Aspen's Water Future: Estimating the Number and Severity of Possible Future Water Shortages

THE CITY OF ASPEN

Headwaters CORPORATION

November 30, 2017

Contents

Impact of Uncertainty on the Number and Severity of Future Water Shortages

Purpose

The City of Aspen water system is supplied in a “run-of-the-river” manner utilizing Castle and Maroon Creeks to meet municipal demands. This run-of-the-river characteristic means that as long as there is water in the creeks, Aspen has access to water. There is minimal water storage in the system, so if anything interrupts these supplies, whether it be long-term drought events induced by climate change, or short-term events such as floods or wildfires damaging critical infrastructure, the City’s water supply is at risk.

In light of these increasing risks and growing demands, the City is assessing the adequacy and resiliency of their current water supplies and water infrastructure. An initial step in this assessment involves estimating the potential frequency and severity of water shortages to the Aspen water system over a range of possible future hydrological and demand conditions. This is based on a concern that existing water supply risks will significantly increase over time due to climate change’s impact on the timing and volume of flows in Castle and Maroon Creeks.

This analysis estimates the frequency and severity of water shortages to the Aspen system assuming water supply and demand conditions anticipated for the year 2065. It assesses upon Castle Creek’s and Maroon Creek’s abilities to fully serve the City’s demands. *At this point in time, it does not consider mitigating measures to prevent or minimize shortages, such as conservation beyond measures currently in effect, supplemental groundwater, or storage.* The analysis focuses upon climate change’s potential impact on the timing and volume of creek flows, and its potential impact on evapotranspiration (ET) both upstream of the City’s water diversion points and on municipal irrigation water demands. In addition to the uncertainties of climate change, this analysis directly addresses other important uncertainties related to the volume of flow and to water demand.

The analysis uses Monte Carlo simulation to examine the combined effects of these numerous uncertainties on the overall uncertainty behind the number and severity of potential water shortages.[1] A characteristic of this method is that there is no single “correct” number of shortages or severity of shortage, the results are expressed in terms of probabilities, equivalently shown as frequency diagrams (histograms), percentiles, or cumulative probability functions. These metrics are more valuable than simple averages because they better describe the uncertainties and allow decision makers to decide how much risk they are willing to take.

The following sections:

- Describe what is meant by a water shortage for Aspen
- Present and discuss an analytical spreadsheet-based model for estimating the number and severity of shortages

[1] Monte Carlo simulation is discussed in Appendix A.

- Identify the uncertain variables most significantly impacting long-term supply and demand, and presents assumptions about their possible values
- Present the results of the Monte Carlo simulation

Definition of a Water Shortage

A shortage occurs when combined flow at the City's diversion points is insufficient to simultaneously meet City demand, deliveries to three irrigation ditches below the City's Castle Creek diversion, and provide for instream flows. Since the City's water rights are senior to the instream flow right, the City and irrigation ditches can deplete the creeks before experiencing their own shortage.[2] Alternatively stated, this analysis assumes that instream flows are already gone when the City experiences a shortage.

Analytical Model

An analytical spreadsheet model of the City of Aspen's raw water supply system was developed to identify possible shortages to municipal and industrial (M&I) or other demands. The model consists of two components:

1. Hydrograph modification tools for Castle Creek and Maroon Creek,
2. An operations tool that uses the streamflows output by the hydrograph tools to meet Aspen's potable and non-potable water demands and identify any shortages.

Based on the availability of historical streamflow data, the period of record for the model is Water Years (WY) 1970-1994 (October 1, 1969-September 30, 1994). The model simulations run on a weekly[3] time step.

Historical Streamflow

Daily historical gaged streamflows for Castle Creek[4] and Maroon Creek[5] above Aspen were the underlying input to the hydrograph tools. The USGS streamflow gages were located several miles upstream of the city's raw water diversion structures, and therefore the historical data were not directly reflective of the water supply available to the city. Field measurements were used by Enartech (1994) to estimate multipliers which can be used to transform the gage measurements to flows at the municipal intakes.[6] Values for the multipliers are input by the model user; the assumed values were 2.43 for Castle Creek and 1.27 for Maroon Creek, although other values can be entered within a specified range. These adjustments are used to account for intervening ungaged tributary inflows, return flows, and other reach gains and losses. The estimated daily streamflows at the municipal intakes were used to

[2] It should be noted that the above definition may not reflect City policies that may be in effect when shortages occur, such as possible decisions on how to allocate limited supplies between instream flows and City-controlled irrigation demands on Castle Creek.

[3] Daily and monthly models were also developed, but based on discussions with the City of Aspen, the project team agreed on a weekly time step to achieve a reasonable balance between computation time and data density.

[4] USGS 09074800 Castle Creek above Aspen, CO

[5] USGS 09075700 Maroon Creek above Aspen, CO

[6] Enartech Inc. 1994. City of Aspen Evaluation of Raw Water Availability. October.

calculate a time series of weekly average streamflow during each year for the period of record. This time series was then condensed into a single hydrograph of average weekly flow.

Hydrograph Modification Utility

The model does not incorporate specific climate change scenarios, but instead allows the user to input and test modifications to the timing of the hydrograph peak and to the magnitude of the flows represented by the hydrograph. For the present analysis, it was assumed that under future conditions the peak flow week would occur earlier (a shift of 2 to 6 weeks depending on the model run) and that flows over the entire hydrograph could range from +10% to -50%. These modifications to peak timing and magnitude of flows were applied to adjust the hydrographs of average weekly flow. The same modification factors were used for both Castle Creek and Maroon Creek. The *patterns* of historical gaged streamflow on each creek were then used to distribute the modified average hydrographs to a pair of modified 25-year weekly streamflow time series for use in the operations tool.

Operations Tool

The operations tool starts with the modified weekly streamflows at the municipal intakes on Castle Creek and Maroon Creek as the water supply available to the City of Aspen, then applies a succession of potable and non-potable demands to identify potential shortages. Non-potable demands are considered first, including the city's downstream irrigation demands on Castle Creek and the Herrick Ditch upstream of the City's Maroon Creek diversion. [7] [8]

Remaining flows on the two creeks are then combined and used meet the City's water demands, which are those that draw on Thomas Reservoir and are then met through the city's distribution system; these include variable indoor, outdoor, and non-potable water uses. Modeled municipal water shortages, if they exist, are identified and quantified. Any water that is left is applied to meet instream flow (ISF) demands. The ISFs are junior water rights held by the Colorado Water Conservation Board for 12.0 cfs on Castle Creek[9] and 14.0 cfs on Maroon Creek[10]. Aspen is committed to an additional 1.3 cfs on Castle Creek, so a combined ISF flow rate of 27.3 cfs is used in the operations tool. Modeled ISF shortages are identified and quantified.

Although the ISFs are decreed separately for the two creeks, the available supply, ISF demands, and potential shortages are evaluated as aggregate quantities in the model because the timing and amount of any shortage would be influenced by the city's operational decisions regarding diversions from each creek into Thomas Reservoir.

---

[7] The headgate for the Herrick Ditch is located upstream of the city's Maroon Creek diversion structure, but as a gaged diversion, it is handled separately and is not a component of the factor used to transform flow from the USGS gage location to the municipal intake.

[8] Herrick Ditch diversions were assumed to be 16 cfs through the irrigation season ending in the second week of October, representing the most water Herrick Ditch used on a daily (or weekly) basis across an entire irrigation season in recent history. This occurred in 2003 and 2016. The portion of the Herrick water right senior to Aspen's is 9.3 cfs. However, for purposes of this planning study, 16 cfs was assumed based on precedent. Reducing Herrick's diversion to 9.3 cfs in the analysis would likely reduce the number of late season shortages.

[9] Case No. W-2947, with appropriation date January 14, 1976

[10] Case No. W-2945, with appropriation date January 14, 1976

Model Output

Output from the model includes the frequency and magnitudes of M&I or ISF shortages. This information is used to generate figures illustrating the likelihood of a given shortage magnitude as well as plots that depict the timing and magnitude of ISF shortages on a grid representing the period of record.

Appendix B shows screen shots of the model's input and output tables, highlighting critical assumptions.

Figure 1 illustrates the operational component of the model through a schematic diagram.

Uncertainties Affecting Supply and Demand

The analysis considers four areas of uncertainty:

1. Annual flow; Period of Record
2. Flow adjustment factors
3. Climate Change
4. Demand

Period of Record

The hydrologic period of record defines the uncertainty surrounding the volume and timing of flow from year to year. This study uses the period 1970 through 1994, corresponding to the years that gages were continuously active on each of the creeks. Since Aspen is run-of-the-river system with minimal storage, Figure 2 shows the estimated average monthly flows at the City's diversion points for the two creeks during this period and their combined flows.

This hydrologic period contains 1977, which is the driest year on record, and 1983 and 1984, representing very wet years in the Colorado River basin. It should be noted that dry years did not occur in succession during the 1970-94 period, like during the 1950's.[11] Nor does the data contain the years since 2000, when Colorado has experienced statistically significant higher average temperatures compared to 1970 through 1994. Also, since the period 1970 through 1994 mostly pre-dates the establishment of statistical trends showing warming in Colorado, any climate change-based impacts occurring between 1994 and the present are likely not reflected in the data.

Extending the hydrological record to include the entire 1950 through present period would be desirable to better quantify the variability of flows, the frequency of critical years, and the possibility of successive critical years. However, for now, this analysis uses the 1970 through 1994 period with the above caveats.

[11] Precipitation data and snowfall data from the Aspen Station indicate that all years but one between 1952 and 1958 had less total *precipitation* than 1977. The year 1953 had substantially less *snowfall* than the 1977 water year, but the remaining years had more *snowfall* than 1977.

