows the rate codes for commercial taps with the corresponding group.

Table 5 – Rate Code Groups for Commercial Premises

UTVSRAT_CODE	UTVSRAT_DESC	COMMERCIAL GROUP
W524	Commercial 3"	CM_Lg
W525	Commercial 4"	CM_Lg
W528[3]	Commercial 10"	CM_Lg
W534	Commercial 3" Outside	CM_Lg
W535	Commercial 4" Outside	CM_Lg
W544	Commercial 3"-Compound	CM_Lg
W545	Commercial 4"-Compound	CM_Lg
W554	Commercial 3" Outside-Compound	CM_Lg
W555	Commercial 4" Outside-Compound	CM_Lg
W624	City FC account 3"	CM_Lg
W625	City FC account 4"	CM_Lg
W644	City FC account 3" Compound	CM_Lg
W645	City FC account 4" Compound	CM_Lg
W626	City FC account 6"	CM_Lg68
W627	City FC account 8"	CM_Lg68
W556	Commercial 6" Outside-Compound	CM_Lg68
W557	Commercial 8" Outside-Compound	CM_Lg68
W546	Commercial 6"-Compound	CM_Lg68
W547	Commercial 8"-Compound	CM_Lg68
W536	Commercial 6" Outside	CM_Lg68
W537	Commercial 8" Outside	CM_Lg68
W526	Commercial 6"	CM_Lg68
W527	Commercial 8"	CM_Lg68
W522	Commercial 1 1/2"	CM_Md
W523	Commercial 2"	CM_Md
W532	Commercial 1 1/2" Outside	CM_Md
W533	Commercial 2" Outside	CM_Md
W542	Commercial 1 1/2"-Compound	CM_Md
W543	Commercial 2"-Compound	CM_Md
W552	Commercial 1 1/2" Outside-Compound	CM_Md
W553	Commercial 2" Outside-Compound	CM_Md
W622	City FC account 1 1/2"	CM_Md

[3] This rate code included in the CM_Lg was not included in the analysis because there are no water use records with this rate code.

UTVSRAT_CODE	UTVSRAT_DESC	COMMERCIAL GROUP
W623	City FC account 2"	CM_Md
W633	City FC account 2" outside	CM_Md
W640	City FC account 3/4" Compound	CM_Sm
W550	Commercial 3/4" Outside-Compound	CM_Sm
W551	Commercial 1" Outside-Compound	CM_Sm
W620	City FC account 3/4"	CM_Sm
W621	City FC account 1"	CM_Sm
W630	City FC account 3/4" outside	CM_Sm
W530	Commercial 3/4" Outside	CM_Sm
W531	Commercial 1" Outside	CM_Sm
W540	Commercial 3/4"-Compound	CM_Sm
W541	Commercial 1"-Compound	CM_Sm
W520	Commercial 3/4"	CM_Sm
W521	Commercial 1"	CM_Sm

3 Demand Estimation Approach

This section describes the main elements for estimating future water demand for the Vulnerability Study. This section is organized following the sections of the graphical user interface (GUI) for the demand estimation tool. Figure 3 shows the GUI of the demand estimation tool.

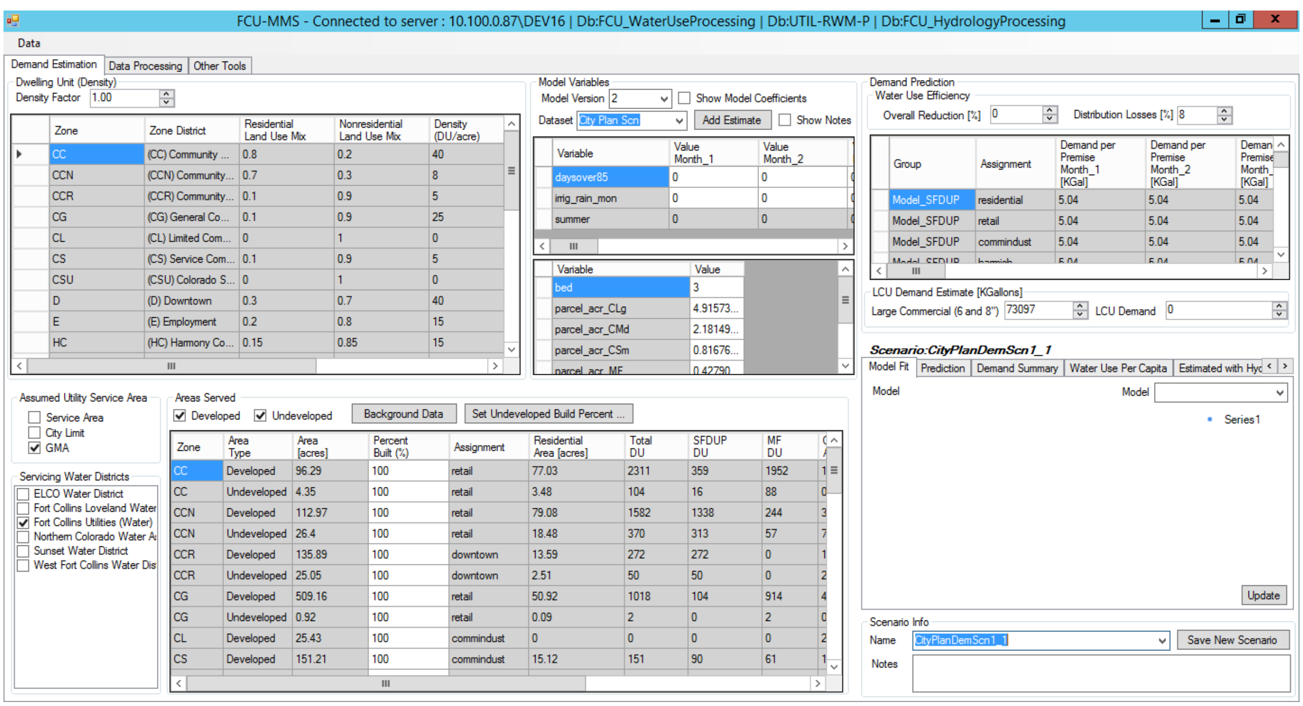


Figure 3 – Main Window of the GUI for the Demand Estimation Tool

In this section, this icon identifies user inputs and knobs implemented for the demand estimation.

The GUI displays read-only fields with gray background and fields with white background are user inputs that are saved as part of the demand scenarios.

3.1 Demand Models

Monthly demand models were developed by FCU using the processed water use data and customer groupings described in Section 2. A set of five models were developed to predict the average water use per premise per month, one model for each of the five water user types. The models estimate water use for single-family and duplex (***SFDUP***) customers, multi-family (***MULTIFAMILY***) customers, commercial small (***CM_SMALL***) customers, commercial medium (***CM_MED***) customers, and commercial large (***CM_LARGE***) customers. The models were developed using multi-regression linear equations and the independent variables were selected based on the expected influence on the water demand and the statistical significance in the regression equation. Table 6 lists the independent variables used in the demand models and provides a brief description of each variable.

Table 6 – List and Description of Variables Used in the Demand Models

VARIABLE NAME	DESCRIPTION
(INTERCEPT)	Equation constant
BED	Number of bedrooms
COMMINDUST	Equals 1 if primarily an industrial or commercial zone
DAYSOVER85	Numbers of days in the month with the max temp over 85
DOWNTOWN	Equals 1 if primarily a downtown zone
HARMISH	Equals 1 if primarily a harmony corridor or employment zone
IRRIG_RAIN_MON	Total rain in the month, only for May through September, equals zero for the other months
PARCEL_ACR_CLG	Parcel size, acres for large commercial
PARCEL_ACR_CMD	Parcel size, acres for medium commercial
PARCEL_ACR_CSM	Parcel size, acres for small commercial
PARCEL_ACR_MF	Parcel size, acres for multi-family parcels
PARCEL_ACR_SMDUP	Parcel size, acres for single family and duplex parcels
RESIDENTIAL	Equals 1 if primarily a residential zone
RETAIL	Equals 1 if primarily a retail zone
SUMMER	Equals 1 if May through Sept
UNEMPRATE	Unemployment rate (monthly)
UNITS	Numbers of units

Table 7 shows a matrix of coefficients for each model and associated independent variable. The cells without a coefficient indicate that the variable is not being used in the corresponding equation.

Table 7 – Multi-Regression Coefficients for Each Variable for Each Demand Model

VARIABLE NAME	MODEL_SFDUP	MODEL_MULTIFAMILY	MODEL_CM_SMALL	MODEL_CM_MED	MODEL_CM_LARGE
(INTERCEPT)	3.339288	-2.48736	-4.55557	16.8763	494.2393
BED	0.649969	--	--	--	--
COMMINDUST	--	--	17.53072	18.07031	0
DAYSOVER85	0.27546	0.314547	0.510495	2.750474	12.36749
DOWNTOWN	--	--	14.10856	7.944732	-477.687
HARMISH	--	--	24.15817	62.20441	-148.861
IRRIG_RAIN_MON	-0.59813	-0.75359	-1.12143	-6.04083	-24.7921
PARCEL_ACR_CLG	--	--	--	--	2.546953
PARCEL_ACR_CMD	--	--	--	5.583365	--
PARCEL_ACR_CSM	--	--	3.819985	--	--
PARCEL_ACR_MF	--	16.72416	--	--	--
PARCEL_ACR_SMDUP	0.168519	--	--	--	--
RESIDENTIAL	--	--	26.85123	60.74893	-189.977
RETAIL	--	--	25.25629	44.90526	-254.067
SUMMER	5.332035	11.26788	15.46997	66.94185	185.1742
UNEMPRATE	-0.05027	0.023827	-0.48881	-1.50572	-8.93112
UNITS	--	2.925005	--	--	--

3.2 Future Premises Estimation

The approach uses the density of dwelling units per acre per planning zone as the basis to estimate the number of premises by zone.

3.2.1 Dwelling Units Density

3.2.1.1 Dwelling Units per Zone

The densities provided by the Fort Collins Planning Department include assumptions on the city's projected infill and vertical growth per zone. Therefore, by using these densities, the user is considering a future growth characteristic.

The Planning Department also provides a residential and non-residential percentage for each zone. The estimation of dwelling units (DUs) is based on the estimated area per zone and the '***Residential Land Use Mix***' value provided by the Planning Department. Premises are associated with water user accounts. Single family residential units are usually associated with a single premise, duplex units could have multiple premises but for this analysis those are assumed to have a single premise. Typically, multifamily complexes have multiple DUs and fewer number of associated premises, with some premises (accounts) used for club houses and pools.

Density Factor The user can use the ***Density Factor*** to evenly reduce or increase all the densities simultaneously to simulate sensitivities around the base future density conditions for the demand estimation. A ***Density Factor*** of 1 is equivalent to the future densities provided by the Planning Department. This factor is applied to the base densities to create the '***Active Density***' value for each zone, which is used in the demand estimation.

Active Density — This variable allows the user to set the density for each planning zone to be used in the calculation of DUs. These values are affected by the ***Density Factor***; however, these results can be overwritten by user inputs. Note that user values will be overwritten if the Density Factor is changed.

The density (i.e., DUs per acre) and the residential area, determined by the residential and non-residential percentages provided by the Planning Department, are used to calculate the number of DUs per zone (‘***Total DU***’).

3.2.1.2 Multi-Family Percentage

The multi-family (MF) percentage of the residential DUs (‘***MF Percent***’) is calculated from the Master Table, using the planning zones and rate codes for residential groups. This calculation is performed for the polygons that are flagged as built, which are premises where the ***Buildable*** field is NULL or 0. Table 8 shows the rate codes used for the single-family/duplex (SF_DU) group and the MF group.

Table 8 – Rate Code and Groups for Residential Premises

RATE CODE	DESCRIPTION	GROUP
W220	Single-family metered	SF_DU
W221	Single-family flat rate	SF_DU
W230	Single-family metered outside	SF_DU
W240	Duplex metered	SF_DU
W241	Duplex flat	SF_DU
W250	Duplex metered outside	SF_DU
W260	Multi-family metered	MF
W262	Master meter	MF
W270	Multi-family metered outside	MF
W272	Master meter outside	MF
W280	Multi-family metered-compound	MF

The number of DUs for multi-family premises is calculated using a representative number of units (DWs) per premise, which is seven units per premise, base on the average of units per multifamily account calculated from the water use data. This average is used in the demand model to estimate the number of premises for the number of multifamily DUs in each zone. For each planning zone, the ***MF Percent*** is computed as the percentage of DUs (i.e., number of premises times the average number of DUs per premise) in each zone with MF rate codes divided by the total number of residential DUs in the zone, calculated as the number of single-family DUs plus the number of multi-family DUs.

3.2.2 Assumed Utility Service Area

There are three service area options available in the demand estimation tool,: (1) FCU service area, (2) city limit, and (3) GMA. These options are used to filter the parcels that are included in the calculation of the served areas for estimating DUs. The groups are defined in the Master Table (see Section 2) and are used to estimate the areas for each planning zone.

The water districts that serve the City and the GMA (‘***Servicing Water Districts***’) are listed under this option and can be used to further filter the parcels to be included in the demand estimation. Figure 4 shows the spatial extent of the FCU service area, the city limit, the GMA, and the water districts that supply water within the GMA. Of note, the FCU Service Area attribute in the current Master Table was generated from the original service area map and was not updated with a revised service area provided in 2018 (Fort Collins Utilities Water). This attribute is used to group the parcels by utility service area and will need to be updated in the future with revised service area map.

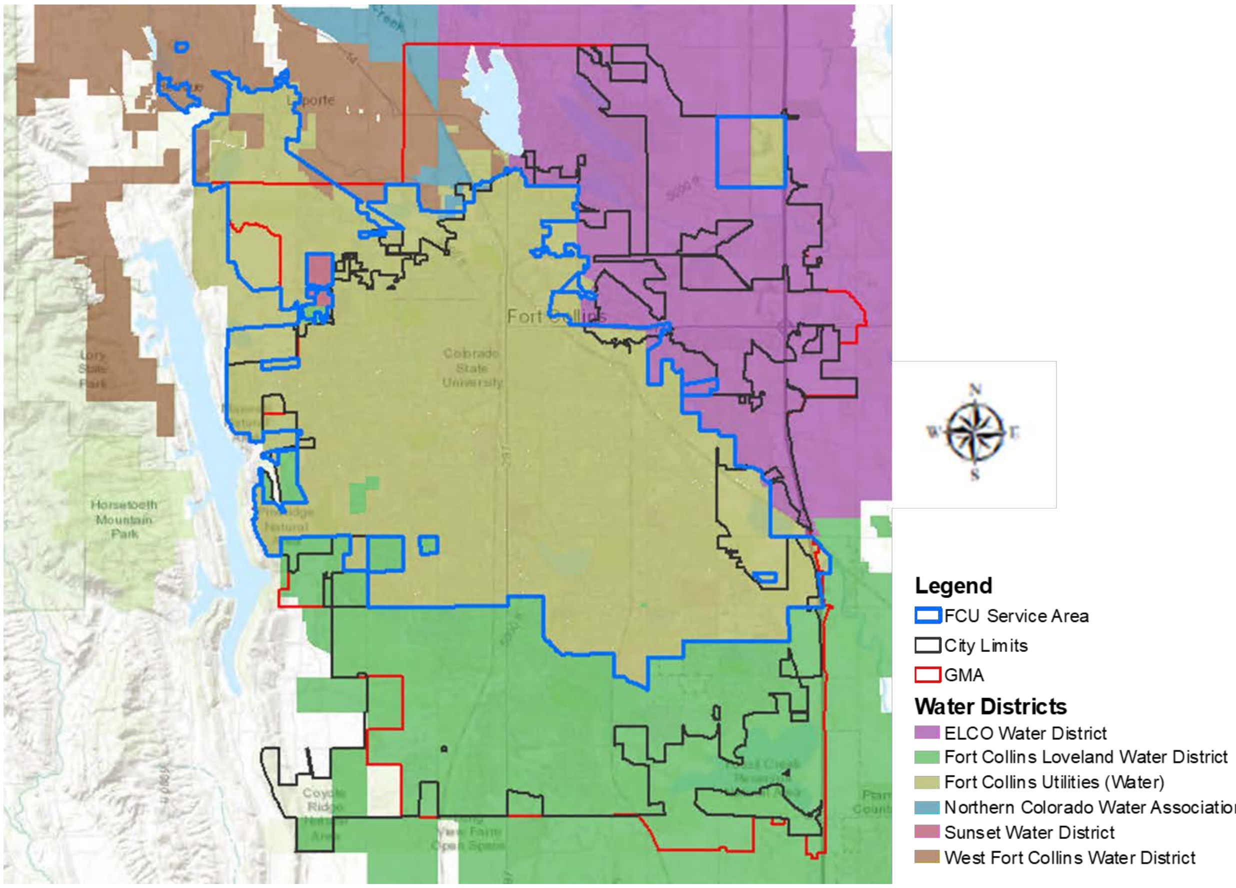


Figure 4 – Spatial Extent of the Service Area, the City Limit, the GMA, and the Water Districts

3.2.3 Areas Served

The Areas Served section includes a breakdown of areas and premises per planning zone and area type, which indicate if the area is currently developed or undeveloped. The areas displayed in this table include the parcels that correspond to the filters in the assumed utility service areas and the water districts served.