Figure 1. Schematic of the Castle Creek and Maroon Creek Operational Model

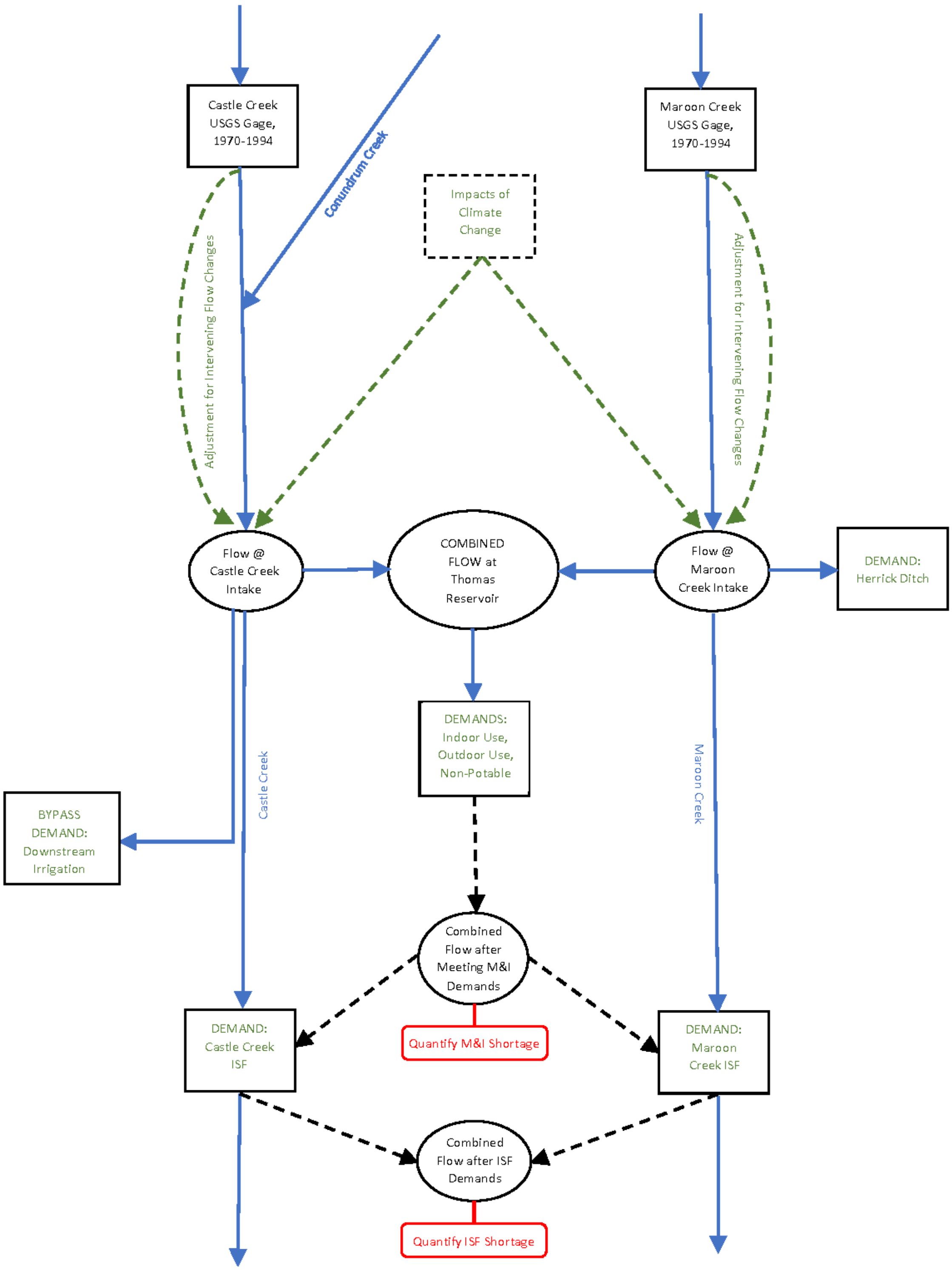
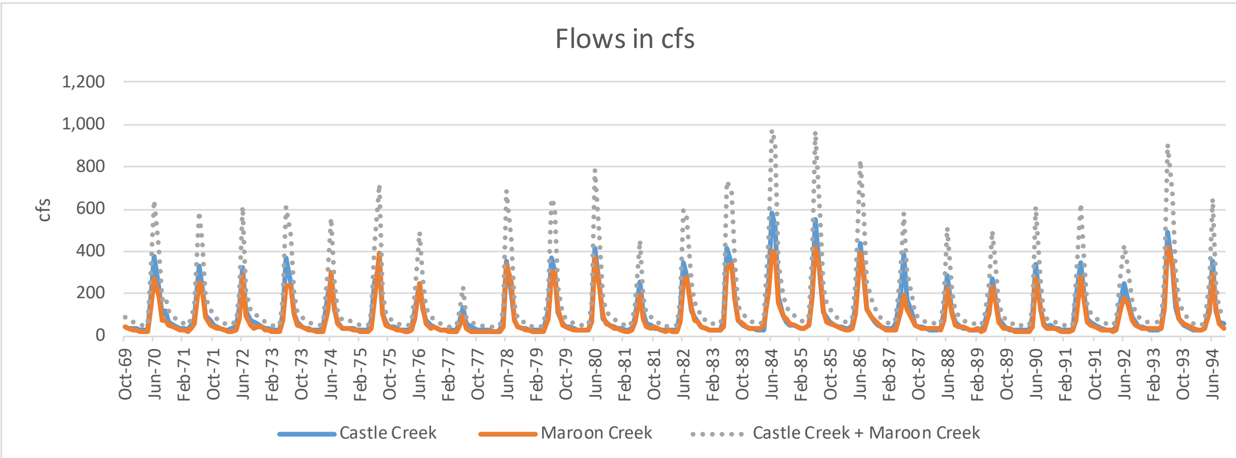


Figure 2. Estimated monthly flows at Aspen's Castle Creek and Maroon Creek diversions.



Flow Adjustment Factors

Stream gages used to measure flows over the period of record were located high in the Castle and Maroon Creek systems, above the City's diversion points and with intervening, ungaged tributaries. As a result, adjustments had to be made to the gaged flows to approximate flows at the City's diversions. For purposes of this analysis, the factors were estimated for each creek incorporating a least squares regression analysis that uses gaged flow as the independent variable and flow at the City diversion point as the dependent variable.

For Castle Creek, an R-square of regression of 0.993 supports a flow adjustment factor of 2.43 for Castle Creek and an R-square of 0.996 supports a flow adjustment factor of 1.27 for Maroon Creek. Although the fit of the regression equation defining the factor is very good, the estimates are limited by a relatively small number of observations primarily taken in 1994. However, subsequent paired observations appeared to confirm these relationships. Also, despite, the good fit, there is still significant uncertainty around the factors, as measured by the standard error of the regressions. Figures 3 and 4 illustrate the uncertainty around the estimates of the flow adjustment factors for Castle Creek and Maroon Creek, respectively. In both cases, the uncertainty is assumed to be normally distributed, or bell-shaped, centering around their expected values.

Figure 3. Assumed uncertainty around the Castle Creek flow adjustment factor

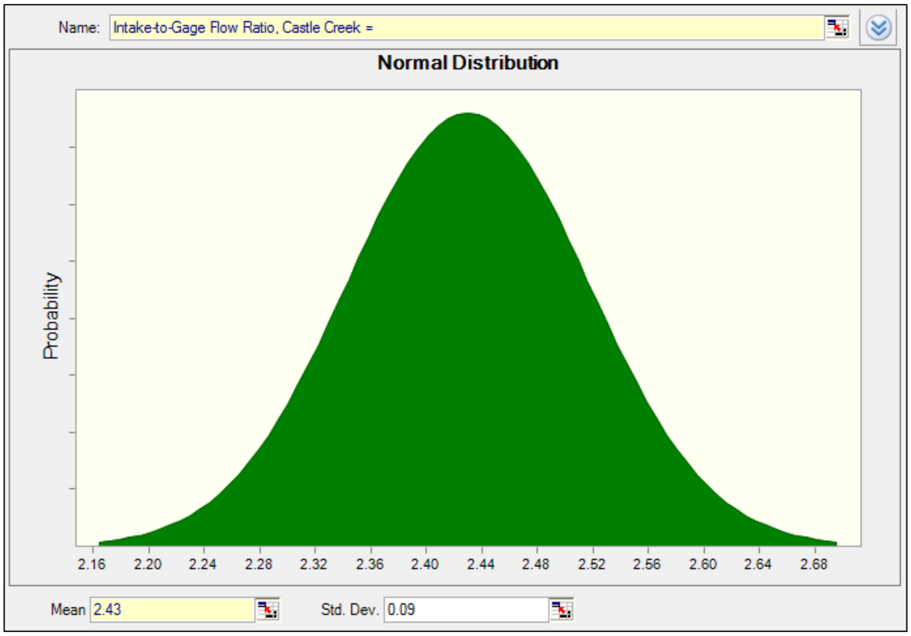
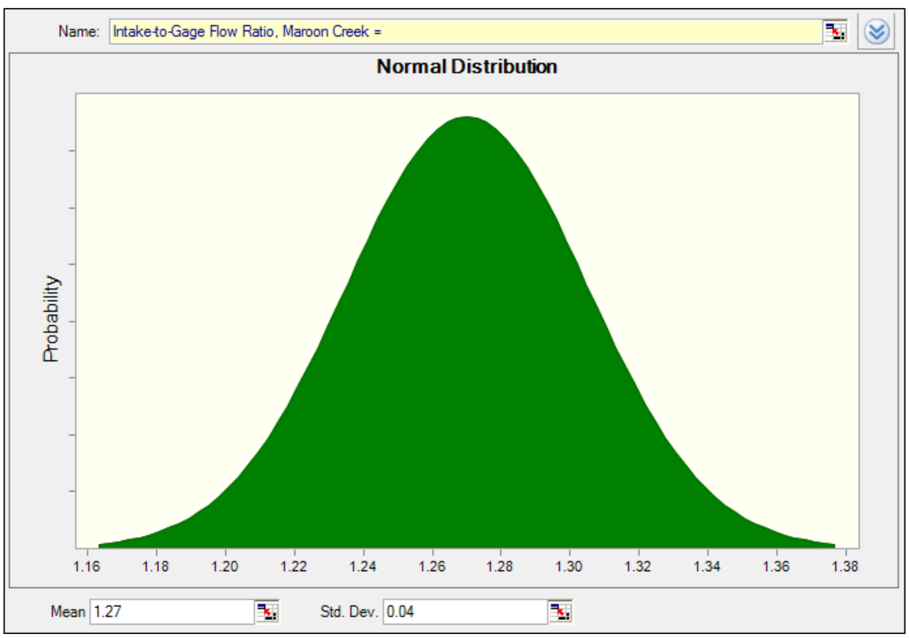


Figure 4. Assumed uncertainty around the Maroon Creek flow adjustment factor



Climate Change

An important component of this effort is to assess the possible impacts of climate change. A previous analysis by Wilson Water Group examined 5 climate change scenarios with varying levels of impact to flow patterns, ranging from about +9% to -19%, concluding that climate change would adversely affect

Aspen's water supply, but not to a level requiring additional infrastructure, such as a storage reservoir.[12] Since the development of these 5 climate change scenarios, there have been questions as to whether a wider range of impacts should now be considered, especially those based on the greater resolution provided by more recent research. It should be noted that much of this recent research has not yet been downscaled to a level readily applicable to Castle or Maroon Creeks, or the Roaring Fork Valley. Although various efforts are underway at the State and major water provider level to adapt this data at a basin level, it is not currently available.[13]

To best incorporate current climate change knowledge, this effort is working with the City's climate change staff and their associates to incorporate recent data and plausible ranges of data into the current modeling framework. The potential impacts of climate change will remain highly uncertain, but the effort described below is an attempt to bracket the possible range of impacts for purposes of assessing the number and severity of possible future water shortages.

More recent climate change research indicates that impacts to flows in the Colorado River and its tributaries may be much more severe than previously thought. Recent research suggests the following:

"Recently published estimates of Colorado River flow sensitivity to temperature combined with a large number of recent climate model-based temperature projections indicate that continued business-as-usual warming will drive temperature-induced declines in river flow, conservatively −20% by midcentury and −35% by end-century, with support for losses exceeding −30% at midcentury and −55% at end-century. Precipitation increases may moderate these declines somewhat, but to date no such increases are evident and there is no model agreement on future precipitation changes. These results, combined with the increasing likelihood of prolonged drought in the river basin, suggest that future climate change impacts on the Colorado River flows will be much more serious than currently assumed, especially if substantial reductions in greenhouse gas emissions do not occur".[14]

Climate change and its uncertain impacts will ultimately affect Castle and Maroon Creeks through the timing and quantity of their future flows. Snowmelt run-off will likely occur earlier in the year over time and the total volume of flow may or may not decline over time. These impacts will be reflected in their hydrographs that show flows over the course of a representative year, at a specific point in the basin.

It should be noted that the existing hydrographs account for existing water use, or evapotranspiration (ET), based on current upstream land uses. With warming associated with climate change, upstream ET will likely increase and further impact the resulting hydrograph, regardless of the precipitation impacts. This increase in ET may also affect Aspen's customers through an increase in outdoor water demand.

To assess overall possible impacts of climate change to the hydrographs, a utility was embedded in the modeling framework which allows the user to specify changes to the hydrographs' timing and shape. By

---

[12] Wilson Water Group. 2016. City of Aspen Water Supply Availability Study 2016 Update. June. It should be noted that the Wilson analysis assumed an operating supplemental groundwater system.

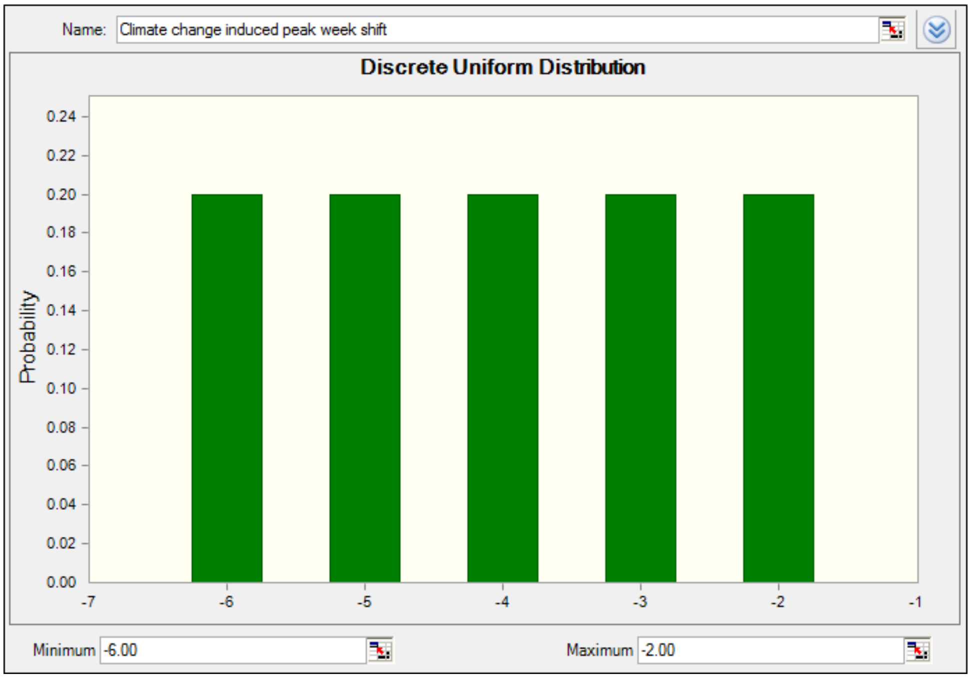
[13] http://onlinelibrary.wiley.com/doi/10.1002/joc.4594/full

[14] Udall, et al. http://onlinelibrary.wiley.com/doi/10.1002/2016WR019638/abstract, l

specifying variables related to the timing of peak flows and the impact to total flow volume, a wide range of possible impacts are considered.