The ***Undeveloped*** area type corresponds to the polygons flagged as buildable lands in the Master Table, which are based on the buildable land map from the Planning Department. Figure 5 shows the general location of the buildable areas in the GMA. The ***Developed*** areas are assumed to be the polygons that are not in the buildable areas.

Percent Built The '***Percent Built***' represents the percentage of the area per zone and area type that is considered for the demand calculations. This parameter is set by the user and allows simulating scenarios prior to build-out conditions, assuming only a fraction of the area selected is served at that time.

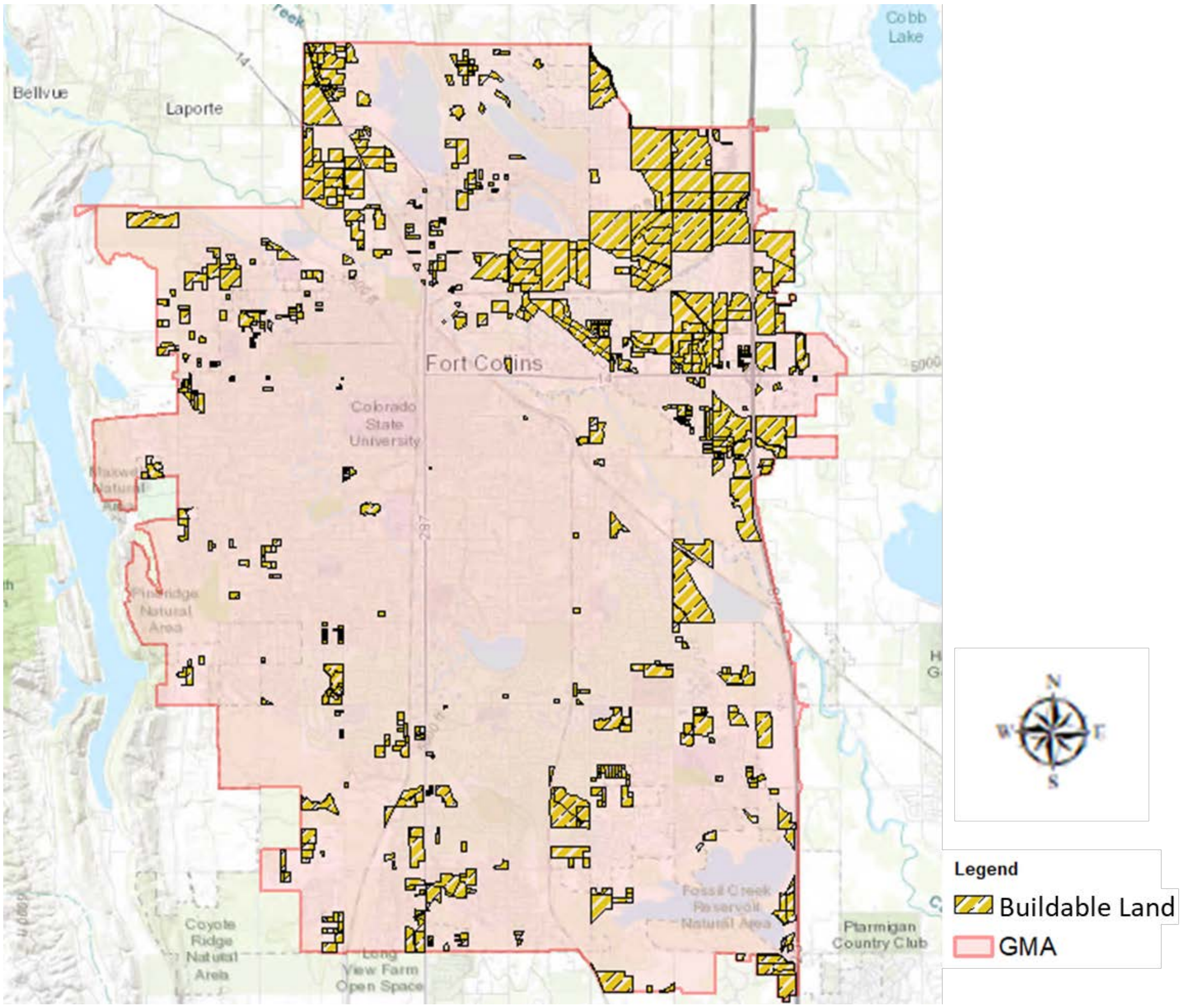


Figure 5 – Parcels Flagged as Buildable in the GMA

The served areas are computed from the Master Table using all the polygons in each zone and grouping them as developed or undeveloped. This calculation includes the spatial filters for water districts and utility service areas, as well as the Percent Built factor. The undeveloped area ('***Area [Acres]***') is computed based on the parcels identified in the buildable layer and the developed areas ('***Area [Acres]***') are calculated from the Master Table for the remaining polygons in the parcel layer in each zone and area type.

The '**Assignment**' is a grouping of the commercial users created to improve the prediction of the demand per premise by the commercial customer models. Each planning zone is put into one Assignment group. Table 9 shows the Assignment corresponding for each planning zone included in the model.

Table 9 – Assignment Group for Planning Zones

ZONE	ZONE_DISTR	ASSIGNMENT
CC	Community Commercial	retail
CCN	Community Commercial - North College	retail
CCR	Community Commercial - Poudre River	downtown
CG	General Commercial	retail
CL	Limited Commercial	commindust
CS	Service Commercial	commindust
D	Downtown	downtown
E	Employment	harmish
HC	Harmony Corridor	harmish
HMN	High Density Mixed-Use Neighborhood	residential
I	Industrial	commindust
LMN	Low Density Mixed-Use Neighborhood	residential
MMN	Medium Density Mixed-Use Neighborhood	residential
NC	Neighborhood Commercial	retail
NCB	Neighborhood Conservation Buffer	downtown
NCL	Neighborhood Conservation Low Density	residential
NCM	Neighborhood Conservation Medium Density	residential
POL	Public Open Lands	nocomm
RC	River Conservation	nocomm
RDR	River Downtown Redevelopment	downtown
RF	Residential Foothills	nocomm
RL	Low Density Residential	residential
RUL	Rural Lands	nocomm
T	Transition	nocomm
UE	Urban Estate	nocomm

3.2.4 Premises per Group

3.2.4.1 Served Area

The demand estimation tool uses the assumed served area to estimate the number of premises and consequently the water demand.

3.2.4.2 Residential Premises

Single-family houses and duplexes are assumed to have a single unit per premise. As is the case with all the regression models, the multi-family water use model predicts water use per premise. Therefore, the number of multi-family units per zone is used to estimate the number of multi-family premises, using the average number of multi-family units per premise for the dataset, which is 7.

3.2.4.3 Commercial Premises

The served area is used to calculate the number of commercial premises, multiplying a calculated density factor, from observed data, by the commercial premises per acre. The current area served per zone is computed from the Master Table using the sum of the parcel polygon areas that have an assigned premise number (i.e., indicating water use in the parcel).[4]

The commercial premises were grouped into small (CM_Sm), medium (CM_Md), and large (CM_Lg and CM_Lg68) taps. Table 5 (Section 2.4.2) shows the rate codes assigned to each commercial group. The number of small, medium, and large commercial premises in each zone is based on the current density of commercial premises for each zone based on the water use data. The current density of commercial premises is computed by dividing the number of commercial premises in each zone by the current area served. The current density of commercial premises per area in each zone is used to estimate the number of commercial premises for each commercial group for each zone, using the total area assumed served in each zone (‘***Area [acres]***’), including the user input for ***Percent Built*** for each zone/area type. Using the total area in each zone is consistent with the commercial density values, which are computed based on the total area rather than the commercial area in the zone. The results of this calculation are the number of premises assumed for each zone/area type combination in columns ***Commercial SM Premises***, ***Commercial MD Premises***, and ***Commercial LG Premises***, respectively for each commercial group.

3.3 Annual Demand Estimation per Premise

The annual demand estimate is calculated using the values inputted for the ***Model Variables***. The demand estimation tool stores the coefficients for the regression models in the database. Each model version is identified with a number and is loaded to the GUI when the tool is initialized into the ***Model Version*** box. The model version used for the Vulnerability Study is 2 and was developed by FCU.

Dataset These are groups of input variables stored in the database for each model version. The available datasets are loaded into the GUI when a model version is selected. New can be added to the database by altering the variables of interest, further described below, renaming the dataset in the Dataset box and selecting the **‘Add Estimate’** button.

Monthly Values The demand estimation tool requires the user to specify monthly values for the weather variables (***‘daysover85’*** and ***‘irrig_rain_mon’***). The summer flag (***‘summer’***) is a binary variable used to identify the summer months for the demand models. The variable ***daysover85*** corresponds to the number of days with maximum temperate above 85˚F. The variable ***irrig_rain_mon*** corresponds to the total rainfall in the month in inches.

Annual Values These variables are constant for each month calculation, so single values are provided by the user. These variables include the average number of bedrooms per premise (***bed***)[5], the average parcel acreage for each group

[4] For this document, developed polygons are defined as those that are not flagged as buildable from the Planning Department layer; however, not all the developed polygons have a premise, or water use, associated with them, so the area served only contains the parcels with an associated premise.

[5] Data from the County Assessors Data provided by FCU.

(***parcel_acr_CLg, parcel_acr_CMd, parcel_acr_CSm, parcel_acr_MF and parcel_acr_SMDUP***), the unemployment rate (***unemprate***)[6], and average number of units per premise (***units***). A description of each variable is available in the GUI by selecting the ***Show Model Coefficients*** option.

Each model version includes a set of five regression models that independently predict the water use per premise in each customer group (‘***Group***’) (i.e., single-family/duplex, multi-family, commercial small, commercial medium, and commercial large). Water use in each ***Group*** is calculated for each ***Assignment***, using the monthly, annual, and assignment flag variables. The total water use for each Group/Assignment combination is calculated by summing the premises calculated in the planning zones for each assignment. The calculation of water use per premise for all the groups is affected by a reduction factor, which could be used to represent conservation program effects or general reduction of water consumption not captured by the model independent variables.

Overall Reduction [%]	This is a factor applied to the water use per premise to all the groups simultaneously.

In some specific cases, the simulated water use per premise is truncated to a minimum value to simulate the winter water use when numerically the model regression produces unrealistic low numbers. The two minimum indoor water uses implemented in the demand estimation algorithm are for the commercial small with non-commercial ***Assignment*** and for commercial large with downtown ***Assignment***, which are 3.481 thousand gallons and 40.391 thousand gallons, respectively. These values correspond to the median of the observed water use for those groups and assignments.

3.3.1 Additional Utility Demands

Demands that are not predicted by the five regression models are added as single values by the user.

Large Commercial (6&8”)	This user-defined variable represents the total annual demand in thousand gallons of large taps of 6” and 8” not otherwise captured by the LCU Demand.
LCU Demand	This variable represents the annual total demand from Large Commercial User (LCU) contracts in thousand gallons.

These additional demands are assumed to be evenly distributed throughout the year, consistent with the way they have been modeled in previous studies.

3.3.2 Utility Demand Estimation

The annual utility demand is computed by adding the individual demand estimated for each Group/Assignment combination plus the large commercial (6&8”) taps and the LCU additional demands. The demand at the water treatment plant is estimated assuming a distribution system losses factor. A typical value for this factor is 8 percent, which is an estimate used in previous

[6] Data from the United States Labor Department (https://data.bls.gov/timeseries/LAUMT082266000000005?amp%253bdata_tool=XGtable&output_view=data&include_graphs=true)

analysis to account for losses from the river to the treatment plant, losses in the treatment process and the distribution losses.

	Distribution Losses [%]	This factor is assigned by the user and applied to the utility demand to account for distribution and treatment system losses. It provides an estimate the raw water demand at the point of diversion.

3.4 Demand Scenarios

The demand scenarios to be used in the FCU modeling system can be created in the demand estimation tool. A demand scenario includes all the user variables needed to generate the annual demand estimate. The user-defined variables are stored in the ***WaterUseProcessing*** database in the ***DEMScenVars*** table and the scenario preferences are stored in the ***DEMScenarios*** table. The user can save and retrieve demand scenarios using the ***Scenarios Info Name*** box. To select an existing demand scenario, the user can simply select from the available dropdown list. To create a new demand scenario, the user needs to change the variables of interest (all white cells can be altered by the user), input a new demand scenario name in the Scenario Info Name box and select the Save New Scenario button.

3.5 Demand Timeseries for MODSIM

Monthly demand time series for input to the FCU system MODSIM model in the FCU modeling system can be created in the demand estimation tool for the scenarios stored in the database. A demand scenario includes all the user variables described above. A set of these variables is combined with monthly weather variables to generate monthly time series of demand. The weather variables are associated with hydrology ensembles, allowing the simulated hydrology to be synchronized with the demand time series. The weather variables in the demand scenario are populated with a time series of weather variables to generate the sequence of monthly demand values for each hydrology set. The current version of the demand estimation tool generates a set of 86 years of monthly demands, compatible with the Vulnerability Study model simulation period.

3.5.1 Weather Variables

Time series of precipitation and temperature are required to compute the weather-related demand model variables. The hydrology sets developed for the Vulnerability Study capture future variability and climate change, resulting in an ensemble of traces, based on paleo reconstruction of wet and dry periods.[7] Each trace consists of a sequence of possible climate occurrences based on historical monthly precipitation and temperature data that is re-sequenced based on the paleo reconstructed statistics, and then altered to simulate climate change.

The historical daily precipitation and temperature records for the CSU gage, provided by FCU, were used to create the weather time series for the demand estimation tool, using the same sequences used for each hydrology dataset developed for the Vulnerability Study[7]. The variables for the demand models calculated from the daily weather variables are the total precipitation in the month and the maximum daily air temperature in the month. The weather time series for the hydrology datasets were processed and stored in the '***FCU_HydrologyProcessing***' database. The precipitation time series for all the hydrology traces are stored in the '***precip_TS_AllTraces***' table, and

[7] RTI International, 2018. *Future Hydrologic Analysis Technical Memorandum*, Fort Collins, October.

the maximum temperature time series for all the hydrologic traces are stored in the '***temp_TS_AllTraces***' table.[8]

3.5.2 MODSIM Demand Catalog

The demand estimation tool allows processing and adding FCU System MODSIM demand time series to the database for each demand scenario and hydrology trace, to be used by the Modeling Management System (MMS). These time series should be created/cataloged in the database before running the model with the MMS. The demand estimation tool can display the time series in the GUI or import them into the modeling system database. The time series for MODSIM are created in the '***UTIL-RWM-P***' database in the table '***DEMTimeseries.***' This operation is achieved in the '***Estimated with Hydrology***' tab by:

- Selecting '***All Hydrologies***' radial button in the GUI Hydrology section
- Checking the '**Add TS to DB**' option
- Clicking '**Calculate TS.**'

3.5.3 MODSIM Demand

The demand estimation tool creates demand time series for the "Citydem" MODSIM node. This demand time series is created using the same method used in the GUI for a single year, in other words, the "Citydem" time series includes the base demand calculated with the regression equations and the specified conservation reduction factor, the large commercial users with 6" and 8" taps demand and the distribution loss factor applied to the sum of the base demand and the large commercial. The corresponding demand time series for each model run is imported into the '***CityDem***' node at run time, based on the specified demand scenario and hydrology trace. Figure 6 shows a sample of the monthly demand time series generated by the demand estimation tool for a few years, for two ensembles for the base climate scenario (CC Scen ID = 1).

[8] A default ID of '3246' was used for the processed weather variables.

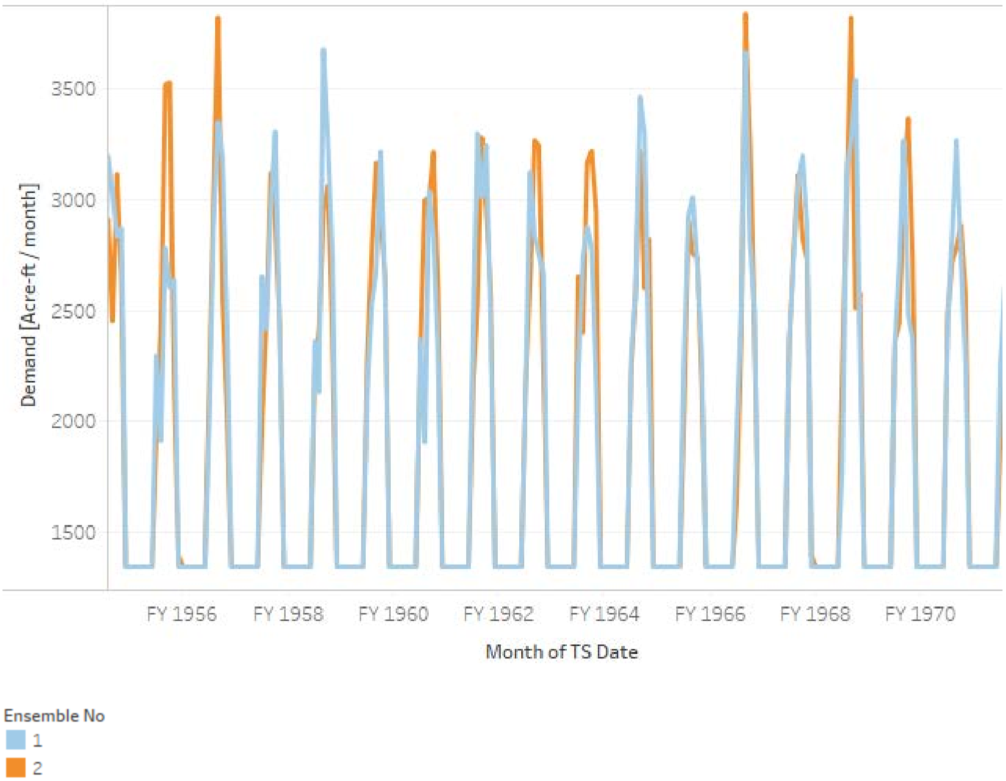


Figure 6 – Example of Monthly Time Series Generated by the Demand Estimation Tool

Appendix 1

Table 10 – Commercial Premises Converted to Multifamily Rate Code the Demand Estimation.

PREM_CODE	ORIGINAL SRAT_CODE	IRRIGATION_ONLY_METER_
63395	W544	No
80626	W544	No
86850	W544	No
88667	W544	No
12035	W522	Club
13105	W522	Yes
15704	W522	Yes
19970	W522	Yes
20315	W523	Club
20317	W523	Yes
21696	W522	Yes
21713	W522	Yes
22707	W523	No
22962	W522	Yes
22973	W522	Yes
24196	W522	Yes
24784	W522	Rec
24784	W532	Rec
24888	W522	Yes
26712	W522	Yes
29965	W522	Rec

PREM_CODE	ORIGINAL SRAT_CODE	IRRIGATION_ONLY_METER_
30844	W522	Yes
30845	W522	Yes
30846	W522	Yes
32185	W522	Yes
33374	W523	Yes
35161	W523	Yes
35788	W523	Yes
35789	W523	Yes
35792	W523	Yes
39031	W523	Yes
40117	W523	Rec
40146	W523	Yes
40147	W523	Yes
41684	W522	Club
42937	W523	Yes
43786	W522	Yes
43787	W522	Yes
45185	W523	Yes
45875	W522	Yes
50067	W522	Yes
51630	W522	Club
51756	W522	Yes
51797	W522	Yes
51875	W522	Yes
51914	W522	Yes
52064	W523	Yes
52069	W523	No
54452	W522	No
54453	W522	No
54867	W522	Yes
55465	W522	Yes
55861	W523	Yes
57060	W523	Yes
57345	W523	Yes
57876	W522	Yes
59135	W522	Yes
62694	W522	No
62979	W522	Yes
63731	W522	Yes
66540	W522	Club
66624	W523	Yes
66747	W522	Yes
67123	W522	Yes
67124	W522	Yes
68796	W522	Yes
71068	W522	Club
71175	W522	Yes
71207	W522	Yes
72246	W523	Yes
73577	W523	Yes
73957	W522	Yes
74159	W522	Yes
74463	W522	Yes
75506	W523	Yes
75952	W522	Club
75954	W523	Yes
75955	W523	Yes
79444	W522	Yes
79967	W522	Yes
84045	W522	Yes

PREM_CODE	ORIGINAL SRAT_CODE	IRRIGATION_ONLY_METER_
84156	W523	Yes
84157	W523	Yes
85306	W522	Yes
87497	W522	Club
88578	W522	No
88590	W522	No
88607	W522	No
88803	W522	No
89602	W522	No
89628	W522	No
89629	W522	No
89630	W522	No
89636	W522	No
89637	W522	No
89871	W522	No
90953	W522	No
12738	W521	Rec
15406	W521	Yes
15705	W520	Club
19672	W520	No
20010	W521	Yes
20386	W520	Club
21033	W521	Yes
21177	W521	Yes
21945	W520	Yes
22043	W520	Club
23892	W521	Club
24785	W521	Yes
24785	W531	Yes
25949	W520	Club
26760	W520	Club
30350	W521	Yes
30873	W521	Yes
31486	W521	Yes
33373	W521	Rec
35783	W521	Rec
37789	W520	Club
38133	W520	Pool
38926	W520	Pool
42131	W521	Yes
42287	W521	Yes
42288	W521	Yes
43539	W520	Club
43980	W520	Club
45872	W520	Club
46525	W521	Yes
48475	W521	No
50336	W520	Club
52347	W521	Yes
54249	W520	No
54250	W520	No
55582	W521	Yes
55610	W521	Yes
56058	W521	Club
58669	W521	Club/Pool
59377	W520	Club
59731	W520	Pool
61328	W520	Yes
61378	W520	Club
62187	W520	Pool

PREM_CODE	ORIGINAL SRAT_CODE	IRRIGATION_ONLY_METER_
64625	W520	No
64748	W520	No
64784	W520	No
64866	W520	No
65139	W521	Club
65599	W520	Rec
65854	W521	Pool
67176	W520	Pool
67382	W521	Pool
68960	W521	Yes
72501	W520	Yes
73576	W521	Club
73943	W521	Club
74570	W520	Pool
74614	W521	Yes
75575	W521	Yes
75601	W521	Yes
75953	W520	Maint
76151	W521	Yes
76352	W520	Pool
76631	W521	Yes
78005	W521	Yes
78573	W521	No
78658	W520	Club
80567	W520	Club
82258	W520	Club/Pool
82338	W521	Yes
82424	W521	Yes
82425	W521	Yes
85869	W521	Pool
86945	W521	Yes
87564	W520	Yes
87811	W520	Yes
89100	W520	Yes
89785	W520	No
90481	W521	Rec
90532	W520	Yes
91151	W520	Yes
91154	W520	Yes

Appendix 2

Table 11- Expected Residential Development Densities by Zone and Expected Split Between Single-Family and Multi-Family Development

	CITY PLAN DEVELOPMENT SCENARIO 2 - TARGETED CHANGES			CITY PLAN DEVELOPMENT SCENARIO 3 - BROAD CHANGES		
PLANNING ZONE	Dwelling Unit/Acre	% as Single Family	% as Multi-family	Dwelling Unit/Acre	% as Single Family	% as Multi-family
CC - COMMUNITY COMMERCIAL	20	5	95	30	1	99
CCN - COMMUNITY COMMERCIAL - NORTH COLLEGE	20	60	40	30	50	50
CCR - COMMUNITY COMMERCIAL - POUDRE RIVER	20	100	0	30	100	0
CG - GENERAL COMMERCIAL	15	5	95	15	1	99
CL - LIMITED COMMERCIAL	15	84	16	15	84	16
CS - SERVICE COMMERCIAL	15	50	50	15	40	60
D - DOWNTOWN	20	5	95	30	1	99
E - EMPLOYMENT	15	5	95	20	5	95
HC - HARMONY CORRIDOR	15	11	89	17	5	95
HMN - HIGH DENSITY MIXED-USE NEIGHBORHOOD	20	10	90	30	5	95
LMN - LOW DENSITY MIXED-USE NEIGHBORHOOD	4	41	59	4	41	59
MMN - MEDIUM DENSITY MIXED-USE NEIGHBORHOOD	15	8	92	17	8	92
NC - NEIGHBORHOOD COMMERCIAL	5	6	94	10	6	94
NCB - NEIGHBORHOOD CONSERVATION BUFFER	15	30	70	15	25	75

	CITY PLAN DEVELOPMENT SCENARIO 2 - TARGETED CHANGES			CITY PLAN DEVELOPMENT SCENARIO 3 - BROAD CHANGES		
NCL - NEIGHBORHOOD CONSERVATION LOW DENSITY	4	96	4	4	96	4
NCM - NEIGHBORHOOD CONSERVATION MEDIUM DENSITY	15	79	21	15	79	21
RDR - RIVER DOWNTOWN REDEVELOPMENT	20	10	90	30	5	95
RF - RESIDENTIAL FOOTHILLS	1.5	100	0	1.5	100	0
RL - LOW DENSITY RESIDENTIAL	4	95	5	4	95	5
UE - URBAN ESTATE	1.5	93	7	1.5	93	7

Appendix D HYDROLOGIC MODELING APPROACH TECHNICAL MEMORANDUM

Technical Memorandum

Hydrology Modeling Approach

Date: December 15, 2017 (Revised February 2, 2018)

From: Noah Friesen, Enrique Triana, Jon Quebbeman and Mark Woodbury

RTI International

To: Fort Collins Utilities

1 Introduction

This technical memorandum (TM) describes the approach that will be adopted for generating hydrologic data for use in the Fort Collins Water Vulnerability Study. Hydrologic inputs required for the Vulnerability Study include time series that contain greater variability than the historical record and reflect potential effects of future climate change.

The results of the Climate Change Literature Review TM prepared for the Vulnerability Study and the proposed hydrologic modeling approach were presented to Fort Collins Utilities (FCU) at a workshop on November 13, 2017. The literature review focused on the general approach, and at the workshop it was decided to adopt the bottom-up approach for the Water Vulnerability Study because:

- It is designed specifically to explore vulnerabilities and risk, which is aligned with the goals of the Fort Collins Water Vulnerability Study;
- Its results allow exploring vulnerabilities in the entire uncertain climate domain (Temperature and Precipitation) rather than having to select representative Global Circulation Models (GCM)s;
- Its results are not influenced by the uncertainty of downscaling GCM large-area projections to smaller catchment areas;
- It focuses the analysis on system sensitivities and conditions anticipated to be critical for the system performance;
- It provides flexibility to implement an adaptive planning approach, tracking trends to trigger corrective actions to vulnerabilities for changes registered in a specific direction of the future domain;
- It facilitates analyses of no regret and robust options by exploring the system response to those options for the entire future domain; and
- It allows estimating system performance as climate science evolves by overlaying future GCM predictions on the vulnerability results, without redoing the analysis.

The final hydrology modeling approach, presented herein, considers input from FCU and Northern Colorado Water Conservancy District (Northern), and addresses questions and concerns brought up at the workshop, especially regarding the modeling of Colorado-Big Thompson Project (CBT) basins. The general steps in the modeling approach are:

1. Generate new ensemble traces of precipitation and temperature;
2. Adjust traces to represent a different T and P climate;
3. Run hydrologic models for each trace and each basin;
4. Disaggregate streamflow results to the Poudre Basin Network (PBN) input points and run the PBN model using inputs;
5. Provide the inputs for the CBT quota model.

2 Hydrology Modeling Steps

The hydrology modeling approach presented in this section will be applied to basins required to determine the water availability for the FCU system model, including the PBN model and the CBT model, which generate input to the FCU system model. The basins for which this approach will be applied include: Poudre River basin, Big Thompson river basin, St. Vrain River basin, Boulder Creek basin, Frasier Creek basin, Willow Creek basin and Upper Colorado River basin. Figure 1 shows the locations of the river basins included in the vulnerability study.

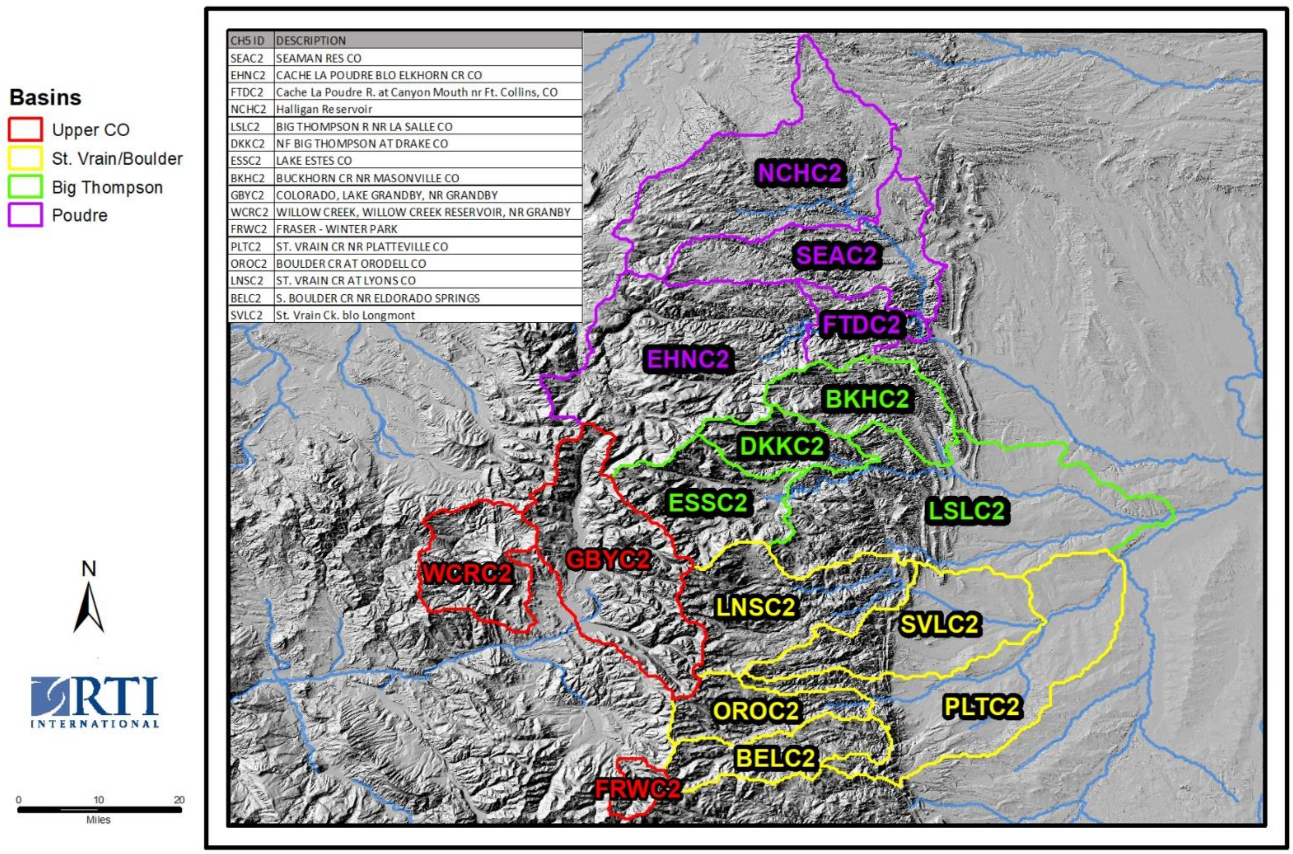


Figure 1 – Map Showing the River Basins included in the Hydrology Modeling for the FCU Vulnerability Study

2.1 Step 1 – Generate Ensembles

The approach to generate precipitation and temperature traces is designed to represent hydrologic variability and future climate change. RTI will generate precipitation (P) and temperature (T) traces based on wet-dry sequence statistics from paleo-hydrology reconstructions. RTI will follow the Block Homogeneous Markov (BHM) technique described by Nowak, Prairie, and Rajagopalan (2007).

RTI will use annual streamflow timeseries for the Poudre River produced by Dr. Connie Woodhouse (University of Arizona) extending back to 1615. This time series will be classified into wet and dry years, using the median annual flow during the observed historical period as the threshold to define wet and dry (Nowak, Prairie, and Rajagopalan, 2007).

RTI will generate 100 traces that are each 86-years long, which corresponds to the current period used in the FCU System model and corresponding data processing tools. Using the BHM procedure, RTI will select an 86-year period from the full paleo period for each of the 100 generated traces. The periods will be selected by sampling periods from the exceedance probability distribution of the representative 43-year running average annual flow from the paleo set to have periods with good representation of the range of wet and dry years estimated in the paleo hydrology. RTI will calculate a matrix of Wet-Dry transitional probabilities using the years in the selected period. The matrix will represent the likelihood that the next year will be dry or wet, based on the current year state. Using a different matrix for each ensemble trace "introduces more drought/surplus variability" (Nowak, Prairie, and Rajagopalan, 2007) compared to using a single matrix and captures more of the multi-year trends that could be washed out using long-term average probabilities. For a given trace, RTI will use the probability of wet and dry years to randomly select a starting state and then use the conditional transition probability matrix to randomly sample the next year type, then use that state to seed the selection of the next period, and so on. This procedure will be used to generate 100 traces of wet/dry year sequences.

RTI will use the models and datasets used in the JFRCCVS. The hydrologic models used in the JFRCCVS were first built for the Missouri Basin and Colorado Basin River Forecast Centers (MBRFC and CBRFC), which includes mean-areal precipitation (MAP) and mean-areal temperature (MAT) time series constructed from individual station records from long-term stations in and near the sub-basins. The River Forecast Centers quality controlled the station data as well as the resulting MAPs and MATs and handled any data filling needs. The time series extend from October 1949 through September 2005 for all the basins to be simulated. RTI will use these same time series and period for this study.