For purposes of incorporating this utility into the analysis, assumptions were made about the uncertainty of the timing and volume of flows. For timing, it was assumed that peak flows could occur anywhere from 2 to 6 weeks earlier by 2065, with equal probability, relative to the 1970 through 1996 data (Figure 5).

Figure 5. The timing of peak run-off relative to 1970 through 1994, number of weeks earlier and the assumed probability for each week.



The combined impact to flows in Castle and Maroon Creeks, and associated upstream ET, are assumed to range from +10% to -55% from the 1970-96 baseline levels. It was further assumed that the probable value is likely skewed towards the low side of this range, as shown in Figure 6.   This results in a mode, or most likely value, near -35%. The assumption about skew is based on recent literature, such as that cited above, stating that impacts may be worse than previously thought.

Figure 6. Assumptions regarding the probability of flow and ET impacts to Castle and Maroon Creek flows resulting from climate change, relative to 1970 through 1994.

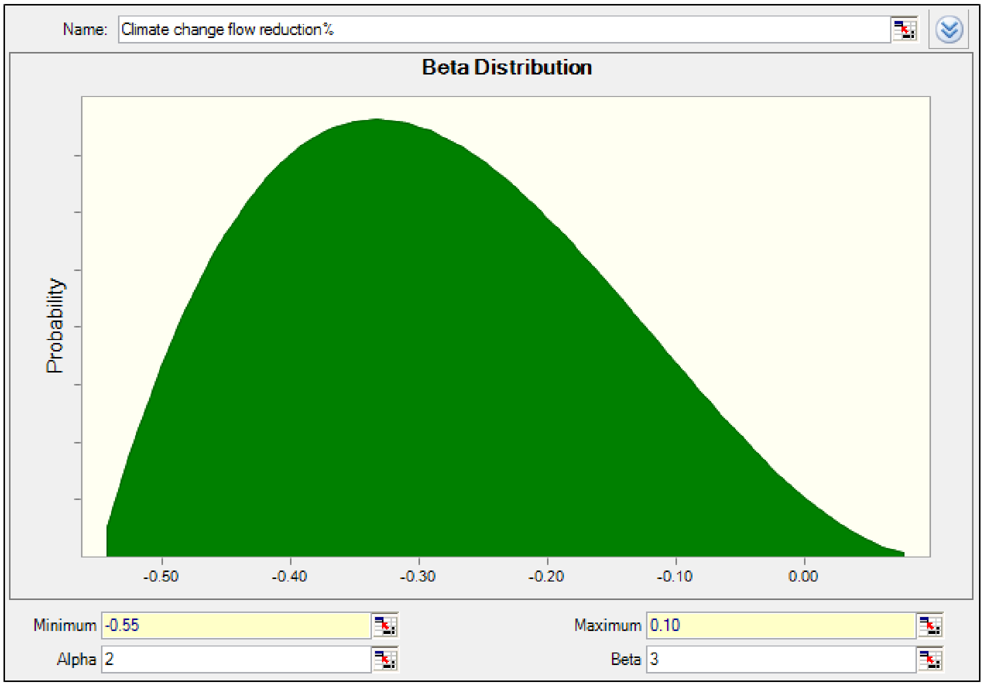
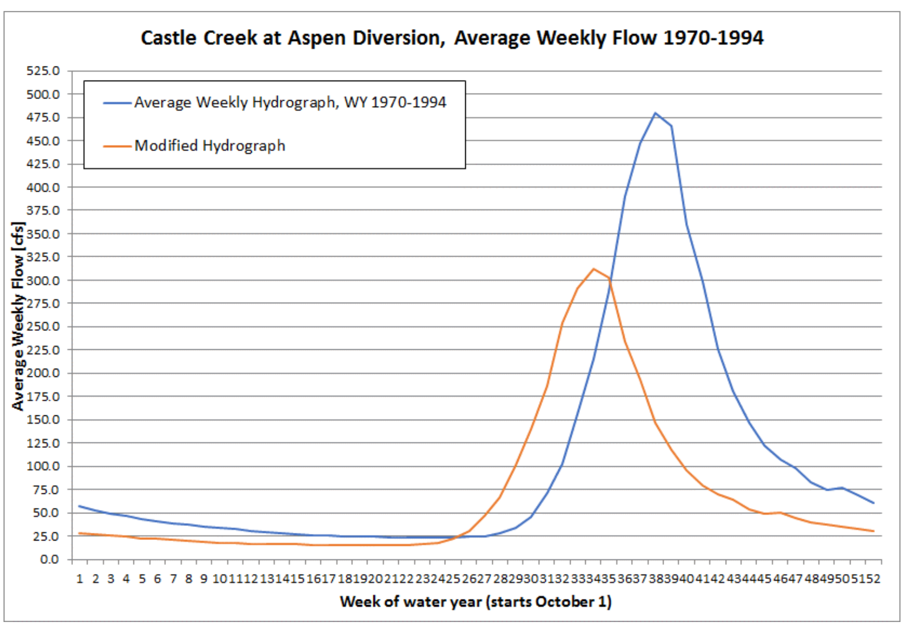


Figure 7 illustrates the baseline hydrograph for Castle Creek and a modified hydrograph based on a single set of alternative assumptions about long-term timing and flow impacts associated with climate change. For this figure, it was assumed that peak runoff occurs 4 weeks earlier and flow is uniformly reduced by 35%, both relative to the period 1970 through 1994. Monte Carlo simulation will examine the probability-weighted range of possible timing and flow impacts, as represented by Figures 5 and 6.

Figure 7. Example of Existing and Alternative Modified Hydrograph



Demand

During the course of this analysis, it became apparent that a land use-based estimate of future water demand would be more useful than simple extrapolations of historical data. This is due to Aspen's relatively high degree of land use control and limited remaining lands to develop. There is wide agreement that a land use approach is desirable and the City is currently taking steps to develop long-term land use maps that incorporate a water demand component. However, at this point in time, there is not a future land use map to base demand estimates upon or plans that can be readily translated to a map. As a result, this analysis uses existing data and previous analyses to develop a probable range of future demand.

It should also be noted that the City of Aspen's water system consists of the City itself, plus territory outside the City limits to the east and to the west, primarily along the Highway 82 corridor. In perspective, in 2010, the City was estimated to have permanent population of about 6,700, but the water service area had a permanent population of about 10,000.

The City has land use controls over a major portion of the water service area but not the entirety. Pitkin County policies will also impact future demand growth. Overall, the City's *water service area* population is estimated to grow to about 12,000 in 2025 and 13,500 in 2035, based on a 1.2% rate of planned population growth. It is likely that much of this growth, if it occurs, will target areas outside the City's current boundaries with future land use requirements between the City and Pitkin County influencing future demands on the City's water system.

Previous Water Demand Estimates and Water Production

The water demand portions of three previous studies have been evaluated with respect to their applicability to this analysis, as summarized in Table 1.

As indicated above, full-time, or permanent, population within the City of Aspen was approximately 6,700 in 2010. It was estimated that Aspen Water served a permanent population of slightly over 10,000 within the Urban Growth Boundary (UGB) when extra-territorial service is included.[15] An issue frequently brought-up while discussing the previous demand studies was the use of a compound population growth rate over a long period of time. For instance, a 1.2% population growth rate over 50 years applied to the City of Aspen would result in a 2065 population in the 12,000 to 13,000 range and a total service area population nearing 20,000, nearly doubling of current levels. These levels of population may be untenable to many Aspen area residents for quality of life reasons. Based on this, there is a probability that measures will be taken through the City's and County's land use processes to limit new single and multi-family housing development. The ultimate limit to these land uses is unknown, as is whether these limits might similarly apply to non-residential land uses, and how these limits might be allocated between the City and County.

[15] Element Water Consulting and Water DM. 2015. *Aspen Municipal Water Efficiency Plan.*

Table 1. Summary of Previous Demand Studies			
Previous study	**Summary**	**Estimated Demand**	**Applicability**
Enartech, 1994	Examined a range of land use build-out scenarios; based on the most expansive, estimated total system buildout would be 19,800 Equivalent Capacity Units (ECU's). There are currently about 17,300 ECU's in the system. This implies that the service area can only growth another 15% to reach buildout.	Build-out demand is estimated to be about 4,300 acre-feet per year, as estimated by Headwaters, based on a 15% increase from its current level; current annual demand at the water treatment plant is about 3,725 acre-feet; a proportional increase in the number of permanent residents would imply a buildout population of about 7,820 in the City and about 11,500 in the City and County combined.	Data point in identifying the possible range of demand growth. It implies that demand would only grow a total of 15% above its current level. This growth could occur anytime over the 2017-2065 period, but implies a compound growth rate of 0.3%.
Wilson Report, 2016	Estimated that demand at the water treatment plant would grow from its 2012 level at a baseline rate of 1.2% per year based on population growth trends. Alternative scenarios of slightly less than 1.2% and 1.8% were also examined.	2065 demand is estimated to be in the range of 6,300 acre-feet per year, as estimated by Headwaters; implied population for the City is over 12,100, a 77% increase over current levels; implied population for Aspen service area would be approximately 20,000.	Data point in the range. The implied population of 20,000 in the Urban Growth Boundary in 2065 may be untenable to those supporting growth management.
Water Efficiency Plan, 2015	Used same baseline demand growth rate as Wilson Report, 1.2%; examined passive and active conservation measures that reduce indoor and outdoor usage for certain customer classes. Period of analysis was 2016-2035.	Essentially same baseline demand through 2035 as Wilson Report, with minor reductions due to passive water conservation. With active conservation and focus on outdoor irrigation, demand is reduced significantly, estimated to grow at a rate of 0.50% between 2015 and 2035.	Since the study has a 20-year time horizon, whether the reduced growth in demand attributable to active conservation can be maintained past 2035 is not addressed.
Aspen and regional land use plans	This includes the Aspen Area Community Plan and Pitkin County's West of Castle Creek and West of Maroon Creek Master Plans	These documents discuss future development trends that would ultimately affect water demand within, or adjacent to, Aspen Water's service area.	Currently, there are no future land use maps to directly link future land uses to demand, although they will likely evolve in the near future.

By examining water demand on a customer class basis, such as single family residential, multi-family residential, commercial, and other types of usage, different rates of growth could be applied to different customer classes.   In response to the above population concerns, the number of customers and associated demand for residential customer classes was assumed to grow at slower rate than for non-residential customer classes.

For this analysis, it was assumed that the rates of growth in residential water usage and non-residential water usage are random variables with a range of possible outcomes.

- Residential water usage is assumed to increase between 0.3% and 0.5%, corresponding to a 2065 Aspen permanent population ranging from about 7,800 to 8,800, or a service area population ranging from 11,600 to about 13,000. The distribution is assumed to be triangular, centering around 0.4%, as shown in Figure 8.
- Non-residential water usage is assumed to increase over time at an annual rate of 1.2%, similar to the rate assumed in previous demand studies, but may vary between 0.8% to 2.0% to reflect uncertainties regarding future growth policies. This distribution is assumed to be slightly skewed to the low side of the range, indicating that it is more likely that non-residential growth will be below 1.2% than above this rate (Figure 9).