Each month in the observed P and T record will be sorted according to the year type (wet/dry) of the corresponding observed streamflow for that year. All months occurring in wet years will be classified as wet, and all months in dry years will be classified as dry, regardless of the precipitation magnitude of the individual month. For each 86-year trace of wet-dry states, RTI will build the P and T time series month-by-month using the wet/dry sequence and randomly sampling each month from the corresponding observed wet/dry monthly groups. The observed 6-hour precipitation and temperature series from the selected month will be used to create the time series.

For example, if the first year in the trace is wet, we will construct the synthetic year by sampling an October from the wet year group, then a November from the wet year group, etc. If the second year in the trace is dry, we will then sample all months for that year from the dry year groups. Using this procedure RTI will use both the observed precipitation and corresponding temperature to build the synthetic traces. Sampling this way allows our traces to contain novel years that may be drier or wetter than any observed year, but are still based on actual observed data. The result of this process is the generation of baseline synthetic 6-hour precipitation and temperature series for input to the JFRCCVS rainfall-runoff models that capture the variability of the long-term historical climate.

Using paleo statistics from other basins and randomly sampling months on all the basins would not maintain the spatial correlation of the system time series. Transition probabilities in the South Platte paleo reconstruction will be used to capture the long-term variability in the flows for all basins, preserving the spatial correlation between the Poudre basin and the other modeled basins needed for the CBT model. The correlation will be maintained by sampling the same observed month for all basins when building the synthetic traces. For example, if we sampled October 1963 as one month in the Poudre basin while building a trace, we would build the traces for the other basins simultaneously using October 1963 for that month. The historical distribution of P and T across the basins during that month will therefore be embedded in the synthetic trace.

2.2 Step 2 – Apply Climate Change Adjustments

Using the bottom-up approach to explore system vulnerabilities to climate change, RTI will define a domain of potential changes of average precipitation and temperature. The 100 traces generated in Step 1 will be used as a baseline to compare against the same traces adjusted for climate change. The future domain will be explored by scaling P and T values by different amounts. RTI will create a set of hydrology traces to represent combinations of changes in P and T.

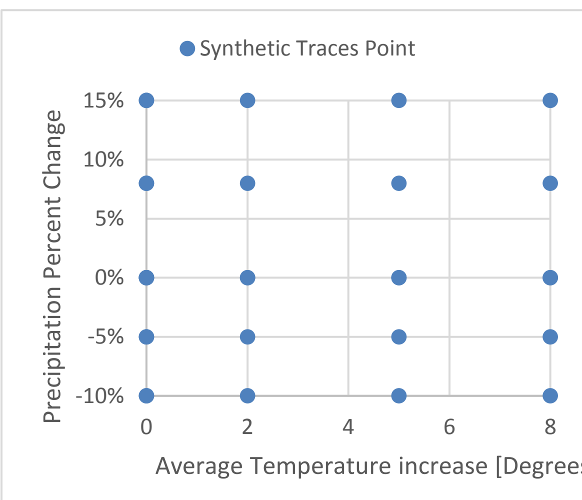


Figure 2 – Grid of Precipitation Change and Temperature increase to Develop Synthetic Hydrologic Traces

A grid of change values will be used to map vulnerabilities, with precipitation changes on one axis and temperature increases on the other. Precipitation changes will range from -10% (relative to current conditions) to +15%. Temperature changes will range from 0 °C to 8 °C above current temperatures. Figure 2 shows the grid with points at the combination of P and T for which synthetic hydrologic traces will be developed. The points in Figure 2 cover the entire domain but increase the detail in regions of the domain initially considered more important for the Vulnerability Study. All 100 traces will be adjusted for each grid point, leading to 1,900 climate change traces, in addition to the 100 baseline traces. These ranges are designed to be wide enough to include the GCM results from CMIP5 and hopefully future CMIP iterations. The National Climate Change Viewer from USGS indicates precipitation changes from -6% to +31%, and temperature increases from 0.6 °C to 4.9°C for the Poudre basin across the different GCMs for the 2050-2074 period (Alder and Hostetler, 2013). While some GCMs indicate that precipitation may increase more than 15%, we do not expect larger precipitation increases to be a source of vulnerability for Fort Collins Utilities.

Following a "bottom-up" approach by applying climate adjustments over a range, rather than matching specific GCM results, will allow a more thorough look at potential future conditions. The range of futures will be modeled and the futures that Fort Collins is vulnerable to can be identified. GCM-based future temperature and precipitation values can be plotted on top of the modeled ranges, to compare vulnerable futures against the futures projected by the GCMs. Figure 3 shows an example of the results of this bottom-up approach, with median vulnerability values for the 100 traces shown with interpolated colors (red to blue) in the T and P grid, and points representing the CMIP3 and CMIP5 GCM results of average change in T and P overlaid in green and purple.

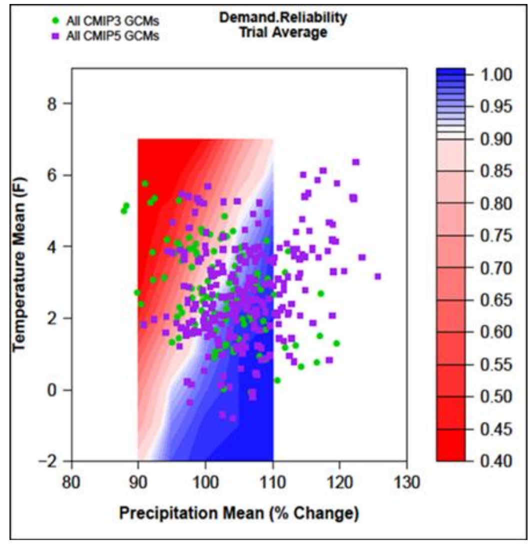


Figure 3. Example of bottom-up approach results
Source: Colorado Springs IWMP

The baseline traces will be adjusted for climate change uniformly. Temperature adjustments will be made by increasing every value in the time series by the adjustment amount. Precipitation adjustments will be made by scaling all values by the adjustment percentage.

While GCM results generally indicate that changes will vary between months, there is little consistency about the magnitude and timing of the variation among the different models (JFRCCVS, Figures 56 and 57). Choosing a single monthly distribution for changes may not accurately represent the true possibilities and running many different distributions would increase the complexity of the analysis for an uncertain benefit.

2.3 Step 3 – Run Hydrologic Models

RTI will use a set of calibrated hydrologic models to transform the baseline and climate-adjusted P and T into streamflow. These are the same models used in the JFRCCVS. Nothing in the models will be changed for this project, other than the precipitation and temperature inputs.

Recognizing that the model results do not perfectly represent reality in the simulated basins, RTI will apply bias-correction to the model output. The principles of the hydrologic models proposed tend to under-simulate large flows and over-simulate low flows. These tendencies are inherent to the modeling approach and cannot be fully eliminated through parameter changes. Quantile mapping is a procedure commonly used to reduce these biases (Gudmundsson et al. 2012). The distribution of the simulation results is adjusted to match the distribution of the observed streamflow. This step also reduces bias from any inaccuracy in the models. RTI will train the quantile mapping on the baseline case, and then use the same adjustments to correct all the results (baseline and climate-adjusted). This allows us to correct the model biases present in all runs while still allowing the results to simulate effects of climate change.

The JFRCCVS also adjusted potential evapotranspiration inputs when running these models to increase potential evapotranspiration (PET) for futures with higher temperatures. More recent research (Milly and Dunne, 2016) has shown that the adjustment procedure used significantly over-estimates the increase in PET. This is because using temperature increases to estimate PET increases ignores other factors that limit PET, such as increased CO2 in the air reducing plant transpiration and vegetation changes due to the changed climate. Additionally, the JFRCCVS found that streamflow was not highly sensitive to PET increases. The ET is generally supply-limited, meaning soil moisture available for evaporating is less than the PET demand, and increasing the PET demand does not increase actual ET unless more soil moisture is available. Based on these factors, no PET adjustments will be made for this study. Note that the PET discussed here is only for natural vegetation in the watershed, and does not apply to irrigated crops. Increased agricultural PET is less limited by natural supply, and its effects for this study will be analyzed in the basin demand sensitivity analysis modeling to be performed by FCU.

The initial plan was to only run the Poudre Basin models and then assume that changes would be correlated with changes in the basins needed for the CBT modeling (Upper Colorado, Big Thompson, Boulder and St. Vrain). RTI investigated the correlations in streamflow changes between these basins using JFRCCVS results and found that the results did not exhibit a very strong correlation. For consistency and to generate a more complete product, RTI plans to also run hydrology models for the CBT basins using the same procedure as for the Poudre (described above). The Poudre Basin is split into 4 modeled sub-basins above the canyon mouth. The Upper Colorado above Lake Granby, Willow Creek, and the Fraser River are modeled as one sub-basin each. The Big Thompson is modeled as 3 sub-basins above Loveland and the St. Vrain and Boulder Creek watersheds are modeled as 4 sub-basins. FCU and Northern authorized the additional 95 hours required for this additional hydrology modeling scope as documented separately (Additional Hydrologic Modeling Estimate TM, 2017).

2.4 Step 4 – Disaggregate Flows and Run Yield Models

The hydrologic models provide flow at the North Fork below Seaman Reservoir and at the Canyon Mouth in the Poudre River Basin. The PBN model requires monthly flow inputs at 11 locations, mostly at higher elevations within the basin. Previous work by Riverside Technology, Inc. and CDM developed spatially disaggregated flows for the Poudre Basin Common Technical Platform (CTP), based on the two lower gage points. That work provides monthly factors for each PBN input point that can be used to distribute the downstream flows. These factors will be applied to the hydrologic model output to calculate inflows to the PBN model. There are other time series in the PBN model that are tied to the base hydrology and considered important for the analysis, i.e., the excess precipitation and the native flows time series. These time series will be re-sequenced based on the closest simulated flow to the base hydrology total flow at the two gages. The PBN model inputs will be organized in the central database for each trace resulting from the previous steps.

The CBT Model is a spreadsheet model that takes annual flows from the different CBT project sources and watersheds affecting other CBT allottee water supplies and estimates the annual quota that would be adopted by the Northern Board under those conditions. Northern will modify the CBT Model to incorporate inputs from the hydrologic models described above, and RTI will summarize and catalog the results from the hydrologic models into the central database developed for the Vulnerability Study. These results will be used by the FCU modeling system in conjunction with the CBT model to estimate an annual CBT quota for the PBN and the FCU system models. Baseline and climate-adjusted flows will be run through the models and cataloged in the central database using the functionality in the data management system (RTI and Stantec 2017) to be used in the Vulnerability Study.

FCU is investigating the changes in system yield for Fort Collins due to potential changes in future agricultural demands, assuming the higher temperatures will drive longer growing seasons with different water requirements within the constraints of the existing water rights. Also, FCU is investigating the effect of lower South Platte demands on the system yield for Fort Collins. The results of that analysis affecting the Vulnerability Study will be reflected in the final modeling approach.

3 Budget and Schedule Considerations

The proposed approach for the hydrologic modeling can be performed within the approved budget for Task 5 (including the CBT basins hydrologic modeling. The proposed activities can be performed within the original schedule (from December 2017 to February 2018) assuming no changes will be performed to the PBN model.

4 References:

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Appendix E FUTURE HYDROLOGIC ANALYSIS TECHNICAL MEMORANDUM

Technical Memorandum

Future Hydrologic Analysis Technical Memorandum

	May 20, 2018
Date:	(Rev.1 Oct 30th, 2018)
From:	Noah Friesen, Colleen Wilson, Enrique Triana, Mark Woodbury RTI International
To:	Fort Collins Utilities (FCU)
Attachments:	Hydrology Traces Dashboard (FlowMetricsV4.twbx) Traces Selection Tool (Trace MCDA v4.xlsx) Precipitation and Temperature generated series (HydrologyDataset_042218.twbx , HydrologyDataset_042218_TEMP.twbx)

1 Introduction

This technical memorandum describes the development of the hydrology dataset developed for use in the Fort Collins Water Vulnerability Study. Hydrologic inputs required for the Vulnerability Study include time series for streamflows, water diversions, and other parameters that may contain greater variability than the historical record and reflect potential effects of future climate change and basin operations.

2 Hydrology Data Development

The hydrology development methods presented in this section were applied to the basins that must be analyzed and simulated to determine the water availability for the FCU system model, which is generated using the Poudre Basin Network (PBN) model and the Colorado-Big Thompson Quota (CBTQ) model. The basins included in the analysis are: Poudre River basin, Big Thompson River basin, St. Vrain River basin, Boulder Creek basin, Fraser Creek basin, Willow Creek basin and Upper Colorado River basin. Figure 1 shows the locations of the river basins included in the hydrological analysis.

Water Vulnerability Study

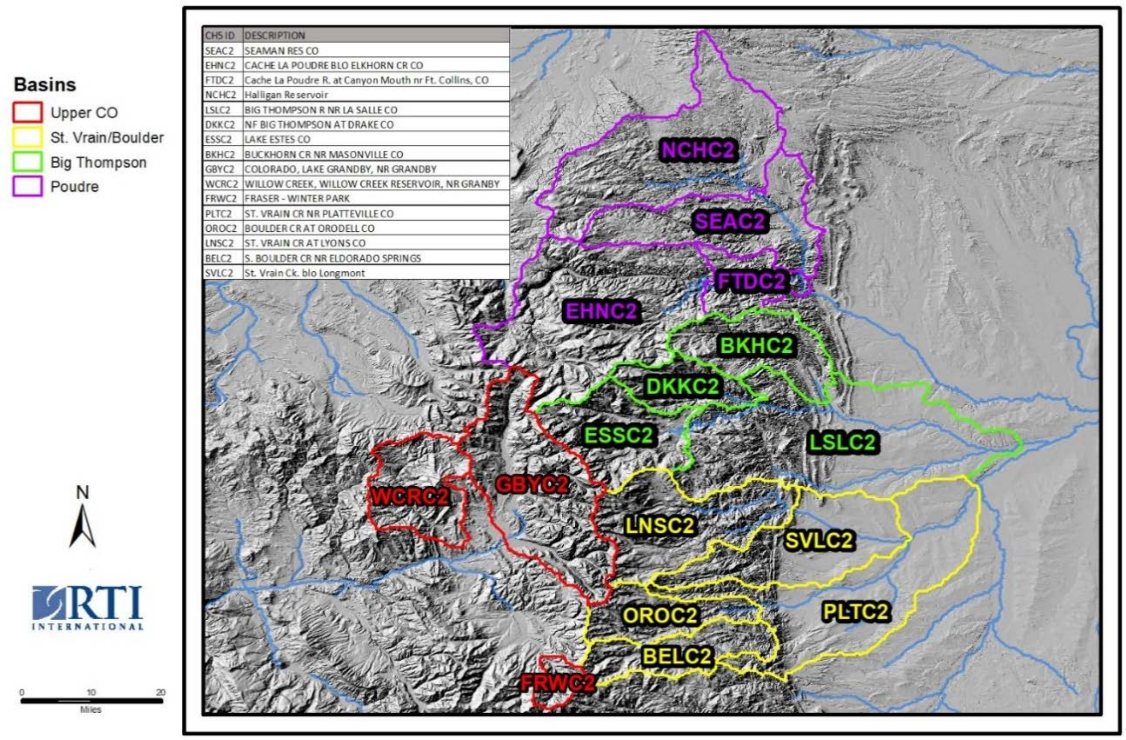

Figure 1 – Map Showing the River Basins included in the Hydrology Modeling for the FCU Vulnerability Study

The approach used to generate hydrologic inputs for the Vulnerability Study modeling is documented in the Hydrology Modeling Approach TM (RTI, 2018), which is key to understanding the presentation of results in this memo. The goal of the hydrology development approach is to generate synthetic sets of potential future hydrological inputs that include variability and large-scale shifts in precipitation and temperature trends due to climate change. The approach is based on the following steps:

- Weather Generation
    - Generate an ensemble of 100 precipitation and temperature traces for use in hydrologic simulations, each being 86 years long, which corresponds to the Fort Collins System model simulation period.
    - For each trace in the ensemble of reconstructed flow records, classify historical years as wet or dry.
    - Identify 100 sets of transition probabilities between wet and dry years based on 100 sub-sets of 86-year samples from the reconstructed record.
    - Construct 100 sequences of year type based on the 100 sets of transition probabilities.
    - Construct 100 synthetic precipitation and temperature traces by sampling entire months from the actual historical record according to year type, based on the 100 sequences of year type.
- Hydrological Modeling
    - Baseline: Generate streamflow traces from each of the 100 precipitation and temperature traces, using the Joint Front Range Climate Change Vulnerability Study (JFRCCVS) hydrologic models.

- o Climate Adjusted: Generate 18 sets of climate-adjusted streamflow traces based on various combinations of temperature and precipitation adjustments from historical conditions.
- Select representative traces for preliminary modeling.
- Pre-process inputs to the PBN model for use in yield modeling.

The following sections summarize the results of the hydrology development and processing to be used in the FCU Vulnerability Study.

2.1 Weather Generation (Ensembles)

Each year in the record of reconstructed flows for the Cache la Poudre River (the “Poudre”) at Canyon Mouth (Woodhouse, 2006) was classified either as a wet or a dry year. This distinction was based on the median annual flow of the reconstructed data. The median of the reconstructed data from 1615-1999 was 286,712 AF. Figure 2 shows the plot of reconstructed annual flows in the Poudre River (blue) with the mean of observed flows (red). Annual flows greater than this threshold were considered “wet” and flows less than the threshold were classified as “dry.”

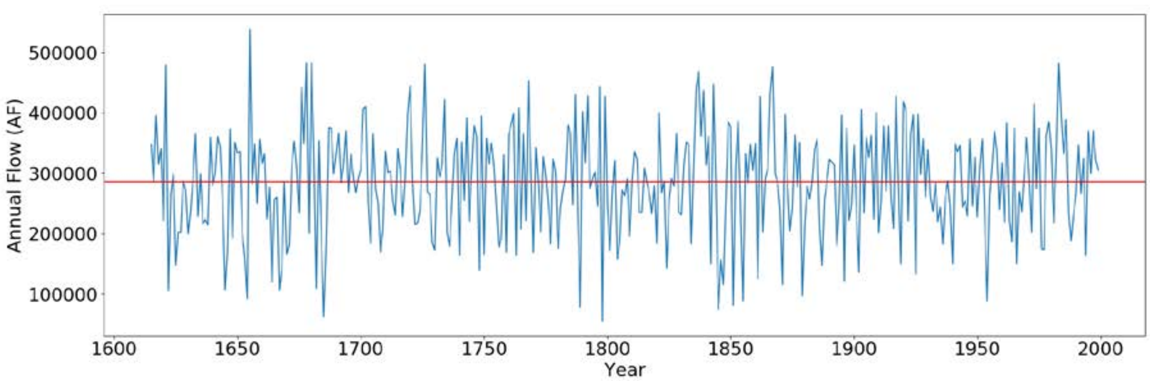

Figure 2 - Plot showing reconstructed annual flows at Canyon Mouth, 1615-1999, in acre-feet (blue) with the mean of observed flows (red).

RTI used a sampling procedure based on the exceedance of dry to wet transition probabilities from rolling windows over the reconstructed period to generate 100 traces that use statistics from a range of wet and dry periods. The selected period for the traces (and the rolling windows) is 86 years that agrees with the current Fort Collins planning model simulation period. The center-half of the selected period was used to calculate the transition probabilities of each window, excluding from the calculation the initial 21 years and the last 22 years of each window to add randomness to the transitional probabilities. Figure 3 illustrates the rolling window concept, showing the first 86-year window (gray) with the 43-year center-half window (orange). For the period of reconstructed values, 1615-1999, we use the center-half windows of 43 years to represent the 86-year windows, with the first center-half window starting in 1636 and the last center-half windows ending in 1977. For each 86-year rolling window, we assigned the center-half window probability of a dry year being followed by a wet year as the representative probability for the rolling window.

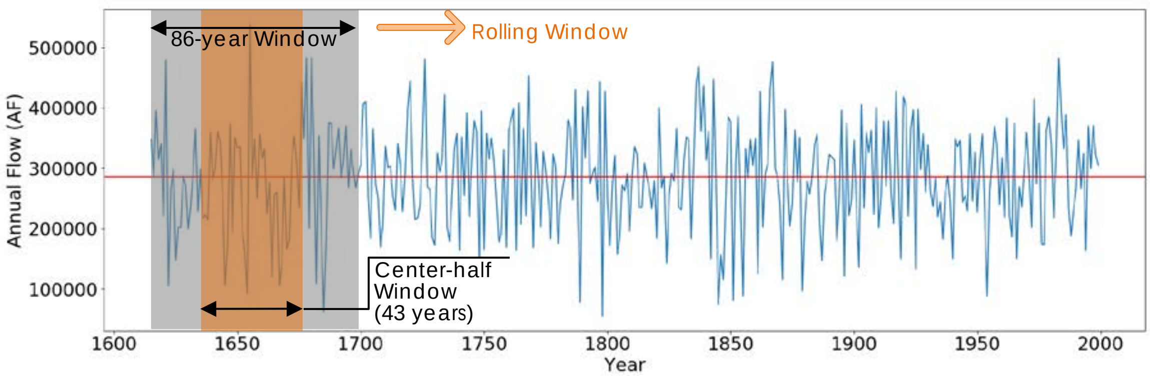

Figure 3 - Diagram showing the rolling 86-year window with the center-half window (yellow) used to calculate the probabilities of dry years being followed by wet years.

The dry-to-wet transition probability, written below as *P(D→W),* is defined by the following equation.

$$P(D \rightarrow W) = \frac{\text{No. of dry years followed by a wet year}}{\text{Total no. of dry years}}$$

The distribution of dry-to-wet transition probabilities in the center-half windows for the reconstructed period is shown in Figure 4.

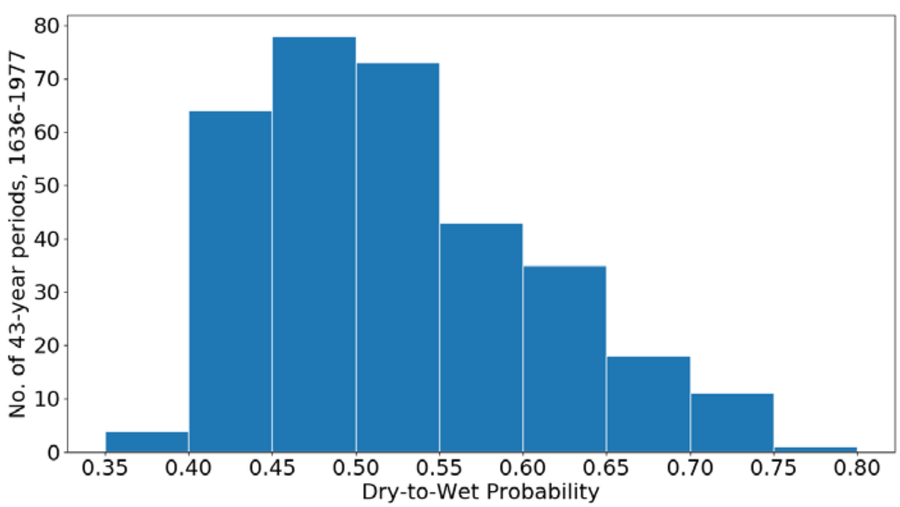

Figure 4 - Histogram showing the distribution of dry-to-wet probabilities for the rolling center-half windows for the reconstructed period

The dry-to-wet probability values representative for all the center-half rolling windows ranged from 0.38 to 0.78. Figure 5 shows the exceedance curve of the dry-to-wet probabilities for all the rolling windows.

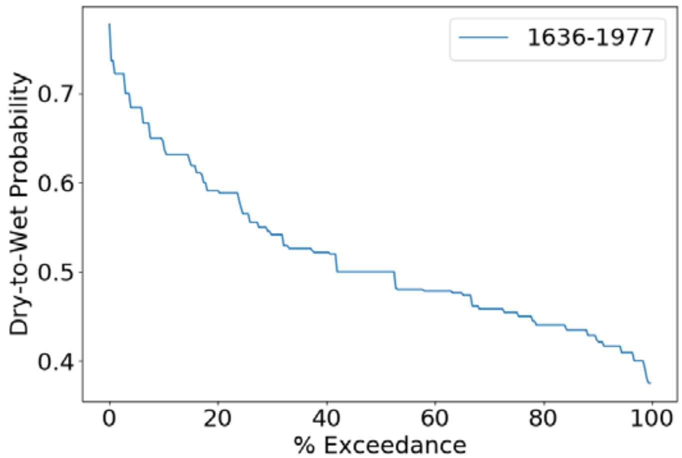

Figure 5 - Plot showing the exceedance curve of dry-to-wet probabilities calculated from the rolling 43-year periods

We performed the selection of 100 rolling windows using the exceedance curve, finding the rolling window that had a representative dry-to-wet transition probability closest to one for each percentage value in the dry-to-wet exceedance curve from 1 to 100 percent. The rolling windows were selected based on the representative transitions probability (center-half windows), but the transition probability matrix for generating the hydrological traces was computed using the 86-year rolling windows to capture in the statistics the random occurrences around the center-half window. Each of the resulting 86-year periods were analyzed to compute four transition probabilities: 1.) probability of a dry year followed by a dry year, 2.) probability of a dry year followed by a wet year, 3.) probability of a wet year followed by a dry year, and 4.) probability of a wet year followed by a wet year. Figure 6 shows a diagram of the four transition probabilities following the transition from the current state to the future state.

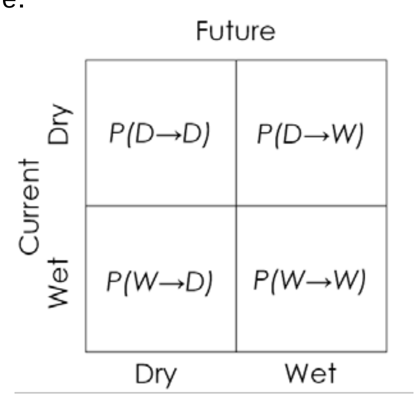

Figure 6 - Diagram showing the breakdown of the transition probability matrix.

For example, for an exceedance probability of 75%, we selected the window having the closest dry-to-wet exceedance value (75.08%) in Figure 5, which is identified with year 1850 that correspond to the first year of the center-half window. Figure 7 shows the 86-year window corresponding to the year 1850. The corresponding dry-to-wet transition probability for the center-half 43-year window is

0.45. The transition probabilities to generate this trace were then calculated using the 86-year window, 1829 to 1915, which resulted in a new dry-to-wet transition probability of 0.52, when including the years before and after the center-half window. The procedure in this example was completed for each percent of the exceedance curve.

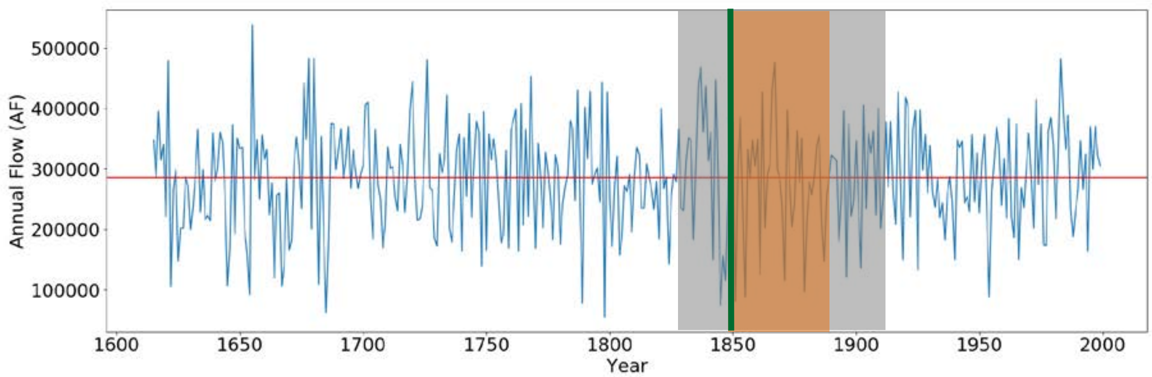

Figure 7 - The 86 years (gray shade) surrounding the year 1850 (green line) were used to calculate transition probabilities for a 75% exceedance. The 43-year period that contributed to the exceedance curve is shown in orange.

The 86-year window transition probabilities for the years corresponding to the 1 percent and 99 percent of the dry-to-wet exceedance curve in Figure 5 are shown in Table 1 and Table 2.

Table 1- Transition probabilities from the lower end of the exceedance curve (year 1737)

P(D→D) **0.45**	P(D→W) **0.55**
P(W→D) **0.53**	P(W→W) **0.47**

Table 2- Transition probabilities from the upper end of the exceedance curve (year 1649)

P(D→D) **0.43**	P(D→W) **0.57**
P(W→D) **0.56**	P(W→W) **0.44**

Historical years with 6-hour observed precipitation and temperature were classified as wet and dry years based on the historical flow at the Poudre River at Canyon mouth, using the median of the reconstructed flow as the classification threshold. Years with annual flow above the threshold were classified as "wet" and years below were classified as "dry." The result was a bin of dry years, and a bin of wet years.

Each of the 100 sets of the annual transition probabilities was then used to randomly generate a sequence of 86 wet and dry years. The result of this process was 100 binary wet/dry sequences of 86 years each. Then, we used each of the binary sequences to engineer an 86-year long synthetic precipitation and temperature trace with 6-hour temporal resolution. For each of the year types in the sequence, we randomly pulled each of the 12 months of precipitation and temperature data (i.e., month-long chunks) from a historical year in the corresponding wet or dry year bins. Note that each month of the engineered series could potentially come from a different year with the corresponding wet/dry classification. For example, when the binary sequence called for a dry year, the January precipitation data was randomly selected from the pool of "Januarys from Dry Years." The same procedure was followed to select precipitation data for February to December for this dry year. The process continued with the next year type of the sequence, sampling months for that year type as described above. As a result, each synthetic precipitation year was composed of twelve month-long chunks originating from potentially different years, which were either all dry, or all wet.

The 100 synthetic 86-year time series of precipitation and temperature generated using this process were imported into dashboards to be visualized and compared. HydrologyDataset_042218.twbx contains the precipitation series summarized per month and the file HydrologyDataset_042218_TEMP.twbx is used to present the corresponding temperature generated series.

2.2 Baseline Hydrological Modeling

The hydrologic models from the JFRCCVS were used to generate streamflow traces for locations contributing to Fort Collins' water supply based on the precipitation and temperature traces described in the previous section. Both the synthetic precipitation and temperature traces and the historical precipitation and temperature data were used in this hydrology dataset. The historical inputs were designated as trace 0. The models were run using the National Weather Service River Forecast System and incorporate the SNOW-17 snow accumulation and melt model and the Sacramento Soil Moisture Accounting Model to calculate natural (unregulated) streamflow. The 16 sub-basins shown in Figure 1 were all modeled as part of this hydrology dataset. The models run at a 6-hour timestep and lag and K routing is used to route flow between sub-basins. The simulation period for the planning model is 86 years and agrees with the length of the synthetic traces. The hydrologic models were setup for 86-year simulation, arbitrarily starting in WY1939 and ending in WY2024 to avoid model issues with dates later than 2030. The historical trace of reconstructed naturalized flows at the control points are shorter and span from WY1950 to WY2008.

The 6-hour time series streamflow results from the hydrologic models were processed and converted to monthly flow averages in cubic feet per second for use in the Fort Collins and Poudre Basin system simulation models, which operate on a monthly time step. The monthly time series were bias-corrected to reduce inherent model errors. The bias correction is designed to account for errors in the hydrologic models due to both calibration errors and bias built into the design of the model. The hydrologic models used for this work tend to underestimate high flows and overestimate very low flows. There are also calibration errors throughout the distribution. Bias correction using the quantile-mapping method helps to reduce this bias. The Tableau dashboard (FlowMetricsV4.twbx) summarizes the streamflow results.

To perform bias correction, estimated monthly natural flow data was available from the JFRCCVS for 5 of the 16 sub-basins in this study: Cache la Poudre at Canyon Mouth (FTDC2), Big Thompson at Drake (DKKC2), St. Vrain Creek at Lyons (LNSC2), Boulder Creek at Orodell (OROC2) and Colorado River at Lake Granby (GBYC2). For each of these 5 locations, the observed natural flows and the simulated historical flows were used to correct all the simulated trace flows. The correction amount was set for each point on the distribution function to match the distribution of simulated historical flows to the distribution of observed natural flows. This creates a set of correction amounts (positive or negative) for the full range of the distribution. So the 10th percentile flows (which can be a different magnitude in the observed flows than in the simulated flows) have a specific correction amount, the 90th percentile flows have a different correction amount, and every other point in the distribution has a correction amount. This set of correction values associated with various percentiles is then applied to each of the 100 generated traces for that sub-basin, and each monthly value in all traces is corrected accordingly. Each sub-basin with observed flows has a separate set of correction values.

See Figure 8 for the model results for FTDC2, and see Figure 9 for an example of the bias correction results at the FTDC2 location with the observed and simulated exceedance curve used to derive the correction and the correction applied to the trace 1 results. In Figure 9, the left plot shows the distributions of the observed and simulated time series and the right plot shows the simulated and corrected curves of trace 1. The difference between the observed and the simulated at each point in the left graph is applied as a correction to the same point on the right graph. So at low flows (below ~90 cfs, 40th percentile), the simulated flows are over-estimated compared to the observed. The correction of the flows below the 40th percentile is therefore negative and the corrected time series is lower than the original for that range.

Table 3 shows statistics for the corrections for each station. The mean row represents the average correction amount over all months in the period of record. The max and min rows represent the largest and smallest corrections in any individual month.