Figure 8. Assumed growth rate for residential water service

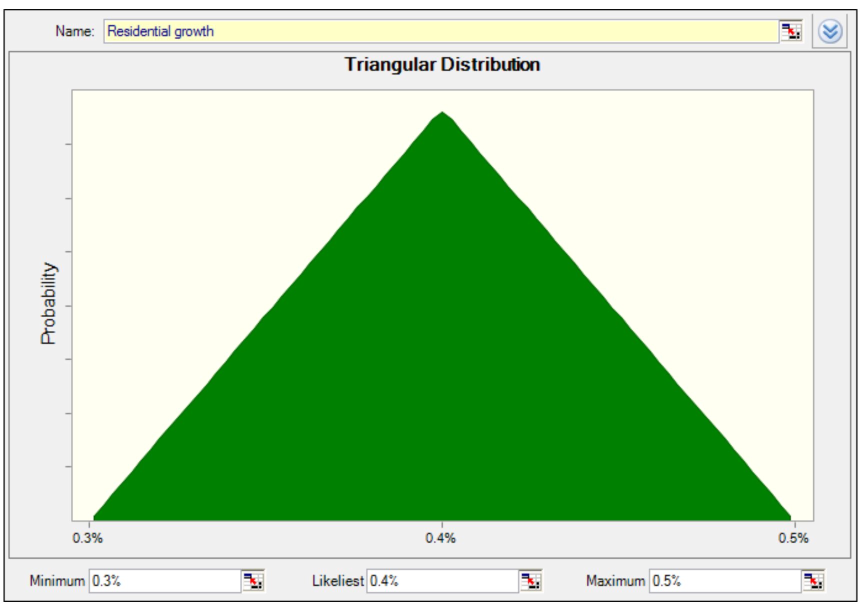
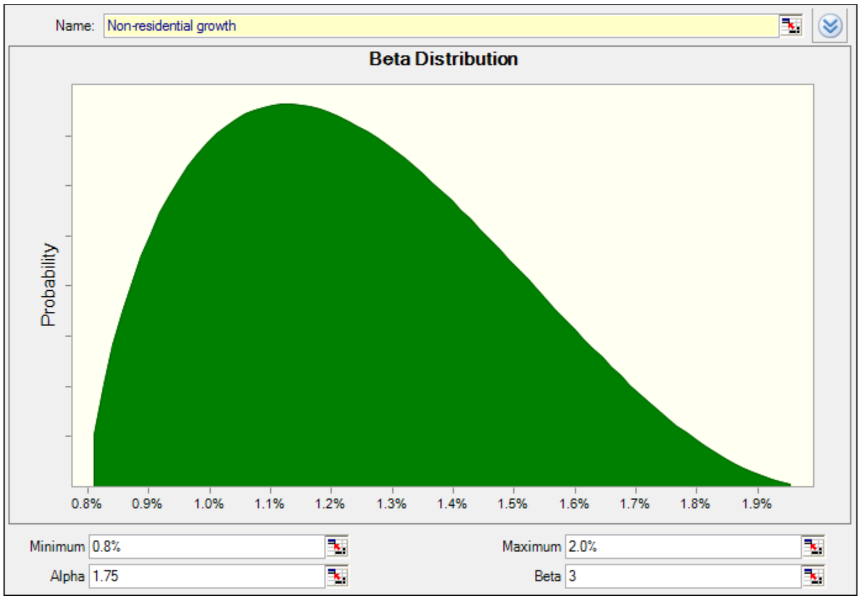


Figure 9. Assumed growth rate for non-residential water service



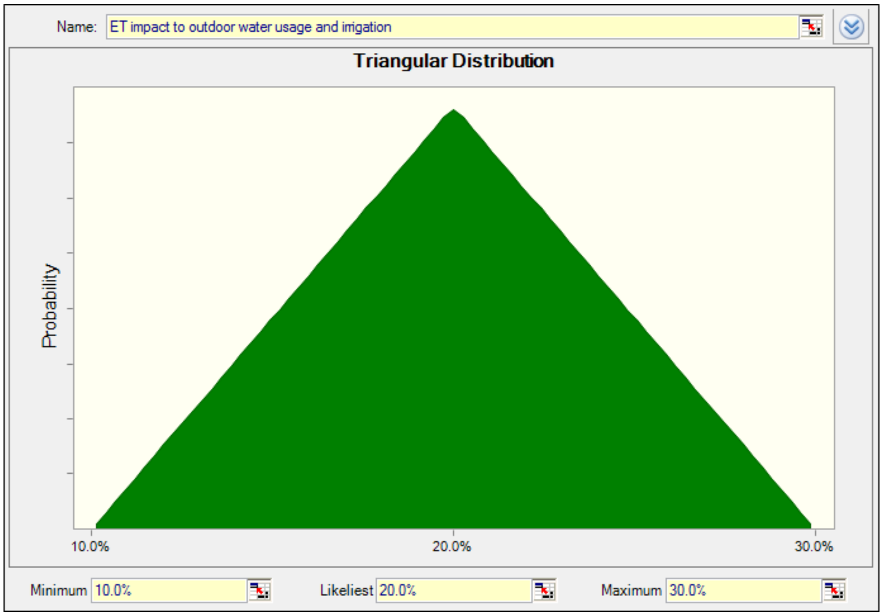
The above assumptions would result in a greater proportion of Aspen's water being used for non-residential purposes. However, at this point, whether these non-residential uses are for commercial enterprises, industries, or extra-territorial service is not specified.

Evapotranspiration Impacts

Although the climate-change induced impacts to flow discussed above are intended to include the impacts of increased upstream ET, there will likely be additional ET-related impacts to Aspen's future outdoor water usage and increased irrigation consumptive use along the three irrigation ditches on Castle Creek. The increase in ET would likely translate to an increase in municipal treated outdoor water demand but irrigation diversions are assumed to remain at their current levels.

Research is still being conducted to estimate the possible ET impacts. However, to provide a placeholder until this research is complete, it is assumed that potential ET impacts may vary from 10% to 30%, with municipal treated outdoor irrigation increasing in the same proportion. It is assumed that the ET impacts are distributed in a triangular manner, centered at 20%, as shown in Figure 10. It is further assumed that ET impacts as applied to outdoor irrigation are correlated to climate change impacts. For instance, if streamflow impacts of climate change are highly adverse, ET impacts are also highly adverse.

Figure 10. Potential ET impacts to outdoor water usage.



Results of the Uncertainty Analysis

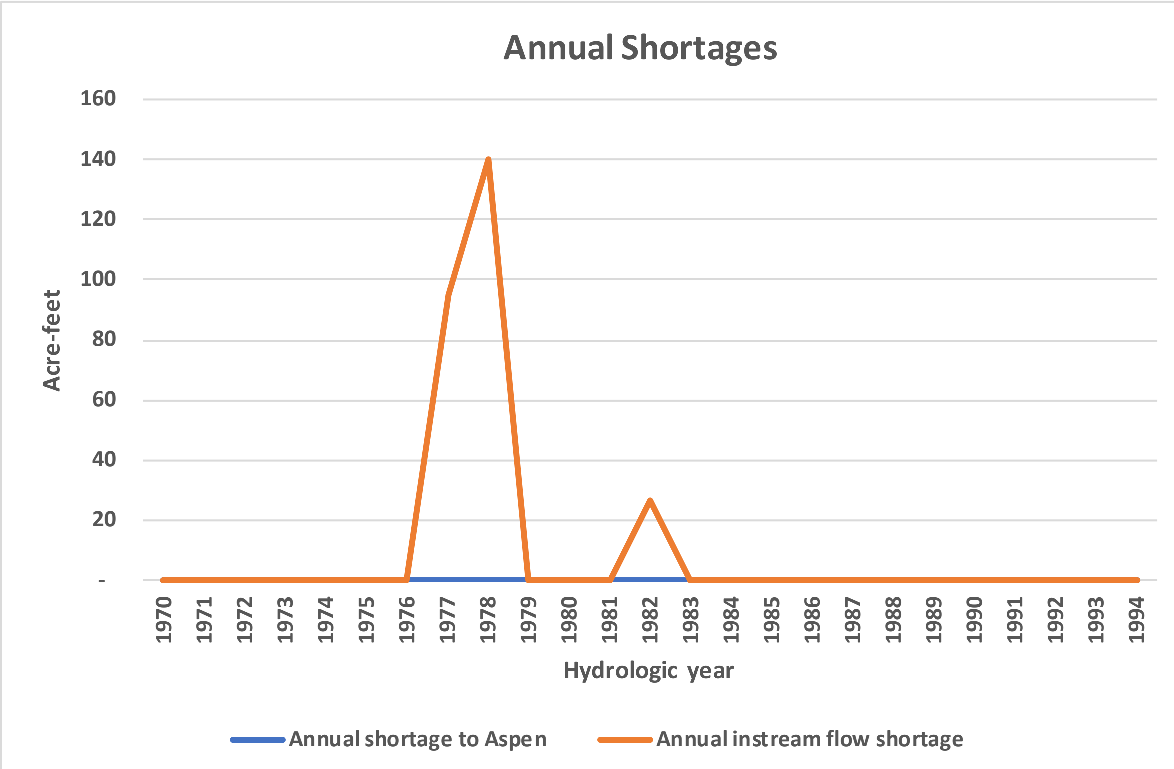
As previously stated, there is not a single result or set of results associated with this analysis. Results are expressed in probabilities. However, for presentation purposes, the adequacy of the Aspen water system to satisfy demands is discussed under three conditions:

1. Current supply and demand conditions
2. Assumed year 2065 conditions assuming the period of record and expected values for uncertain variables. Alternatively stated, no uncertainty is considered
3. Year 2065 conditions assuming the period of record and uncertainty with respect to flow uncertainty, utilizing Monte Carlo simulation

Current Supply and Demand Conditions

Under current water supply and demand conditions, and no climate change, there are no estimated shortages to the Aspen water system and very minor impacts to the instream flows (Figure 11). The impacts to instream flows primarily occur during simulated 1977 drought conditions.

Figure 11. Shortages associated with current supply and demand conditions.



Year 2065 Conditions With No Uncertainty

Other than the uncertainty associated with the hydrological period of record, Figure 12 shows possible shortages assuming year 2065 supply and demand conditions. This assumes that uncertain variables identified in previous sections, specifically flow adjustment factors, climate change, and demand variables are set at their expected values with no uncertainty.

- Flow adjustment factors are fixed at 2.43 and 1.27 for Castle and Maroon Creeks, respectively.
- Climate change is expected to move peak flows back by 4 weeks and reduce flows by 35% when ET impacts are considered, both compared to 1970-94 conditions
- Residential water demand is expected to increase at an annual rate of 0.4% and non-residential water demand is expected to increase at an annual rate of 1.2%.

Figure 12. Estimated shortages for year 2065, no uncertainties considered.

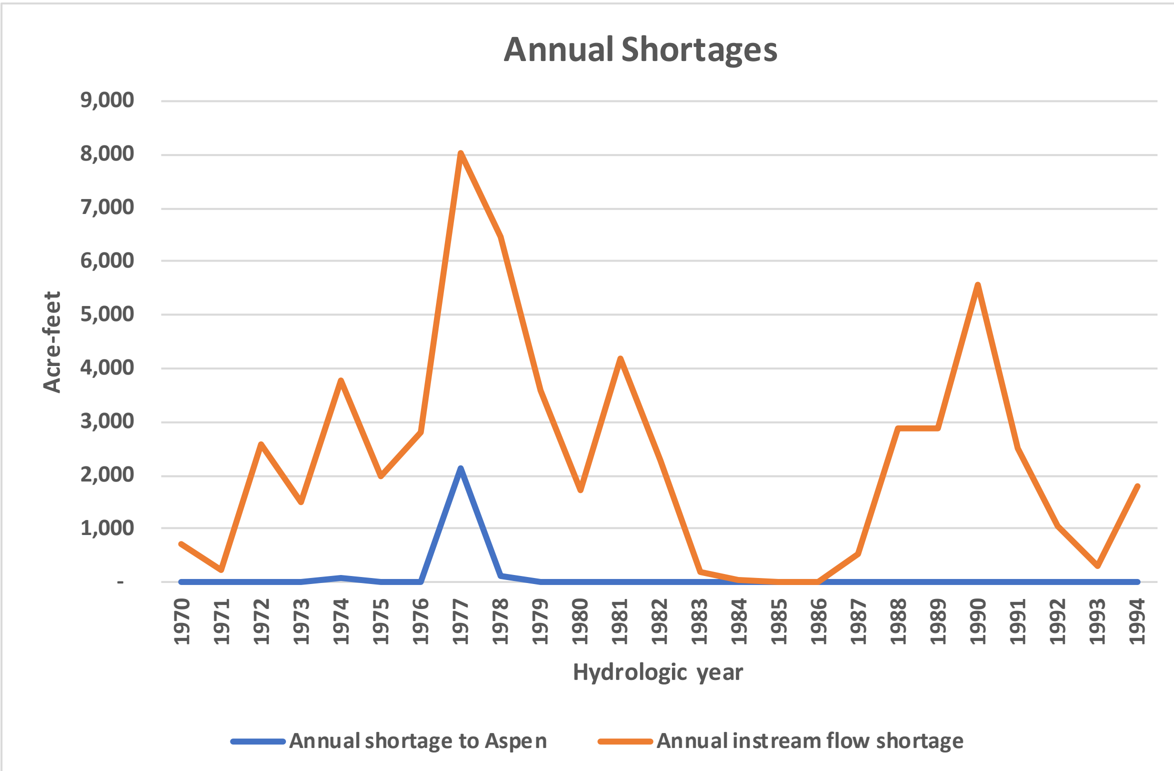


Figure 13 shows that instream flows are estimated to be adversely affected in nearly every year but the City's supply is affected in just one, the 1977 hydrologic year.