For sub-basins upstream of a point with observed data, the correction amount was scaled down proportionally to the relationship between the flow of the upstream point and the point with observed data, for a given month. As an example, the uncorrected total flow in a given month at the Canyon Mouth may be 100 cfs, which is the 10th percentile flow for that trace. The uncorrected flow on the North Fork below Seaman Reservoir is 50 cfs for the same month and trace. If the 10th percentile correction amount for the Canyon Mouth is 2 cfs, the correction applied to the North Fork will be 1 cfs. In another month, the Canyon Mouth flow may be 200 cfs (15th percentile) with Seaman Reservoir still at 50 cfs. If the correction amount at that percentile is 3 cfs, the correction at Seaman Reservoir that month would be only 0.75 cfs.

The Canyon Mouth bias correction was used in this way to also correct the Cache la Poudre below Elkhorn Creek (EHNC2), Halligan Reservoir (NCHC2), and Seaman Reservoir (SEAC2) flows. The bias correction at Drake (DKKC2) was used to correct the Lake Estes sub-basin (ESSC2).

The remaining sub-basins that did not have observed data or downstream observed data were not corrected. Correcting these other points using upstream or adjacent basins would potentially distort the results by forcing the flow distribution at the corrected point to match the flow distribution at the observed point. Even adjacent basins may have quite different distributions. Discussions during the project have indicated that the Poudre Basin is the most important to Fort Collins Utilities' water supply, followed by the Upper Colorado Basin. The entire Poudre Basin and the Colorado River above Lake Granby were bias corrected. The other uncorrected streamflow locations in the Big Thompson Basin, St. Vrain Basin, and Upper Colorado Basin watersheds are included in this analysis mostly for CBT allocation modeling and will not be used directly in the PBN model.

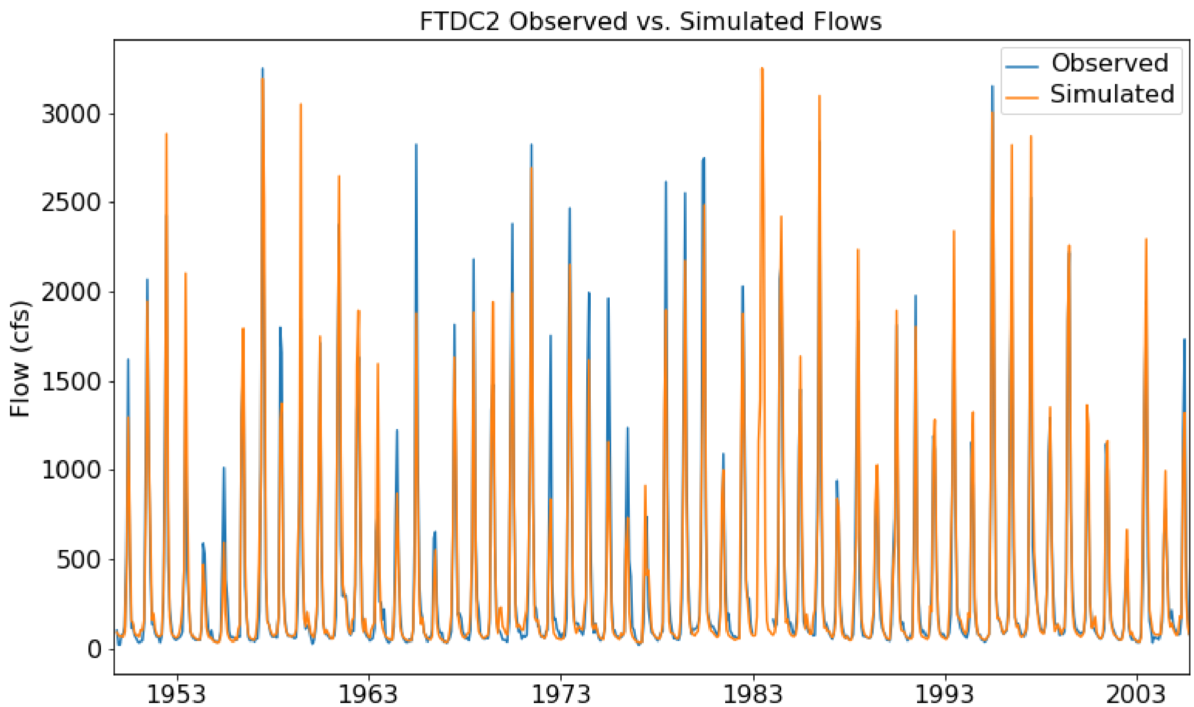

Figure 8 – Model Simulation Results for FTDC2

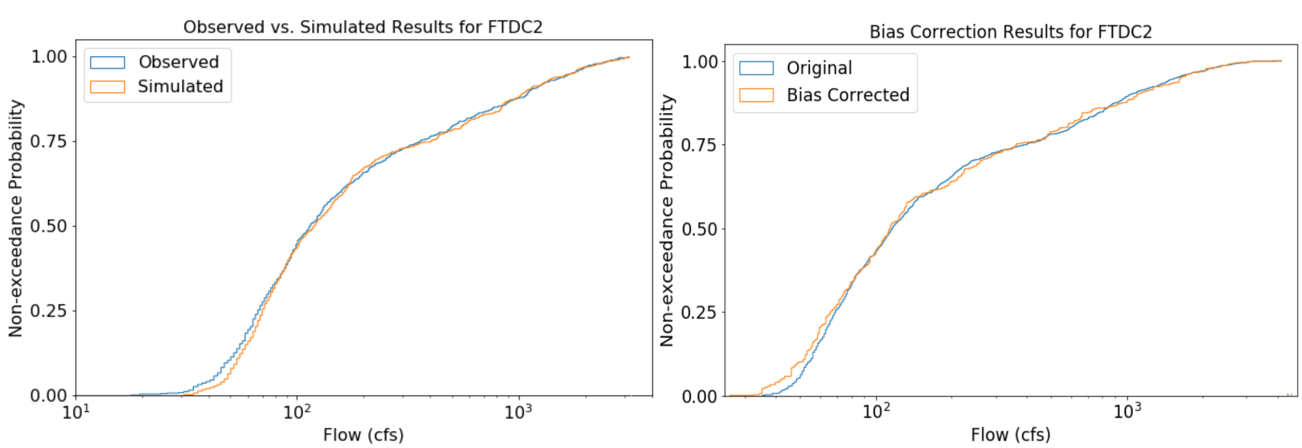

Figure 9 – Non-exceedance plots showing bias correction for FTDC2 (trace 0) and the result with bias-correction for trace 1.

Table 3 - Description of Corrections at Locations with Observed Flows

	FTDC2	DKKC2	LNSC2	OROC2	GBYC2	FRGC2
Mean correction (%)	-2.1	1.8	-2.5	4.1	-0.8	-7.1
Max correction (%)	11.6	74.0	15.3	44.9	23.1	9.4
Min correction (%)	-25.6	-28.0	-63.9	-36.9	-36.1	-17.8

2.3 Climate Adjusted Hydrological Modeling

In addition to the baseline modeling for all sub-basins and traces that is based on historical climate conditions, the climate scenarios defined in the Hydrologic Approach Technical Memo (RTI, 2018) were used to perturb inputs to the previously described hydrologic models to produce climate-adjusted streamflow traces. A climate scenario consists of a combination of temperature expressed as a deviation in °F from historical temperature conditions, and precipitation expressed as a deviation in percent from historical precipitation conditions. Figure 9 shows the selected scenarios in the Hydrologic Approach Technical Memo. Table 4 shows the names of the climate scenarios and their corresponding adjustment of temperature and precipitation.

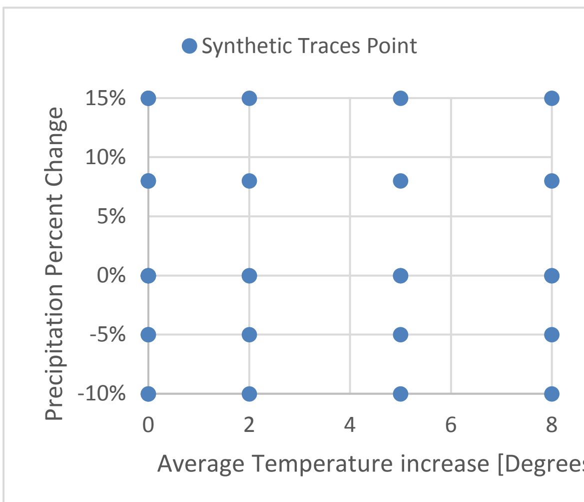

Figure 10 – Grid of Precipitation Change and Temperature increase to Develop Synthetic Hydrologic Traces

Table 4 – Climate Scenario Name and Definition

Scenario Number	Name	∆T [°F]	∆P [%]
1	Base	0	0
2	CC:T0P0	0	0
3	CC:T2P0	2	0
4	CC:T5P0	5	0
5	CC:T8P0	8	0
6	CC:T0P-10	0	-10
7	CC:T2P-10	2	-10
8	CC:T5P-10	5	-10
9	CC:T8P-10	8	-10
10	CC:T0P-5	0	-5
11	CC:T2P-5	2	-5
12	CC:T5P-5	5	-5
13	CC:T8P-5	8	-5
14	CC:T0P7	0	7
15	CC:T2P7	2	7
16	CC:T5P7	5	7
17	CC:T8P7	8	7
18	CC:T0P15	0	15
19	CC:T2P15	2	15
20	CC:T5P15	5	15
21	CC:T8P15	8	15

Precipitation and temperature adjustments were defined for each scenario in the Hydrologic Approach Technical Memo, and the hydrologic model inputs were adjusted accordingly. For example, scenario 15 is defined as a 2 °F temperature increase and 7% precipitation increase. To run scenario 15, the input temperatures for all sub-basins and traces were increased by 2 °F compared to the baseline for all timesteps in the simulated period. The input precipitation values were all increased by 7% for all timesteps. These changes were made by scripts that adjust the hydrologic model input files at run time, without having to create new input files.

The results from the climate adjusted hydrologic model runs were saved and processed the same way as the baseline results, including bias-correction. Figure 11 shows example monthly results for the Canyon Mouth gage, trace 1. Three climate scenarios are shown in addition to the baseline results. The scenarios all show earlier runoff due to temperature increases, and the volume of runoff depends on the change in the precipitation as well as the temperature. See the Tableau dashboard for further exploration of these results.

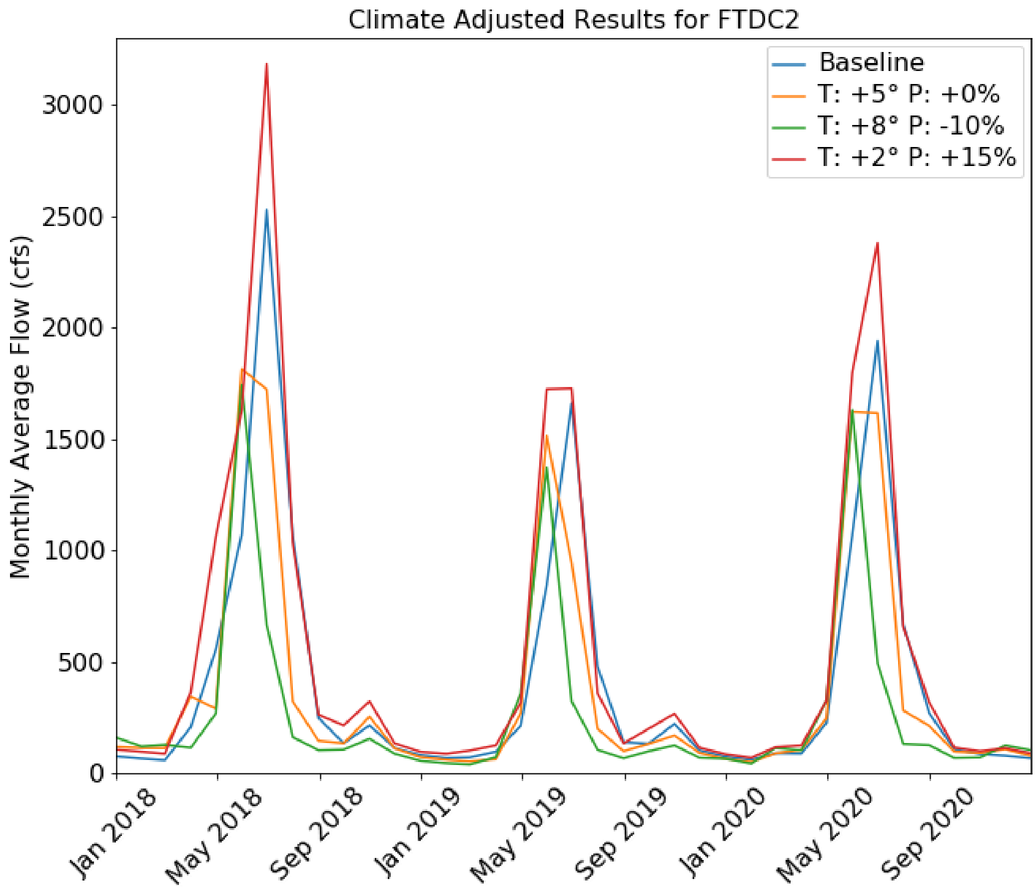

Figure 11 – Climate adjusted results example for FTDC2, trace 1.

2.4 Selection of Representative Traces

For the initial modeling of the impact of various risks in the Vulnerability Study, only 5 or 6 of the 100 traces will be used to allow more detailed analysis and initial exploration of vulnerabilities and system performance. This section describes the method used to select those representative traces.

A procedure and a selection tool were developed through discussions with Fort Collins Utilities to choose traces for this detailed modeling. A set of 24 metrics or statistical measures was developed for application to each baseline trace (Scenario 1) simulated streamflow that help describe the overall hydrologic characteristics of the traces, particularly the dry periods. The streamflow metrics include overall average value, minimum value, minimum of 3, 5, and 10-year moving averages, and resiliency among others. Based on input from FCU, a few of the metrics were selected as being the most relevant and useful for describing key hydrologic parameters of interest for selecting traces for the Vulnerability Study. Table 5 includes the definition of the metrics used in the selection of representative traces.

Table 5 – Definitions of Streamflow Trace Performance Metrics Selected for Analysis

Metric	Narrative
MovingAvg3_Min	Minimum three-period moving average of the average annual flows
MovingAvg5_Min	Minimum 5-period moving average of the average annual flows
MovingAvg10_Min	Minimum 10-period moving average of the average annual flows
Dry to Wet Probability (Resilience measure)	Number of months below the threshold (i.e., median flow) followed by a period above the threshold, divided by number of periods below the threshold
Average Dry Flows (Vulnerability measure)	Average of the values below the threshold (i.e., median flow) using periods below the threshold as a fraction of the threshold. For example, a value of 0.5 indicates that the average value when the value is below the threshold is 50% of the threshold.

An Excel-based selection tool[1] was developed that can be used to rank the traces from driest to wettest by weighting the different metrics according to user preferences. Each metric is given a score with a user-assigned weight and can be used in the ranking. For each metric a trace rank is calculated based on its position with respect to the extreme (i.e., drier or wetter) expected value. The score for each trace is computed multiplying the rank by the user selected metric weight and summing the weighted ranks for all the metrics. The traces are then sorted according to their total score and the top 10 are displayed. Scores from multiple basins and the 16 modeled points for a trace can be combined using weights for the selection of the top 10.

In discussion with Fort Collins Utilities the metrics used to select the representative hydrologic traces are the minimum value of the 3- and 10-year running average, resilience, and vulnerability. Metrics were all given an equal weight in the selection process. Resilience is defined here as the probability of having a wet year following a dry year, and vulnerability is the average of the annual streamflows in all the years with annual flow below the median annual flow. Two key locations were selected for the analysis of representative traces: the Cache la Poudre at Canyon Mouth and Colorado River above Lake Granby locations. These were used with equal weights.

The representative traces were selected based on the frequency that they ranked in the top 10 on the following analyses:

(1) Considering one metric and basin at a time, the top 10 traces in each case (i.e., the traces that had the highest metric scores, for example the lowest minimum 3-year running average annual streamflow) were compiled for the selection process. The results include 8 sets of 10 traces from all the metric/basin combinations (i.e., 4 metrics and 2 basins).

(2) The 4 metrics for each basin individually and the 4 metrics with the 2 basins were all equally weighted and used to select three additional sets of top10 traces that had a high rank when those factors were considered simultaneously.

Table 6 shows the top 10 traces for the 11 sets that resulted from the previous analysis and were used in the selection. From the 11 sets of top 10 traces, the traces that were present in the top 10

[1] File name: Trace MCDA v4.xlsx

most often were selected as the representative traces. An additional representative trace was the 50th ranked trace (i.e., median trace) with the 4 metrics and the 2 basins considered simultaneously and having equal weighting. The six traces chosen as the representative traces for use in the detailed risk assessment modeling are: **15**, **63**, **95**, **47**, **67** and **52**. Traces 15, 63, and 95 were present in the top 10 for many of the metrics and represent 3 of the top 4 traces when all metrics and basins are included at the same time. The other trace in the top 4 is 84, which has its driest period at the end of the trace, making it difficult to see the effects in the modeling results. Instead, trace 67 was selected, which appears in the top results several times and has an extended dry period in the middle of the record. Trace 47 appears in the top 10 only three times but is the driest trace at the Canyon Mouth when considering the 10-year average, which should make it a good trace for analysis. Finally, the trace ranked 50th out of 100 using all the metrics and both basins is 52.