The impact to instream flows may be severe under the climate change and demand conditions assumed here, even without considering uncertainty. This is shown in Figure 14, which shows combined instream flow levels in Castle and Maroon Creeks. These combined flows should be 27.3 cfs or greater to ensure that minimums can be met for each creek.[16] The impacts appear to be most severe during the fall months, but are also chronic during the winter months.

[16] Negative values in Figure 13 should be interpreted as 0, or no instream flow.

Figure 13. Impact to Instream Flows with no Uncertainties Considered.

Figure 13. Spells Plot - Periods when Combined Castle Creek + Maroon Creek Flow <=27.3 cfs after Meeting all but ISF Demands

	Jan				Feb				Mar					Apr				May					Jun				Jul				Aug					Sep				Oct				Nov					Dec			
CY Wk	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
WY Wk	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	1	2	3	4	5	6	7	8	9	10	11	12	13
1969																																								20	15		26						26	25	25	24
1970	26	26	27	26	24	23	23	24	25																																											
1971								27	27	25	27																											24	18	21	16										26	24
1972	24	26	26	25	24	23	23	23	24	26																			20	12	14	10	17	12	11	21	15	20	14	15	17								27		27	26
1973	25		23	22	22	20	19	17	19	21	22																											19	16	18	13	25	23					27	25	26	24	25
1974	26	26	25	24	23	21	20	19	19	21	25																				21	19	16	6.2	-0.1	2.7	-0.3	-0.7	-3.3	3.7	2.5	18	19							26	25	24
1975	25	23	22	23	22	22	22	20	21	24	23																											22	14	14	12	26	25					27	26	26	25	24
1976	24	22	23	23	22	21	24	22	24	25																					27	19	18	16	13	11	7.1	6.2	12	16	11	23	20		27	25	24	22	22	22	21	21
1977	20	20	19	18	17	16	16	16	16	17	19	24													14	-13	-13	-22	-20	-16	-17	-17	-12	-10	-12	-8.5	-5.8	-10	-13	-6.7	-7.5	7	7	18	16	15	15	14	13	14	13	14
1978	14	15	14	14	14	13	14	14	15	16	17	23																						14	9.3	13	8.5	5.8	2.2	4.3	1	15	16	25	25	25	24	22	20	21	21	19
1979	18	17	17	17	17	17	17	17	18	19	22																										18	13	11	14	11	26	24				27	25	24	22	21	22
1980	22	22	22	22	22	21	22	22	23	24	26																											23	18	21	18											
1981			25	22	21	20	18	18	19	19	22	27																21	14	11	4.3	3.1	8.2	2.7	4	12	13	7.1	4.3	7.6	6.3	22	20			27	26	24	21	21	19	14
1982	12	13	16	22	23	22	21	24	25	24	26																																									27
1983					27	25	25	25	25	27																													24		25											
1984																																																				
1985																																																				
1986																																																				
1987								27	26																												18	15	12	15	13		27						26	24		26
1988			26	24	26	26	26	27																				21	11	10	20	12	12	13	11	9.7	16	14	12	13	8.3	20	17		27			25	23	24	24	23
1989	23	22	24	26	26	23	25	26	23	22																								15	7.5	10	7.8	9.8	7.9	11	5.8	19	16	25	24	24	24	22	22	19	19	17
1990	16	17	15	16	17	18	18	20	23	23	25																		26	18	10	4.3	14	5.4	1.8	6.3	-0.8	7.4	4.7	14	12	25	23				27	24	24		21	21
1991	21	21	20	18	18	19	19	18	18	20	21	26																					27	16	16	25		26	17	25	17		25							27		26
1992	25	24	25	22	22	23	23	23	24	23																											17	23	20	19	15		27									
1993																																																				
1994				27	23	25	24	25	25	24	26																		26	22	23	20	24	13	11	23	12	11	7.7													

Year 2065 Conditions With Uncertainty

The Monte Carlo simulation examined about 10,000 different, probability-weighted combinations of climate change, flow adjustment factors, and demand.

Municipal Shortages

In contrast to the "certain" case above, the presence of uncertainties associated with climate change, the flow adjustment factors, and demand reveals a significant probability that there may be more than just one shortage to the Aspen water system. Figure 14 shows the following probabilities in a cumulative manner:

- The number of years with shortages to the City of Aspen over the 25-year hydrologic period of record
- The number of years with shortages exceeding 100 acre-feet
- The number of years with shortages exceeding 1,000 acre-feet

For the first panel of Figure 14, the cumulative plot shows that with a probability of 0.80, or 80%, there are one or more shortages over the 25-year period of record; with a probability of 0.10, or 10%, there are 12 or more shortages over this period; and so on.

For the second panel of Figure 14, the cumulative plot shows that with a probability in the range of 0.40 to 0.50, there will be one or more shortages of 100 acre-feet or more; with a probability of 0.10, or 10%, there are 5 or more shortages over 100 acre-feet during this period; and so on.

The third panel shows that with something less than 5% probability, there may be several shortages greater than 1,000 acre-feet.

Figure 14. Summary of shortages to the City of Aspen municipal supply over the 1970-1994 hydrologic period of record (3 panels).

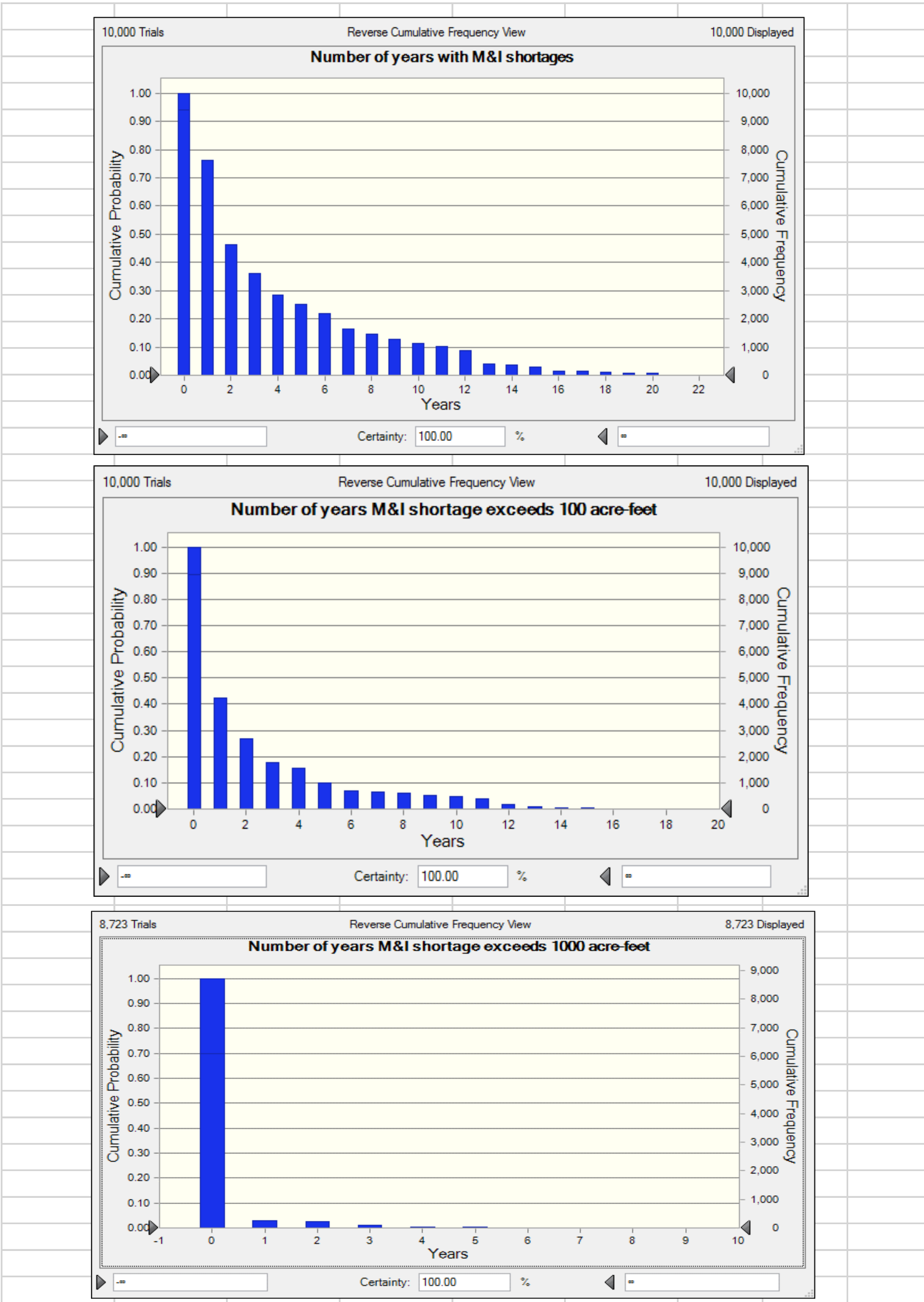


Table 2 summarizes these frequencies and severities of shortages in terms of probabilities.

Table 2. Frequency and severity of shortages to the Aspen Water system.

Probability	"Odds"	Number of M&I shortages	Number of M&I shortages > 100 acre-feet	Number of M&I shortages > 1,000 acre-feet	Maximum annual shortage, acre-feet
0.0020	1/500	22	18	8	2,312
0.0100	1/100	19	15	5	2,279
0.0200	1/50	15	9	4	2,246
0.1000	1/10	12	5	1	2,033
0.5000	1/2	2	1	1	1,783

- With a probability of 0.002, or 1/500 odds, there may be as many as 22 shortages to Aspen's water system over the 25-year hydrologic period of record, with 18 of those exceeding 100 acre-feet and 8 exceeding 1,000 acre-feet.
- With a probability of .01, or 1/100, there may be as many as 19 shortages over the 25-year hydrologic period of record, with 15 exceeding 100 acre-feet, and 5 exceeding 1,000 acre-feet. This is the level of risk that many water supply managers plan for.
- With a probability of 0.10, or 1/10 odds, there is still estimated to be 12 shortages over the 25-year hydrologic period of record, with 1 over 1,000 acre-feet.
- At even odds, or 50-50, there may still be as many as 2 shortages over the 25-year hydrologic period of record, with 1 over 1,000 acre-feet.

Instream Flows

A shortage to the City of Aspen means that instream flows have been depleted. So, with whatever frequency municipal shortages are experienced, Castle and Maroon Creeks are dewatered at approximately the same frequency. To graphically illustrate this, Figure 15 shows instream flows for the 1 in 100 outcome from above, where the creeks are dewatered 19 years out of 25. The impact to the ecosystem is not estimated but would appear to be very severe.

Figure 15. Impact to Instream Flows with Uncertainty (1 in 100 occurrence).