Table 6 – Top 10 Traces for each of the Analyses used to Select the Representative Traces

Set	1	2	3	4	5	6	7	8	9	10	11
Metric	Min (Mov.Avg 3-yr)	Min (Mov.Avg 10-yr)	Resilence	Vulnerability	Min (Mov.Avg 3-yr)	Min (Mov.Avg 10-yr)	Resilence	Vulnerability	All	All	All
Rank\Station	FTDC2	FTDC2	FTDC2	FTDC2	GBYC2	GBYC2	GBYC2	GBYC2	FTDC2	GBYC2	All
1	83	47	15	58	84	67	95	11	15	95	15
2	15	18	13	44	15	84	15	69	84	84	84
3	84	84	91	15	95	70	98	59	63	11	63
4	67	6	95	86	70	47	3	63	35	63	95
5	8	31	87	29	63	6	11	99	3	15	3
6	78	98	7	35	83	95	52	4	87	78	98
7	47	67	35	6	16	63	74	84	29	67	69
8	18	81	60	63	78	76	6	57	60	76	29
9	95	3	84	60	52	83	17	96	98	4	81
10	87	83	96	78	11	25	18	41	69	98	6

Note:
- FTDC2 - The Cache la Poudre at Canyon Mouth
- GBYC2 - Colorado River above Lake Granby

2.5 PBN Input Preparation

The hydrology results described above capture more natural variability and more climate effects than the historical observed streamflow record, and thus represent sets of different potential conditions in the basin. The simulated naturalized flows are the source of the hydrology inputs for the PBN model. Several PBN model inputs in addition to the naturalized streamflows are also associated with the hydrology of the base existing conditions model. These model inputs were determined in the current model using the historical record of basin streamflows, diversions, and other observed or calibrated data. Because there was no straightforward way to adjust all the model inputs for the new variability introduced by the resequenced historical hydrology and the climate-adjusted hydrology, Fort Collins Utilities performed sensitivity analyses to determine the effect of those time series on the Fort Collins simulated yield. These analyses were used to select the method of handling those inputs in the generation of the hydrology input datasets for the PBN model for the Vulnerability Study. This section describes the hydrologic time series processing methods implemented for simulating future conditions in the PBN model.

2.5.1 Disaggregate Flows

The naturalized streamflows generated in earlier steps were used to compute annual streamflows at 11 inflow points for the PBN model that represent the upstream water availability for the different hydrology sets. RTI used the method developed for the Common Technical Platform (CTP), which is the modeling platform used for the Halligan Reservoir Enlargement EIS and Northern Integrated Supply Project EIS. It uses naturalized flows for the Canyon Mouth (FTDC2) and North Fork (SEAC2) gauges and a set of monthly factors to estimate the PBN inflows as a function of the naturalized flows at FTDC2 and SEAC2. The monthly factors for all the PBN inputs are shown in Table 7. To create each PBN monthly streamflow input the FTDC2 and SEAC2 flow was multiplied by the appropriate fraction for each month in the record.

Table 7 – Disaggregation Flow Factors for the PBN Inputs

MODSIM Point	DS Point	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
NATBARNES	Canyon Mouth	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.02	0.02	0.02	0.02
NATCHAMBERS	Canyon Mouth	0.07	0.1	0.11	0.05	0.05	0.06	0.17	0.21	0.14	0.14	0.13	0.11
NATCOM	Canyon Mouth	0.14	0.13	0.13	0.14	0.14	0.14	0.11	0.09	0.12	0.12	0.12	0.12
NATJWCRK	Canyon Mouth	0.02	0.02	0.03	0.01	0.01	0.01	0.04	0.05	0.03	0.03	0.03	0.03
NATLONG	Canyon Mouth	0.03	0.04	0.04	0.02	0.02	0.02	0.07	0.08	0.06	0.05	0.05	0.04
NATPETERSON	Canyon Mouth	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.01	0.01
NATUP	Canyon Mouth	0.72	0.67	0.67	0.75	0.75	0.74	0.57	0.5	0.61	0.61	0.63	0.65
NATTWIN	Canyon Mouth	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
NATWORSTER	North Fork	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
NATHALLIGAN	North Fork	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
NATNRFRK	North Fork	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28

The PBN hydrologic input time series computed for all the traces were imported into the database and cataloged based on the climate change scenario and the trace number. The scenario names and IDs used to catalog the hydrology results into the database are shown in Table 4.

2.5.2 Other Time Series Inputs

It was identified that several input datasets, in addition to the disaggregated natural flow nodes described in section 2.5.1, would need to be developed in preparation for the modeling efforts of different hydrological scenarios for the Vulnerability Study. FCU staff performed several sensitivity analyses to help determine what method and level of effort should be used to develop the input datasets. The modeling constructs that were associated with the hydrology state and a function of the future conditions are:

- agricultural demands in the basin
- the downstream end of the network of water users in the South Platte River below the Kersey gage, referred as the "fish bone"
- excess precipitation construct, and
- trans-basin diversions

The following sections describe each of these sensitivity analyses and the resulting strategy for adjusting existing condition PBN inputs to reflect different future hydrologic conditions.

2.5.2.1 Sensitivity to Increasing Agricultural Demands in the Basin

PBN modeling simulations require input data for agricultural water demands in the Poudre Basin. There was a concern that increased agricultural demands under certain climate change scenarios could significantly decrease yields of FCU water supplies. FCU staff performed a sensitivity analysis to determine if FCU water supplies are sensitive to increased agricultural water demands in the Poudre Basin to help inform how to develop input data for future modeling simulations.

The sensitivity analysis effectively simulated an extended irrigation season and increased water demand during the irrigation season by approximately 10% per year to see if the increased demands impact FCU water supplies. The results of the analysis showed little decrease (less than 1% reduction in the Storage Reserve Factor) in the yields of FCU supplies. FCU staff determined that this minor impact did not warrant extensive effort to develop adjusted agricultural input data to represent different hydrologic conditions for future modeling scenarios. The base agricultural demands will be re-sequenced to account for water use in wet and dry periods for different hydrologic conditions.

2.5.2.2 Sensitivity to Increasing Demands from Other South Platte Basin Water Users

PBN modeling simulations also require input data which represents demands from other water users in the South Platte basin. There was a concern that increased South Platte demands under certain climate change scenarios could significantly decrease yields of FCU water supplies. FCU staff performed a sensitivity analysis to determine if FCU water supplies are sensitive to increased Poudre basin water demands from water users in the South Platte to help inform how to develop input data for future modeling simulations.

This analysis reduced available supplies in the South Platte basin by approximately 10% per year, thus forcing demands in the basin to seek water supplies further upstream in the Poudre Basin. The results of the analysis showed little decrease (less than 1% reduction in the Storage Reserve Factor) in the yields of FCU supplies. FCU staff determined that this minor impact did not warrant extensive effort developing adjusted input data to represent future water use by other South Platte water users for future modeling scenarios.

2.5.2.3 Excess Precipitation Construct

One PBN construct that is also tied to the hydrological regime consists of a demand node which represents native vegetation's water demand (NATIVE) and a supply node that represents the excess precipitation on croplands that is not removed from the system by evapotranspiration

(PRECIP). These nodes are part of a PBN construct that represents groundwater inputs and interactions to the Poudre River that are used to support calibration of basin inflows and operations with gaged flows along the river. There was a concern that changes in the NATIVE and PRECIP values under certain climate change scenarios could significantly decrease yields of FCU water supplies. FCU staff performed two sensitivity analyses to help determine if FCU water supplies are sensitive to changes in the NATIVE and PRECIP node inputs to help inform how to populate the nodes in future modeling scenarios.

The first sensitivity analysis populated the nodes with re-sequenced input data using one of the wet-dry year sequences developed for the alternate hydrology based on the paleo-derived transition probabilities. The second sensitivity analysis used monthly averaged input data from the existing model period of record for time series of the NATIVE and PRECIP model nodes. Both analyses resulted in notable changes to the yields of FCU water supplies and had consequential impacts to the Storage Reserve Factor in the modeling simulations. FCU staff and RTI explored correlations between other factors and these nodes but did not find any strong correlations. Although there are notable changes to FCU water supply yields, FCU staff understands that in the original development of the PBN these nodes and associated constructs were populated using '*like-year*' values from historical periods for synthetic modeling periods. This method uses time series values from the historical period to represent time series of future conditions based on similarities of flows at selected locations. Given its use in prior FCU modeling efforts, it would be reasonable to use like-year values from historical data for future hydrological scenarios for the Vulnerability Study.

2.5.2.4 Trans-basin Diversions

The FCU trans-basin imports from the Upper Colorado River basin into the Poudre River basin are simulated as inflow time series in the PBN model. These inflows are based on the historical diversions, which were determined by the system operators based on different factors, including water rights, availability of water in the diverting basin, storage availability and operations in the receiving basin, diversion capacities, repairs and maintenance schedules. Trans-basin diversions are a significant component (nearly 15% of the average native flows in the basin) of the FCU yield on an annual basis and are the drivers of the FCU's Reuse Plan; therefore, it is important to determine appropriate trans-basin diversion time series for modeling of future conditions.

An extensive analysis was performed to attempt to correlate the historical trans-basin diversions with naturalized flows at stream gages in both East Slope and West Slope basins. Correlations were investigated using monthly flows, annual flows, seasonally segregated flows, and other methods to attempt to find an approach for estimating historical trans-basin diversions from historical naturalized streamflows. Unfortunately, none of the analyses showed strong correlations between those variables. Based on this outcome, FCU staff recommended adopting the like-year approach to estimate trans-basin diversions, since this method was used to develop input data for sites without measured diversions in the previous versions of the PBN.

2.5.2.5 Recommended Like-Year Modeling Approach

The sensitivity analyses for the excess precipitation construct and the trans-basin diversions showed that impacts on the FCU yield could be significant. Therefore, it is necessary to implement an approach for representing those inputs synchronized with the future hydrological conditions to be simulated for the Vulnerability Study. An approach based on the *like-year*, used in previous PBN analyses, is recommended to estimate these PBN input time series for future conditions. Although the results of the agricultural demand sensitivity analysis and the South Platte water users' sensitivity analysis suggest these inputs have little impact on FCU water supplies, for consistency, it is recommended to use a *like-year* approach for these time series as well to simulate future conditions.

The *like-year* approach determines values for the new time series based on values from a historical year with the most similar total annual flows at key locations. For example, if simulated year N has an annual streamflow for the Cache la Poudre River at Canyon Mouth of 25,100 acre-feet, the PBN input data from the historical year with the annual streamflow at the Canyon Mouth closest to 25,100 acre-feet would be used to populate the time series for simulated year N. For trans-basin diversions the conditions in both the Poudre River basin and the Colorado River basin are drivers of the diversion, so the recommended *like-year* approach was based on the sum of flows at the Cache la Poudre River at Canyon Mouth and the Colorado River at Granby Lake to select the historical year to represent the future conditions. That selected historical year was used to create the time series for all the PBN input datasets. This method adjusts PBN inputs to be consistent with the magnitude of flows for future conditions, according to the reduction/increase in simulated naturalized flow compared to historical conditions. Using the same like-year for all the input time series populated using the like-year approach preserves the relationships between the East Slope and West Slope operations captured in the historical data. For the selected alike year, the historical monthly time series were used for creating the synthetic time series of the PBN inputs. Table 8 shows the list of PBN names that are processed with the like-year approach.

Table 8 – List of PBN Nodes Processed with the Like-Year Algorithm

Node Name	Node Name	Node Name
ARTHUR	LARNO2	R17L
BHEATON	LARWELD	R18L
BIJOUCANAL	LIDDLEDITCH	R19L
BOXELDER	LILCACHE	R1L
BOYD	LONETREE	R20L
BRAVODITCH	LOWERPLATTE	R21L
CARLSONDITCH	LOWLINEDITCH	R22L
CHAMBERSDITCH	NATIVE	R23L
COY	NEWCACHE	R24L
DAVISBROTHERS	NEWMERC	R25L
EMPIRECANAL	NORTHSTERLING	R26L
FORTMORGAN	NPIC	R27L
FTCART_c	OGILVY	R28L
FTCLAR2_c	PAWNEEDITCH	R29L
FTCNMER_c	PETERSONDITCH	R2L
FTCPVLC_c	POWELLBLAIR	R30L
GREELEY3	PREWITTINLET	R31L
HARMONYNO1	PVLC	R32L
HENDERSONSMITH	R10L	R33L
ILLIFPLATTE	R11L	R34L
JACKSON	R12L	R35L
JACKSONLAKE	R13L	R36L
JONES	R14L	R37L
LAKE2	R15L	R38L
LAKECANAL	R16L	R39L

Node Name
R3L
R40L
R41L
R42L
R43L
R44L
R45L
R4L
R5L
R6L
R7L

Node Name
R8L
R9L
RAMSEYDITCH
REDLION
RIVERSIDECANAL
SCHNIEDERDITCH
SOUTHPLATTE
SOUTHRESERV
SPDEMAND
SPDEMAND2
SPRINGDALE

Node Name
SPWCPEX
STERLINGNO1
TAMARAKDITCH
TAYGIL
TRIRENT
UPPERPLATTE
WELDONVALLEY
WHITNEY
WSSC
WSSC_RF

2.6 Tools for Yield Modeling

RTI catalogued the hydrology sets into the FCU modeling system database and built tools to process inputs for the PBN model based on the future conditions and the time series generation recommended approach. The hydrology sets cataloged for the Vulnerability Study are composed of (1) the inputs to the PBN model, estimated from the simulated naturalized flow inputs, and (2) the naturalized flows simulated at the key locations.

RTI developed a tool to calculate the PBN inputs for the different hydrological scenarios that extracts the current time series in the PBN model (i.e., historical) to the database and resequences the time series to create PBN inputs for each alternate hydrology. The processed time series are written into the MODSIM version 7 ADA format to be imported into the PBN model at run time using the new modeling system functionality.

3 References:

RTI International, 2018. *Hydrology Modeling Approach TM*. Fort Collins Utilities Water Vulnerability Study. February.

Woodhouse, C.A. and J.J. Lukas. 2006. Multi-century tree-ring reconstructions of Colorado streamflow for water resource planning. Climatic Change 78: 293-315.

Appendix F SCENARIOS FOR VULNERABILITY ANALYSIS

Technical Memorandum

Scenarios for Vulnerability Analysis

Date: January 2, 2019 (Revised 01/25/2019)
From: Chip Paulson, Lisa Fardal, Neil Stewart
To: Fort Collins Utilities

1.0 INTRODUCTION

As part of the City of Fort Collins Utilities (Utilities) Water Supply Vulnerability Study (Study), potential risks and uncertainties to both the Utilities water supply system and the Colorado-Big Thompson (C-BT) project, operated by the Northern Colorado Water Conservancy District (Northern Water), were identified, scored, and prioritized. These identified and prioritized risks and uncertainties are summarized in the *Risk Identification Technical Memorandum* (TM).

To quantify the impacts of these risks and uncertainties to the performance of Utilities' water supply system, baseline conditions for future scenarios were established in the three simulation models used in the Study. "Baseline conditions" consist of existing or currently planned water resources infrastructure and water rights portfolio, and existing operations. Next, the prioritized risks and uncertainties were assembled into scenarios that capture a variety of potentially impactful futures. These scenarios will be simulated in the three models and their performance will be compared to baseline conditions, quantifying their impact to the water supply system. This will help inform Utilities on which future conditions create significant vulnerabilities for their water supply system.

This TM presents the baseline assumptions for the three models used for the Study and the future conditions scenarios that will be simulated in them.

2.0 BASELINE ASSUMPTIONS

As noted above, baseline conditions are a future system state with existing or planned infrastructure, a portfolio of existing or planned water rights, and existing operations and policies surrounding water deliveries. Baseline conditions represent the conditions against which vulnerability impacts and, in later studies, proposed system improvements would be compared. Assumptions for baseline conditions were established in the three models included in the Study: the C-BT Quota Model, the Poudre Basin Network (PBN) Model, and the Fort Collins System Model (FC System Model). The baseline conditions across all three models do not include any identified risks or climate altered hydrology and are intended to represent the most reasonable future for planning purposes. Results of water supply system performance under the baseline conditions will be used to assess the impact of the selected scenarios and the vulnerability of the Fort Collins water system.

2.1 C-BT QUOTA MODEL

The C-BT Quota Model, developed and maintained by Northern Water, has several input controls for simulation in the model. This section presents the baseline settings for those input controls, organized similarly to how they are presented in the C-BT Quota model. All risks under “Simulation Settings” are off. These settings were set based on discussions between Northern Water and Fort Collins Utilities’ staff.