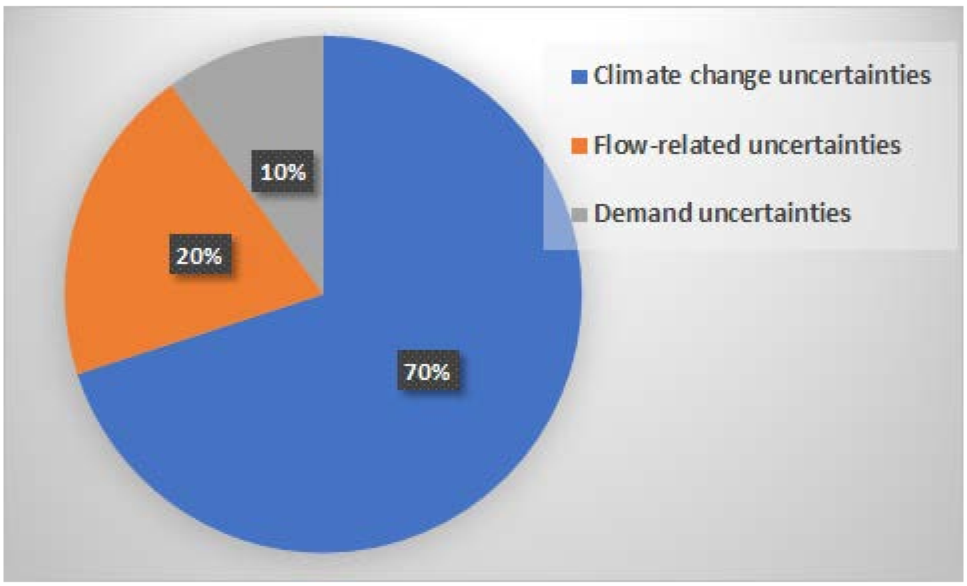
	Jan				Feb				Mar					Apr				May					Jun			
CY Wk	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
WY Wk	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
1969																										
1970	17	16	17	16	14	14	15	16	19	26																
1971	18	18	20	19	19	19	19	18	20	23																
1972	15	16	17	16	15	14	15	15	18	24																17
1973	15	18	15	14	13	12	12	11	14	19	25															
1974	17	16	16	15	14	13	12	13	14	19																
1975	16	14	14	14	14	14	14	13	16	22	26															
1976	15	14	15	14	13	13	15	15	18	23															27	19
1977	12	12	11	11	10	9	9	10	11	15	21													14	-19	-32
1978	8	8	8	8	7	7	8	9	10	14	19															
1979	10	10	10	10	10	10	10	11	13	18	25															
1980	14	13	14	13	13	13	14	15	17	22																
1981	19	18	16	14	13	12	11	12	14	18	24														18	-0.8
1982	6	7	9	14	14	14	14	16	19	22																
1983	18	17	18	18	17	16	16	17	19	25																
1984	21	20	18	19	20	19	20	21	22	26																
1985						27	27	26	27																	
1986	24	24	23	23	22	21	21	22	24																	
1987	24	23	21	19	18	18	19	18	20																	23
1988	18	18	17	15	16	17	17	19	24																	24
1989	14	14	15	16	16	15	16	18	18	20																
1990	9	10	9	9	10	11	11	13	18	21																
1991	13	13	12	10	11	11	12	11	13	18	23															
1992	16	15	16	14	14	15	15	16	18	21																
1993	18	19	20	19	19	19	20	22	25																	
1994	20	18	19	17	14	16	16	17	19	22																

	Jul				Aug					Sep				Oct				Nov					Dec			
CY Wk	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
WY Wk	40	41	42	43	44	45	46	47	48	49	50	51	52	1	2	3	4	5	6	7	8	9	10	11	12	13
1969														3.4	0.5	14	13	21	20	19	18	17	16	15	15	14
1970			21	14	14	13	8	16	10				16	15	13	25	24			27	25	24	22	21	21	19
1971				21	19	13	9.4	15	19	19	7.1	2.6	-1.1	4.1	1.1	16	15	23	22	20	19	19	17	16	15	15
1972	7.1	-3.7	-8.7	-12	-4	-6.3	-5.7	-7.2	-6.9	0.7	-3.3	-0.1	-3.4	-0.1	1.6	23	20	25	23	20	19	18	16	17	16	16
1973				23			18	14	10	8.8	5.9	-0.5	-2.2	1.8	-1.3	12	11	19	19	17	17	16	15	15	14	15
1974	21	1.3	1.3	-2.5	-0	-0.4	-5.8	-11	-14	-11	-13	-13	-15	-7.5	-8.1	7	8	18	17	17	17	17	17	16	15	15
1975							22	14	6.7	7.2	5.9	1.7	-3.4	-0.5	-1.8	13	12	20	19	18	17	16	16	15	15	15
1976	20	6.6	1.9	-3	4.4	-0.9	-4.5	-4.6	-6	-5.6	-8.2	-8.7	-4.8	0.9	-2.1	11	9	17	15	14	13	13	13	13	12	12
1977	-28	-32	-31	-29	-25	-25	-23	-21	-22	-18	-17	-20	-21	-14	-15	0	0	9	8	7	7	7	6	7	6	7
1978				22	19	6	2.1	-5.7	-8	-4.5	-7.3	-9	-11	-7.1	-9.1	5	6	14	14	14	13	13	11	12	12	11
1979								20	9.3	7.2	-0.8	-4	-5.2	-1	-2.7	12	12	20	20	17	15	14	14	12	12	13
1980			27	19	21	14	14	8.1	6.7	8.9	14	2.2	-0.6	4.2	2.1	17	15	23	22	20	18	19	18	18	17	18
1981	-3.3	-7.7	-12	-13	-11	-11	-11	-13	-12	-4.8	-4.6	-8.2	-9.7	-5	-5.6	10	9	18	17	15	14	14	12	12	11	7
1982								25	17	18	17	20	22	24	17		25			24	23	22	20	19	19	17
1983											12	6.3	3.3	9.2	6.9	21	19		27	25	23	22	21	20	19	20
1984												26	23	26	23											
1985							25	18	16	24	19	19	13	16	18		26						26	24	24	23
1986												21	21	23	20							27	26	24	23	22
1987	20	10	5.8	13	23	23	14	21	6.2	6.4	-1.2	-2.9	-4.5	0.2	-1	14	14	24	23	19	16	16	15	14	17	16
1988	9.2	-7.5	-14	-14	-0.1	-5.5	-8.1	-6.7	-7.2	-6.3	-2.7	-3.5	-4.9	-1.4	-4.2	9	7	16	15	16	16	15	13	14	14	14
1989		22	3.6	19	20	8.3	4.2	-4.8	-9.2	-5.9	-7.7	-6.5	-7.5	-2.8	-5.9	8	6	14	14	13	13	13	12	11	10	9
1990	20	11	-5.1	-9.4	-7	-10	-7.4	-11	-13	-8.6	-13	-8	-9.5	-0.6	-1.5	12	11	19	18	16	15	14	14	16	12	12
1991			19	9.9	13	6.1	0.9	-4.3	-3.8	3.4	8.6	4	-1.7	6.8	1.8	14	12	21	20	19	19	19	18	16	17	16
1992		26	11	15	10	14	6.7	8.7	9.7	7.8	-1.7	2	0.4	2.6	0.2	14	13	23	22	20	18	17	17	17	17	18
1993											22	14	7.7	10	10	24	21			25	23	22	21	19	17	19
1994	17	1.5	-5.2	-6.6	1.4	-0.2	-1.1	-6.6	-6.8	2.1	-5.2	-5.8	-7.6													

Sensitivity of the Results to Risk Assumptions

Figure 16 shows the contribution to variance attributable to the sources of uncertainty. Assumptions about climate change account for 70% of the overall uncertainty surrounding the number and severity of shortages, with assumptions about the flow adjustment factors and demand contributing 20% and 10% to the overall variability, respectively. This indicates that climate change may be the most effective area in which to develop better data. It is notable that demand plays a relatively small role in the overall variability, although it plays a more significant role in the severity of the shortage.

Figure 16. Sensitivity of the results to risk assumptions.



Appendix A: Monte Carlo Simulation as a Tool for Assessing Supply and Demand Uncertainties

What is Monte Carlo Simulation?

Monte Carlo simulation performs risk analysis by building models of possible outcomes by substituting a range of values—a probability distribution—for any factor that has inherent uncertainty. It then calculates results over and over, each time using a different set of random values from the probability functions. Depending upon the number of uncertainties and the ranges specified for them, a Monte Carlo simulation could involve thousands or tens of thousands of recalculations before it is complete.[17]

For Aspen, factors containing inherent uncertainty include the flows of Castle Creek and Maroon Creek, how those flows are statistically adjusted at the City's diversion points, the possible impact of climate change, and future municipal water demands. The results are estimates of the frequency and severity of potential future water shortages.

This brief definition of Monte Carlo simulation will be further developed in subsequent sections.

The Benefit of Monte Carlo Simulation

The analysis contained in this document differs from Aspen's previous analyses in how it deals with long-term water supply demand uncertainties, including potential future climate change impacts. Previous analysis followed a traditional path of defining a limited number of plausible supply and demand scenarios incorporating various combinations of these uncertainties and comparing the impacts of each. Although this type of scenario analysis is common, and is a useful starting point for planning, it is not without some shortcomings.

- The number of scenarios are generally limited in number. For instance, the previous WWG analysis of Aspen's water needs considered about 15 different combinations of climate change impacts and demand growth, with the assumptions underlying each appearing within reasonable bounds. Although reasonable, in general this scenario building leaves a lot to the analyst and doesn't consider the full probable range of combinations of the uncertainties, especially those combinations that might have a low probability of occurring yet may have significant consequences to the water provider.
- Unless otherwise noted, there are no insights about the probability of the outcomes. That is, the scenarios are often weighted the same because they are assumed to have the same probability of occurring.
- A limited and unweighted range of possible outcomes is not useful for determining thresholds, or tipping points, where the risk of an action, or inaction becomes critical.

[17] http://www.palisade.com/risk/monte_carlo_simulation.asp

In response to these shortcomings, combined with the substantial uncertainties associated with climate change, this analysis uses Monte Carlo simulation to consider a much wider range of assumptions and possible outcomes. The assumptions are probability-weighted in the sense that their underlying uncertainties are explicitly addressed and incorporated into the analysis. As a result, there is not a single point estimate of underlying water needs, or in Aspen's case, the number of possible municipal water shortages over a 25-year period. Instead of a single outcome, or point estimate, the outcomes are expressed in terms of probabilities. As an example, the outcome could be:

… "*there is a 40% probability that there will no shortages over the 25-year period of analysis; there is a 10% probability that the City will experience shortages in 12 years or more and experience at least one shortage in excess of 1,000 acre-feet in 2 years out of 25; there is a 1% probability that there will be shortages in 15 years or more, with shortages in excess of 1,000 acre-feet in 4 years out of 25".*

Although more complicated than simply asserting whether supplies are adequate or not over a limited range of assumptions, expressing results in terms of probabilities is a realistic format more useful for decision-making. It focuses discussion to where it belongs: the impacts of inherent risks and uncertainties, and the willingness of decision-makers to accept these risks or take measures to hedge against them.

Monte Carlo Simulation and Climate Change

An issue like climate change is well-matched for Monte Carlo simulation because little is certain about the potential climate change impacts to Castle Creek and Maroon Creek. Despite the attention given to the subject of climate change in municipal water supply planning, models adapting the results of larger climate change models to local basins are still under development for many Colorado basins and have inherent uncertainties of their own. Information to date reflects a degree of certainty that temperatures are rising and peak run-off dates are getting earlier in the year. Plant evapotranspiration (ET) rates appear to be increasing as a result of the higher temperatures. However, climate change's potential impact to the long-term timing and volume of run-off remains highly uncertain.

In response to these major uncertainties, including the uncertainties about the shape of the underlying probability distribution itself, available information was used to define the likely distributions around the timing of run-off, in terms of weeks relative to the period 1970-1994, and average weekly flows, also relative to 1970-1994. Discussion of this process is contained in the main body of this report. In combination with the other uncertain variables, Monte Carlo simulation was then used to assess a very wide range and large number of combinations of climate change-induced timing and flow combinations, approximately 10,000 different combinations, weighted by probability. The results of this process are also contained in the main body of this report, but it should be noted that sensitivity analysis associated with the Monte Carlo simulations indicated that the uncertainties of climate change was the major driver behind uncertainties in the number of possible shortages, much more so than demand uncertainties.

Implementing Monte Carlo Simulation

Although the term Monte Carlo suggests a gaming application, this method of simulation has wide application and acceptance, including for water resources planning, financial planning, and energy exploration.

The benefit of Monte Carlo simulation is its ability to simultaneously consider a large number of combinations and uncertainties, far more than the number considered in previous analyses. As a greater number of combinations are created through Monte Carlo simulations, a statistical picture begins to develop regarding the probability and severity of shortages over the hydrological period of record. That is, how often does demand exceed supply given these various combinations of uncertain supply, demand, and climate change values?

How these combinations are "matched-up" depends on the assumptions made about the uncertain variables. Input values used in a Monte Carlo analysis are, in technical terms, probability-weighted because the analyst assigns probabilities to their frequency of occurrence. These probabilities describe how the variable might range around its estimated value. Some probabilities can be described with a normal, bell-shaped, distribution, meaning that it is equally likely that the value might fall below or above its estimated value. Figure A-1, below, is a depiction of a normal distribution for a hypothetical example. As can be seen, the distribution is symmetric around the expected value of 180 in this example.

Figure A-1. Hypothetical Example of a "Normal" Statistical Distribution

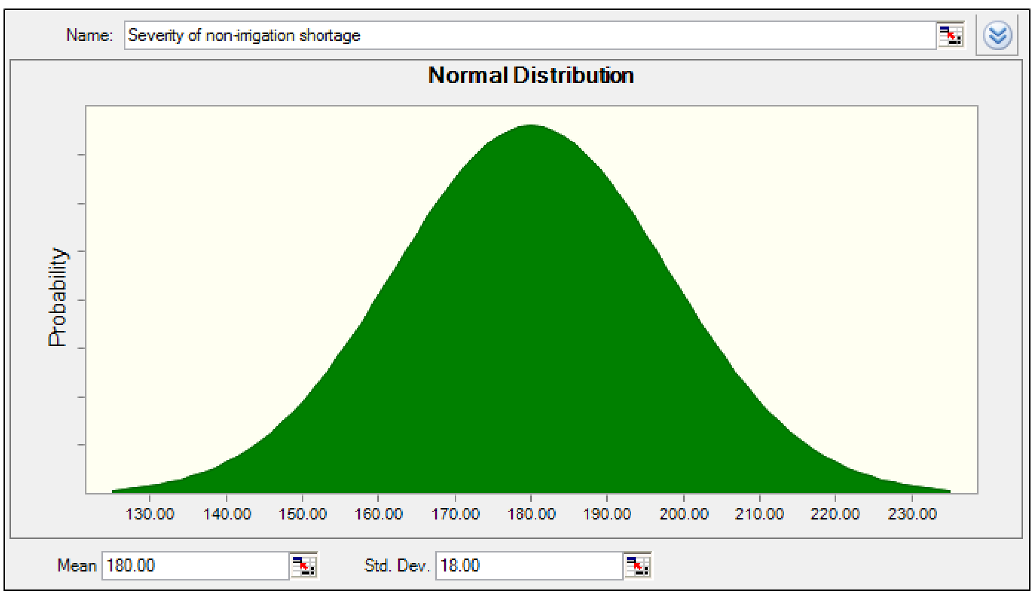
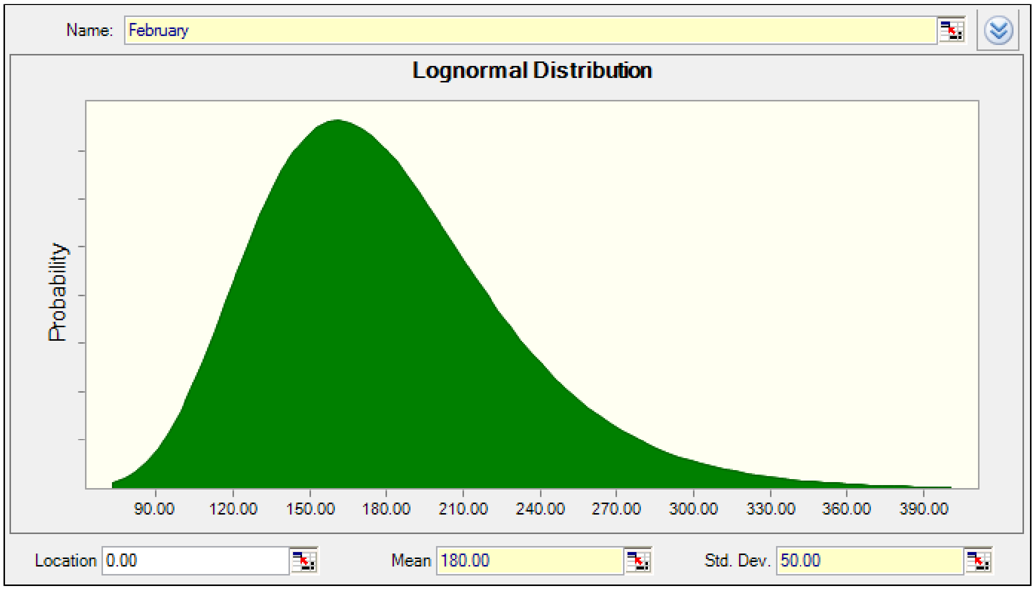


Figure A-2 illustrates an alternative depiction of this variable as having skewed characteristics. The mean is the same, 180, but there is a higher probability that the value is higher than 180 than below it. Alternatively stated, the distribution in Figure A-2 has a long tail, indicating that although the probability is small, a large impact is possible.

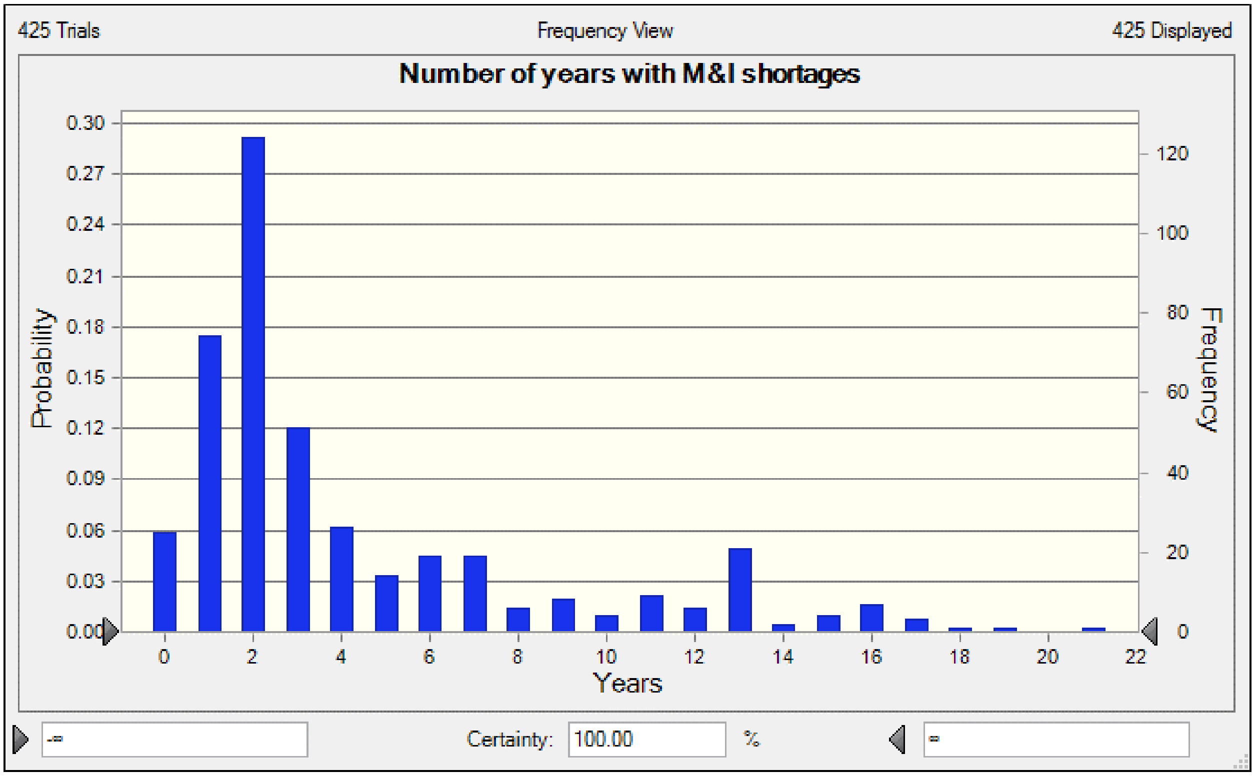
Figure A-2. Hypothetical Example of a Non-Normal Skewed Statistical Distribution



Variability in time series and cross-sectional data is often used to assist in developing these distributions, although informed judgment may also play a role when data is lacking. Many uncertainties in water planning are non-normal, or skewed, in nature because they are influenced by sometimes erratic weather patterns with periodic extreme events. Monte Carlo simulation is the best tool available for incorporating combinations of these skewed characteristics.

Given assumptions about the uncertainties affecting a municipality's water supply reliability and their statistical characteristics, what sort of output can be expected? Figure A-3 is an example of the type of output that Monte Carlo simulation can create. It shows a hypothetical output that summarizes the number of shortages over a 25-year period of record. As a result of variables that have non-normal distributions, the graphic shows that most of the time there are only 2 shortage years of the 25 considered. However, it is much more likely that there will be more shortages of this magnitude rather than fewer. There may be as many as 16 to 18. Again, the example is hypothetical, but this type of data tells decision makers that reliance upon averages and most likely values does not always paint the full picture.

Figure A-3. Example Monte Carlo Output for Hypothetical Example



Appendix B: Model Screenshots

Figure B-1. Screen shot of Maroon Creek assumptions: flow adjustments between the Maroon Creek gage and City diversion; adjustments for climate change.

Note, green highlighted cells represent uncertain variables examined with Monte Carlo simulation

User Interface

Maroon Creek at Aspen Diversion - WY 1970-1994

Properties of Average Weekly Hydrograph
*52-week hydrograph
*Leap year days excluded from calculations
*December 24-31 treated as an 8-day week (arbitrary)

Min Weekly Flow =	20.2	cfs		
Max Weekly Flow =	363.5	cfs		
Peak Week of Water Year =	39			
Dates of Peak Flow =	25-Jun	to	1-Jul	

User Inputs

(1) Enter a multiplier ratio to translate flows at the upstream USGS stream gage to flows at the downstream municipal intake

			Expected value	
Intake-to-Gage Flow Ratio, Maroon Creek =	1.27	Example: Enartech 1994 assumed a ratio of 1.25	1.27	
		NOTE: If gage values are desired, enter a value of 1		

(1) Enter value between -6 weeks (earlier peak) and +6 weeks (later peak)

				Peak week shift	
Peak Shift =	-4	weeks	OK!	-4	-3

(2) Select Option from Pull-down Menu Below (Click yellow box and pull-down will appear)

Flow Modification Options = Modify Entire Hydrograph

(3) Enter percent flow reduction as a decimal value between -1 and 1

			Percent flow reduction	
			-0.35	Expected value
Peak Modification Factor =	-0.35	OK!		
			Beta dist'n	

(4) For Modify Peak Flow Only option enter a value between MIN = 20.2 cfs and MAX = 363.5 cfs.

				Min, with ET impacts	-0.55
				Max	0.1
Peak Modification Threshold =	50	cfs	OK!		

Output Graphs

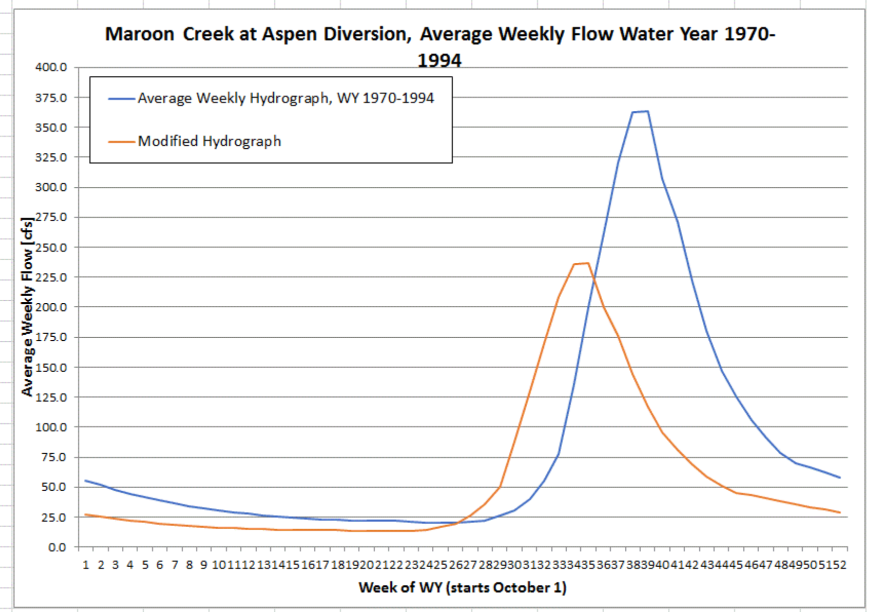


Figure B-2. Screen shot of Castle Creek assumptions: flow adjustments between the Castle Creek gage and City diversion; adjustments for climate change

Note, green highlighted cells represent uncertain variables examined with Monte Carlo simulation

User Interface

Castle Creek at Aspen Diversion - WY 1970-1994

Properties of Average Weekly Hydrograph
***52-week hydrograph**
***Leap year days excluded from calculations**
***December 24-31 treated as an 8-day week (arbitrary)**

Min Weekly Flow =	23.6	cfs		
Max Weekly Flow =	479.4	cfs		
Peak Week of Water Year =	38			
Dates of Peak Flow =	18-Jun	to	24-Jun	

User Inputs

(1) Enter a multiplier ratio to translate flows at the upstream USGS stream gage to flows at the downstream municipal intake

Gage Flow Ratio, Castle Creek = 2.43 Example: Enartech 1994 assumed a ratio of 2.30 2.43
NOTE: If gage values are desired, enter a value of 1

(2) Enter value between -6 weeks (earlier peak) and +6 weeks (later peak)

Peak Shift = -4 weeks **OK!**

(3) Select Option from Pull-down Menu Below (Click yellow box and pull-down will appear)

Flow Modification Options = Modify Entire Hydrograph

(4) Enter percent flow modification as a decimal value between -1 and 1

Peak Modification Factor = -0.35 **OK!**

(5) For Modify Peak Flow Only option enter a value between MIN = 23.6 cfs and MAX = 479.4 cfs.