- **Table 2.1** shows the baseline settings for initial storage contents, assuming Chimney Hollow is operational.
- **Table 2.2** shows the baseline settings for the C-BT municipal and industrial (M&I) and agricultural ownership controls
- **Table 2.3** shows the baseline settings for the Windy Gap controls
- **Table 2.4** shows the baseline settings for the additional controls

Table 2.1 - Initial Storage Contents in CBT Quota Model

Storage Item Name	Starting Value (acre-feet)
Lake Granby, Horsetooth and Carter Lake (LG+HT+CL) Beginning of Year (BOY) Active Contents	550,000
M&I C-BT Carryover Storage	20,000
Agricultural C-BT Carryover Storage	0
Windy Gap Storage in Lake Granby (LG)	0
Windy Gap Storage in Chimney Hollow (CH)	90,000
First Year Potential Regional Pool	0

Table 2.2 - C-BT M&I Ownership and Demand and Agricultural Demand

Item Name	Item Value
Initial M&I C-BT Units (1000 of units)	263.5
Annual Percent Increase in M&I Units (%)	0
Final M&I C-BT Units (1000 of units)	263.5
Initial Average M&I C-BT Demand (thousand acre-feet)	146.7
Annual Percent Increase in M&I Demand (%)	0
Final Average M&I C-BT Demand (thousand acre-feet)	146.7
Lease M&I Surplus C-BT to Agriculture	On

Table 2.3 - Windy Gap Input Settings

Windy Gap Item Name	Item Value
Project On/Off	On
In-Lieu Program	Off
Firming Project	On
Units not in Firming Project	40
Units in Firming Project	440
Demand, Non-Firming Project Participants (thousand acre-feet)	4
Demand, Firming Project Participants (thousand acre-feet)	26
Max Annual Firming to Move to Chimney Hollow (thousand acre-feet)	30

Table 2.4 - Additional Model Inputs

Item Name	Item Value
Annual Carryover Program Shrink (%)	10
Carryover Limit (%)	20
Regional Pool Program	On
Non-Charge Program	On
East Slope C-BT Priority Diversions	On

2.2 PBN MODEL

Baseline settings in the PBN model will be the same as those described in the CTP Modeling Report (CDM Smith, 2013). No additional adjustments will be made. A new suite of hydrologic traces based on the current climate were developed for this Study, as summarized in *Future Hydrologic Analysis TM #6*. These traces change some of the inputs to the PBN and will be used in the non-baseline simulated scenarios.

2.3 FC SYSTEM MODEL

The FC System Model Data Management System (DMS) controls inputs to the MODSIM model that simulates operations of the Fort Collins water supply system. This section presents the baseline settings for the DMS input controls organized similarly to how they are presented in the DMS.

- **Table 2.5** shows the baseline settings for the Halligan Reservoir input controls. Halligan Reservoir is assumed to be enlarged as described in the draft Halligan Reservoir Enlargement EIS documents for baseline conditions.
- **Table 2.6** shows the baseline settings for the demand input controls.
- **Table 2.7** shows the baseline settings for the water rights input controls.
- **Table 2.8** shows the baseline settings for the C-BT project input controls.

Table 2.5 - Halligan Reservoir Input Settings

Reservoir Input Item	Item Value
Reservoir Size (acre-feet)	8,125
Initial Volume (% of Total)	90
Link to LCUwc Season Capacity, acre-feet/year	2,388

Table 2.6 - Demand Input Settings

Demand Input Item	Item Value (acre-feet/year)
Large Contractual User – Single Use	3,004
Large Contractual User – Wholly Consumable	5,110
Population-Based Demand	28,304
Total Demand	**36,418**

Table 2.7 - Water Right Input Settings

Water Right Item	Item Value (Useable Shares)
C-BT	18,855
NPIC	3,563.75
NPIC # CBT units per share	3.2
WSSC	26.42
PVLC	201.21
New Mercer	59.62
Larimer Number 2	79.53
Arthur	440.88

Table 2.8 - C-BT Input Settings

Item Name	Item Value
C-BT Obligations, Total (shares)	3,411
% Reduction for Pipeline Decrees (%)	0
C-BT Rentals	Off
C-BT Carryover	On

The Total Demand value for the baseline modeling (Table 2.6) differs from previous modeling efforts due to how two specific demands are being captured in the updated modeling structure. The new modeling structure explicitly captures reuse plan related demands as part of the new Reuse Plan construct. The Large Contractual User – Wholly Consumable demand and the C-BT Obligations demand are therefore reduced accordingly. Additionally, the previous population-based demand value included demands related to an agreement with Fort Collins-Loveland Water District. This demand is now captured as part of the C-BT Obligation value in Table 2.8, as it better reflects operations. It should be noted that for the Baseline simulations, Colorado State University (CSU) is included within the population-based demand (as shown in table 2.6), but future scenario simulations, that use the Demand Tool, will reference CSU's contractual obligations as a Large Contractual User – Single Use demand.

3.0 SCENARIOS FOR SIMULATION

Scenarios of risks and uncertainties for simulation were assembled by Utilities and Northern Water staff. When assembling scenarios, there were several categories with different options that could be selected. This section summarizes the categories for simulation and identifies the options for consideration. Additionally, subsection 3.5 presents the identified scenarios that will be simulated, including the baseline. Model settings for these scenarios are assumed to be a future condition that is not necessarily tied to a specific year. Hydrology is run over a wide range of temperature and precipitation combinations that could take place anytime between now and a distant future year. Demand scenarios are developed through a demand model with inputs based on potential future scenarios. Finally, system risks are events that could happen anytime between now and the distant future.

3.1 HYDROLOGY

A new suite of hydrologic traces based on the current climate were developed for this Study, as summarized in *Future Hydrologic Analysis TM #6*. These traces include 100 synthetic traces of re-sequenced historical years and the historical hydrology, for a total of 101 available hydrologic traces. Due to simulation time constraints, not all 101 available hydrologic traces may be necessary for a given scenario. Therefore, a subset of 6 synthetic traces was selected from the full 100 using a process described in Section 2.4 of *Future Hydrologic Analysis TM #6*. This subset captures different drought types that are similar to, or more serve than droughts in the historical record to more robustly assess performance.

When assembling a scenario, it can have one of the three following hydrology options:

- Historical hydrology only
- Subset ensemble containing the 6 selected synthetic traces and the historical hydrology
- Full ensemble of 100 synthetic traces and the historical hydrology

Ultimately, each scenario simulated will be run under the full ensemble of 100 synthetic traces.

3.2 CLIMATE CHANGE SCENARIOS

The hydrologic traces, based on historical hydrology, as described in Section 3.1 can be adjusted by offsets in temperature and precipitation to capture the effects of potential future climate change. A total of 20 combinations of temperature and precipitation offsets (including no-change) can be applied to the hydrologic traces as described in *Future Hydrologic Analysis TM #6*. Temperature varies up to 8 degrees F warmer than current conditions, and precipitation varies between 10 percent drier and 15 percent wetter than current conditions.

When assembling a scenario, it can have one of the two following climate change options:

- No change in temperature or precipitation
- Full temperature and precipitation offset range (20 climate options)

3.3 DEMAND SCENARIOS

Demand scenarios will be generated by the Demand Model described in *Future Demand Estimating Methods TM #3.* In addition to representing effects of population growth, development density and development type, demand forecasts from the Demand Model will be tied to overall climate (temperature and precipitation offsets), and the specific sequence of hydrology for each hydrologic trace. Utilities will choose two demand levels for simulation in future scenarios.

3.4 SYSTEM RISKS

System risks were identified and prioritized by staff from Utilities for their system and by staff from Northern Water for the C-BT system, as described in *Risks and Uncertainties TM #4*. The prioritized risks and uncertainties listed in **Table 3.1** were available for inclusion within a scenario. How these system risks are simulated is described in Section 4.1 of the *Risks and Uncertainties TM #4*.

Table 3.1 - List of Prioritized Utilities and Northern Risks and Uncertainties

ID	Risk or Uncertainty Name
A9a	Reuse Plan Gone
A9b	Reuse Plan Interrupted
AN2	Colorado River Hydrology Uncertainty / Major Outage of C-BT Project
D1	Demand Risks
O1	Outage – 24" Pipeline
O11	Outage - Pleasant Valley Pipeline
O17	Halligan Reservoir Not Enlarged
O18	No C-BT Carryover Storage
O2	Outage – 27" Pipeline
O3	Algal Blooms in storage reservoirs
O4	Outage - Michigan Ditch
O5	Outage - Horsetooth Reservoir Outlet
O8	Outage - Joe Wright Reservoir
ON12	Conveyance Systems to Horsetooth Outage
ON17	Farr Pump Plant Outage
ON18	Adams Tunnel Outage
ON19	Lake Granby Dam/Dike System Outage
ON20	Windy Gap Plant Outage
W1	Wildfires in Poudre Basin watershed
WN4	Wildfires – Northern East Slope

3.5 IDENTIFIED SCENARIOS FOR SIMULATION

Utilities Staff, in coordination with other stakeholders, identified 13 total scenarios for simulation, including baseline. These 13 scenarios are described below and summarized in **Table 3.2**. (Note: Utilities may revise one or more of these scenarios based on the results of the baseline analysis and pending simulations of individual system risks.)

- **Baseline** – As part of any vulnerability assessment, baseline conditions need to be established to quantify the negative impacts from other risks and/or uncertainties. The Baseline scenario developed for simulation in this study does not include any system risks, increased demands or climate-change influenced hydrology and the settings are listed in Section 2.0.

- **Climate Change Impacts** – Two of the highest perceived impactful risks were longer droughts not captured in the historical record and the compounding impacts of climate change (change in runoff volume and timing). This scenario includes the full hydrologic ensemble and a range of potential future climate change conditions. Because future climate change conditions include a no-change future, how climate change may worsen these drought conditions will be quantified. No additional system risks are included.

- **Loss of Storage** – Utilities presently has limited storage in their water supply system, potentially making them vulnerable to any future conditions where that limited storage is further reduced. This scenario captures the impacts to the water supply system if both the Halligan Reservoir expansion EIS is denied and Utilities loses their C-BT Carryover Storage account as decisions regarding both are ultimately beyond Utilities control. This scenario will be applied across all climate change options and hydrologic trace ensembles.

- **Increased Demands** – While future demand estimates account for uncertainty in water use and population, a scenario was included to capture the impacts of uncertain future demand growth. This scenario captures two potential demands generated from the Demand Tool as well as an increased demand outside the current planning horizon that is a fixed percentage higher than the greatest Demand Tool trace. This scenario will be applied across all climate change options and hydrologic trace ensembles.

- **Halligan Permitting Denial** – The baseline assumption includes the expansion of Halligan Reservoir, which at the time of Study has not competed the permitting process or been constructed. Because of the uncertainty around that assumption, this scenario is included to represent a future condition where the expansion of Halligan Reservoir expansion does not happen. This scenario will be applied across all climate change options and hydrologic trace ensembles.

- **Poudre River System, Acute Outage** – Infrastructure to deliver yield from the Poudre River to the city is potentially vulnerable to failures due to either natural disasters (landslides or wildfires) or emergency maintenance outages. This scenario captures the impact of a short - term outage of the 24-inch Pipeline, the 27-inch Pipeline, and the Pleasant Valley Pipeline, which are simulated as one link in the FC System Model. This scenario will be applied across all climate change options and hydrologic trace ensembles.

- **Poudre River System, Environmental Impacts** – Yields from the Poudre River are potentially vulnerable to prolonged environmental impacts that could cause constraints in delivery and treatment infrastructure. This scenario quantifies impacts on water supply performance due to algal blooms or environmental issues resulting from wildfires in source watersheds (e.g. increased sediment deposition). This scenario will be applied across all climate change options and hydrologic trace ensembles.

- **C-BT System, Acute Outage** –Utilities receives a significant portion of their yield from the C-BT project; therefore, risks to that system are included in the vulnerability analysis. There are a variety of potential causes for a short-term outage of critical C-BT delivery infrastructure such as an outage of the Adams Tunnel or Farr Pumping Plant. This scenario captures the impact of this C-BT infrastructure risk to the performance of the Utilities water supply system. This scenario will be applied across all climate change options and hydrologic trace ensembles.

- **C-BT System, Long-Term Reduction** – It is not possible to predict if or when actual flows in the Colorado River below Lake Powell will fall below 75 million acre feet on a 10 year rolling average, how long actual flows in the Colorado River below Lake Powell could be below 75 million acre feet on a 10 year rolling average, or whether and how such flows would, under the Colorado River Compact or Upper Colorado River Compact, affect Colorado-Big Thompson Project diversions. Given these uncertainties, for purposes of the Vulnerability Study, Utilities assumed that in the event of a long-term C-BT project outage, the C-BT quota will be set to 25% for a 10-year period. This assumption was made by Utilities based on total storage capacity in the C-BT system and the potential length of this type of outage. It is intended to capture the possible effects of a wide range of conditions that could affect C-BT deliveries over an extended period and does not represent any defined future Colorado River Basin or C-BT scenario.

- **Horsetooth Reservoir Outage** – Lack of redundancy with the Horsetooth Reservoir outlet works puts deliveries of Utilities' yield from this reservoir at risk. Recent problems with the outlet works have shown that this type of risk can occur; therefore, it was included as a scenario. This scenario will be applied across all climate change options and hydrologic trace ensembles.

- **Reuse Plan Changes** – There are future uncertainties around the Reuse Plan due to changes in water use and energy generation facilities, which are outside Utilities' control. This scenario captures impacts to water supply system performance due to either an elimination of the Reuse Plan or changes to it that reduce the available supply to Utilities. This scenario will be applied across all climate change options and hydrologic trace ensembles.

Table 3.2 - Summary of identified scenarios for simulation

ID	Scenario Name	Hydrology Trace	Climate Change	Demand Scenarios	System Risks
1	**Baseline**	Baseline trace	None	Baseline Demands	None
2	**Climate Change Impacts**	Full ensemble (101 traces)	All	Baseline Demands	None
3	**Loss of Storage**	Full ensemble (101 traces)	All	Two selected Demand Model Scenarios	No Halligan Expansion, no Carryover – Entire simulation period.
4	**Increased Demands**	Full ensemble (101 traces)	All	Two selected Demand Model Scenarios plus one Scenario with a fixed increase	None
5	**Halligan Permitting Denial**	Full ensemble (101 traces)	All	Two selected Demand Model Scenarios	No Halligan Expansion – Entire simulation period.
6	**Poudre River System - Acute Outage**	Full ensemble (101 traces)	All	Two selected Demand Model Scenarios	24 - inch Pipeline, 27 - inch Pipeline, and PVP. 100% outage for 12 months starting in October of year 10.
7	**CBT System - Environmental Impacts**	Full ensemble (101 traces)	All	Two selected Demand Model Scenarios	Algal blooms – CBT water use shut off for one year, June through October; East slope wildfires – effective for 3 years (CBTQ model) Both risks start in a randomly selected dry-year(1).
8	**Poudre River System - Environmental Impacts**	Full ensemble (101 traces)	All	Two selected Demand Model Scenarios	Algal blooms – CBT water use shut off for one year, June through October; Wildfires – effective for 10 years. 24 - inch Pipeline, 27 - inch Pipeline, and PVP. Year 1 - 100% outage from June to September, Years 2 – 10, 25% from April - October. Both risks start in a randomly selected dry-year(1).

9	**CBT System – Acute Outage**	Full ensemble (101 traces)	All	Two selected Demand Model Scenarios	Adams Tunnel outage - 25% quota for 3 years starting year 11.
10	**CBT System – Long-Term Reduction**	Full ensemble (101 traces)	All	Two selected Demand Model Scenarios	Quota set to 25% for 10 years following a randomly selected dry-year[(1).]
11	**Horsetooth Reservoir Outage**	Full ensemble (101 traces)	All	Two selected Demand Model Scenarios	O5- Horsetooth outage for 9 months starting in October year 10.
12	**Reuse Plan Change 1**	Full ensemble (101 traces)	All	Two selected Demand Model Scenarios	A9a – 100% outage – Entire simulation period.
13	**Reuse Plan Change 2**	Full ensemble (101 traces)	All	Two selected Demand Model Scenarios	A9b – 50% reduction – Entire simulation period.

Note: (1) Dry year is selected by binning current hydrology into dry, average and wet groups. A random year is then selected from within the dry bin. The same random year is used for all “dry-year trigger” scenarios

4.0 CONCLUSIONS AND NEXT STEPS

Utilities staff set baseline assumptions for the three water resources models used in the Study to quantify impacts and assess vulnerability. Additionally, staff assembled hydrology, climate, demand, and system risk settings into 13 scenarios that capture a variety of potential future conditions that could threaten Utilities' water supply system. The next step is to simulate the conditions for each scenario and use the resulting water supply system metrics and level of service goals to identify the scenarios of concern to Utilities based on their impacts to water system performance.

Design with
community in mind