Peak Modification Threshold = 50 cfs **OK!**

Output Graphs

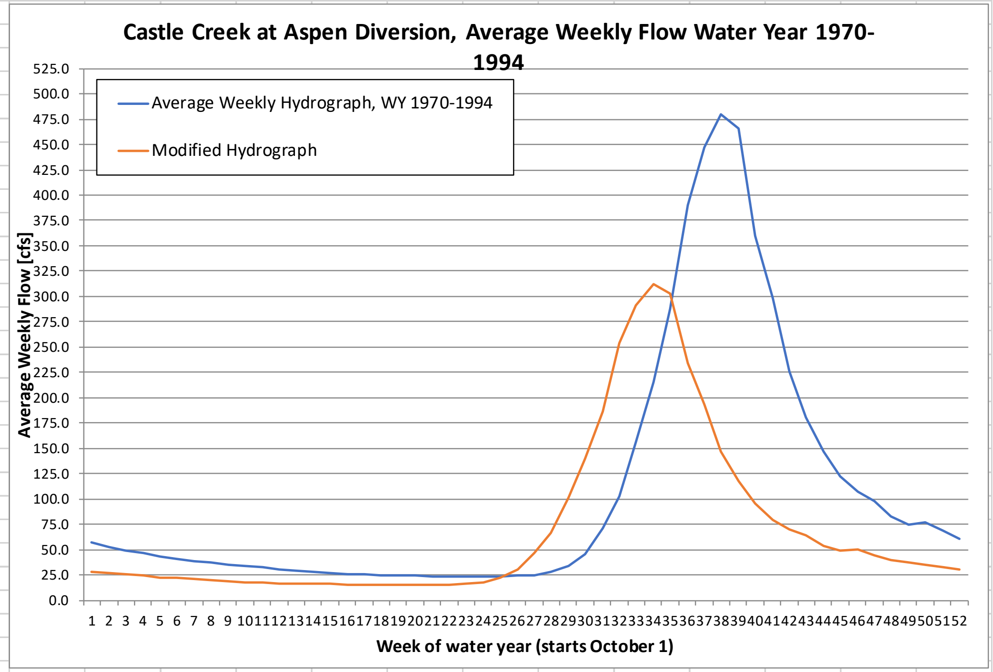


Figure B-3. Screen shot of operations routing component.

City of Aspen
Water Supply System Model
Castle Creek and Maroon Creek

Developed by HWC/smt
REVISED July 17, 2017

Herrick Diversion Rate =	16	
Herrick IRR start week =	35	start May 28
Herrick IRR stop week =	2	end October 14

ISF Right	Flow [cfs]
Castle Creek	13.3
Maroon Creek	14.0

7

			Thomas Reservoir Demands			14.1				Bypass Demands						17	17		ISF Bypass Demand		456	456	
	WY	Week	Indoor Use [cfs]	Outdoor Use [cfs	Non-Potable Use [cfs	TOTAL Thomas Reservoir Demand [cfs]	Castle Creek at Gage [cf	Depletion between Gage and Intake [c	Estimated Flow at Castle Creek Intake [c	Downstream Irrigation Demand [cfs	Available to City at Castle Creek Intake after IRR and AUG bypass [cfs]	Estimated Flow at Maroon Creek Intake [c	Herrick Ditch Diversion [cfs]	Available to City at Maroon Creek Intake after Herrick [cfs]	TOTAL Available at Both Intakes before M&I and ISF [cfs	Combined Flow Remaining after Meeting M&I Demands [cfs]	M&I Shortage	Magnitude of M&I Shortage [cfs]	Castle Creek ISF [cfs]	Maroon Creek ISF [cfs]	Combined Flow Remaining after Meeting ISF Demands [cfs]	ISF Shortage	Magnitude of ISF Shortage [cfs]
	1970	1	3.6	0	0.1	3.7	27.3	2	27.3	13.2	14.1	26.5	16	10.5	24.5	20.8	NO	0.0	13.3	14.0	-6.5	YES	6.5
	1970	2	3.6	0	0.1	3.7	25.1	2	25.1	13.2	11.9	23.8	16	7.8	19.7	16.0	NO	0.0	13.3	14.0	-11.3	YES	11.3
	1970	3	3.6	0	0.1	3.7	23.8	2	23.8	13.2	10.6	22.3	0	22.3	32.9	29.2	NO	0.0	13.3	14.0	1.9	NO	0.0
	1970	4	3.6	0	0.1	3.7	22.6	2	22.6	13.2	9.4	20.5	0	20.5	30.0	26.3	NO	0.0	13.3	14.0	-1.0	YES	1.0
	1970	5	4.8	0	0.4	5.2	21.4	0.5	21.4	0	21.4	18.9	0	18.9	40.3	35.1	NO	0.0	13.3	14.0	7.8	NO	0.0
	1970	6	4.8	0	0.4	5.2	21.2	0.5	21.2	0	21.2	18.0	0	18.0	39.2	34.0	NO	0.0	13.3	14.0	6.7	NO	0.0
	1970	7	4.8	0	0.4	5.2	20.2	0.5	20.2	0	20.2	18.5	0	18.5	38.7	33.5	NO	0.0	13.3	14.0	6.2	NO	0.0
	1970	8	4.8	0	0.4	5.2	19.4	0.5	19.4	0	19.4	18.3	0	18.3	37.7	32.5	NO	0.0	13.3	14.0	5.2	NO	0.0
	1970	9	4.8	0	0.4	5.2	17.3	0.5	17.3	0	17.3	17.2	0	17.2	34.4	29.2	NO	0.0	13.3	14.0	1.9	NO	0.0
	1970	10	5.1	0	0.2	5.3	15.7	0.5	15.7	0	15.7	16.2	0	16.2	32.0	26.7	NO	0.0	13.3	14.0	-0.6	YES	0.6
	1970	11	5.1	0	0.2	5.3	15.8	0.5	15.8	0	15.8	15.3	0	15.3	31.1	25.8	NO	0.0	13.3	14.0	-1.5	YES	1.5
	1970	12	5.1	0	0.2	5.3	16.9	0.5	16.9	0	16.9	14.3	0	14.3	31.2	25.9	NO	0.0	13.3	14.0	-1.4	YES	1.4
	1970	13	5.1	0	0.2	5.3	16.4	0.5	16.4	0	16.4	13.3	0	13.3	29.6	24.3	NO	0.0	13.3	14.0	-3.0	YES	3.0
	1970	14	4.6	0	0	4.6	17.9	0.5	17.9	0	17.9	13.6	0	13.6	31.5	26.9	NO	0.0	13.3	14.0	-0.4	YES	0.4
	1970	15	4.6	0	0	4.6	17.3	0.5	17.3	0	17.3	14.0	0	14.0	31.3	26.7	NO	0.0	13.3	14.0	-0.6	YES	0.6
	1970	16	4.6	0	0	4.6	17.6	0.5	17.6	0	17.6	14.4	0	14.4	32.0	27.4	NO	0.0	13.3	14.0	0.1	NO	0.0
	1970	17	4.6	0	0	4.6	17.7	0.5	17.7	0	17.7	13.0	0	13.0	30.6	26.0	NO	0.0	13.3	14.0	-1.3	YES	1.3
	1970	18	4.9	0	0	4.9	16.6	0.5	16.6	0	16.6	12.3	0	12.3	28.8	23.9	NO	0.0	13.3	14.0	-3.4	YES	3.4
	1970	19	4.9	0	0	4.9	16.3	0.5	16.3	0	16.3	12.1	0	12.1	28.4	23.5	NO	0.0	13.3	14.0	-3.8	YES	3.8

Figure B-4. Screen shot of Demand assumptions

Note, green highlighted cells represent uncertain variables examined with Monte Carlo simulation

Existing demand

Month	Indoor demand, cfs	Outdoor use, cfs	Non-potable	Irrigation demand
1	3.1	0	0	0
2	3.3	0	0	0
3	3.1	0	0	0
4	3.0	0	0	0
5	3.2	3.1	0	6.8
6	3.2	6.2	0.1	20.5
7	3.2	5.2	0.1	16.1
8	3.2	3.4	0	15.4
9	3.2	2	0.3	12.2
10	2.4	0	0.1	11
11	3.2	0	0.4	0
12	3.4	0	0.2	0

2065 demand

Month	Indoor demand, cfs	Outdoor use, cfs	Non-potable	Irrigation demand
1	4.6	-	-	-
2	4.9	-	-	-
3	4.6	-	-	-
4	4.5	-	-	-
5	4.8	4.6	-	8.2
6	4.8	9.2	0.1	24.6
7	4.8	7.7	0.1	19.3
8	4.8	5.1	-	18.5
9	4.8	3.0	0.3	14.6
10	3.6	-	0.1	13.2
11	4.8	-	0.4	-
12	5.1	-	0.2	-

Demand growth

	% of total demand	Cap on growth	Weighted growth rate
Residential growth	50%	0.4%	0.20%
Non-residential grov	50%	1.2%	0.60%
Expected value, weighted			0.80%

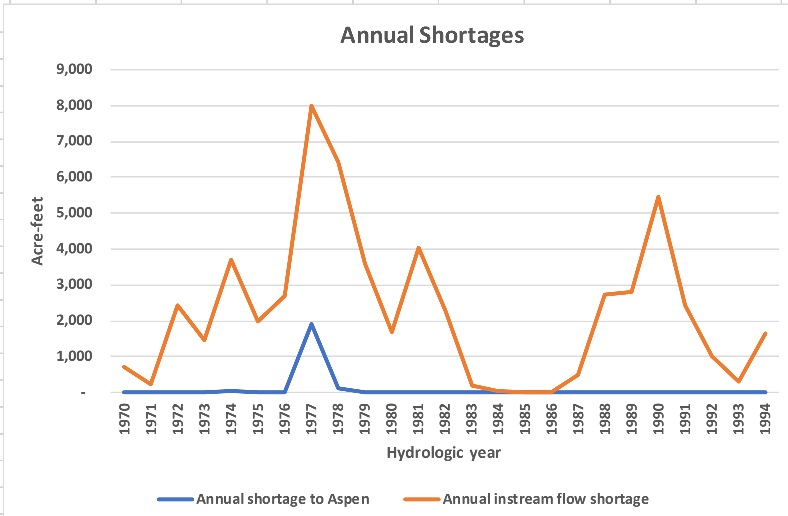
ET impact to outdoor water usage

Expected impact		20.0%
Low	Most likely	High
10%	20%	30%

Figure B-5. Screen shot of shortage estimates with expected values for demand, flow adjustments, and climate change

Note: Monte Carlo simulation examined about 10,000 different combinations of plausible demands, flow adjustment factors, and climate change impacts. The following graphic represents results from a single combination.

WY	Annual shortage to Aspen	Annual instream flow shortage
1970	-	719
1971	-	215
1972	-	2,418
1973	-	1,466
1974	39	3,696
1975	-	1,971
1976	-	2,710
1977	1,922	7,994
1978	103	6,410
1979	-	3,569
1980	-	1,700
1981	-	4,023
1982	-	2,264
1983	-	176
1984	-	33
1985	-	-
1986	-	-
1987	-	500
1988	-	2,710
1989	-	2,804
1990	3	5,444
1991	-	2,446
1992	-	1,020
1993	-	292
1994	-	1,635



Number of years with M&I shortages		4
Number of years M&I shortage exceeds 100 acre-feet		2
Number of years M&I shortage exceeds 1000 acre-feet		1

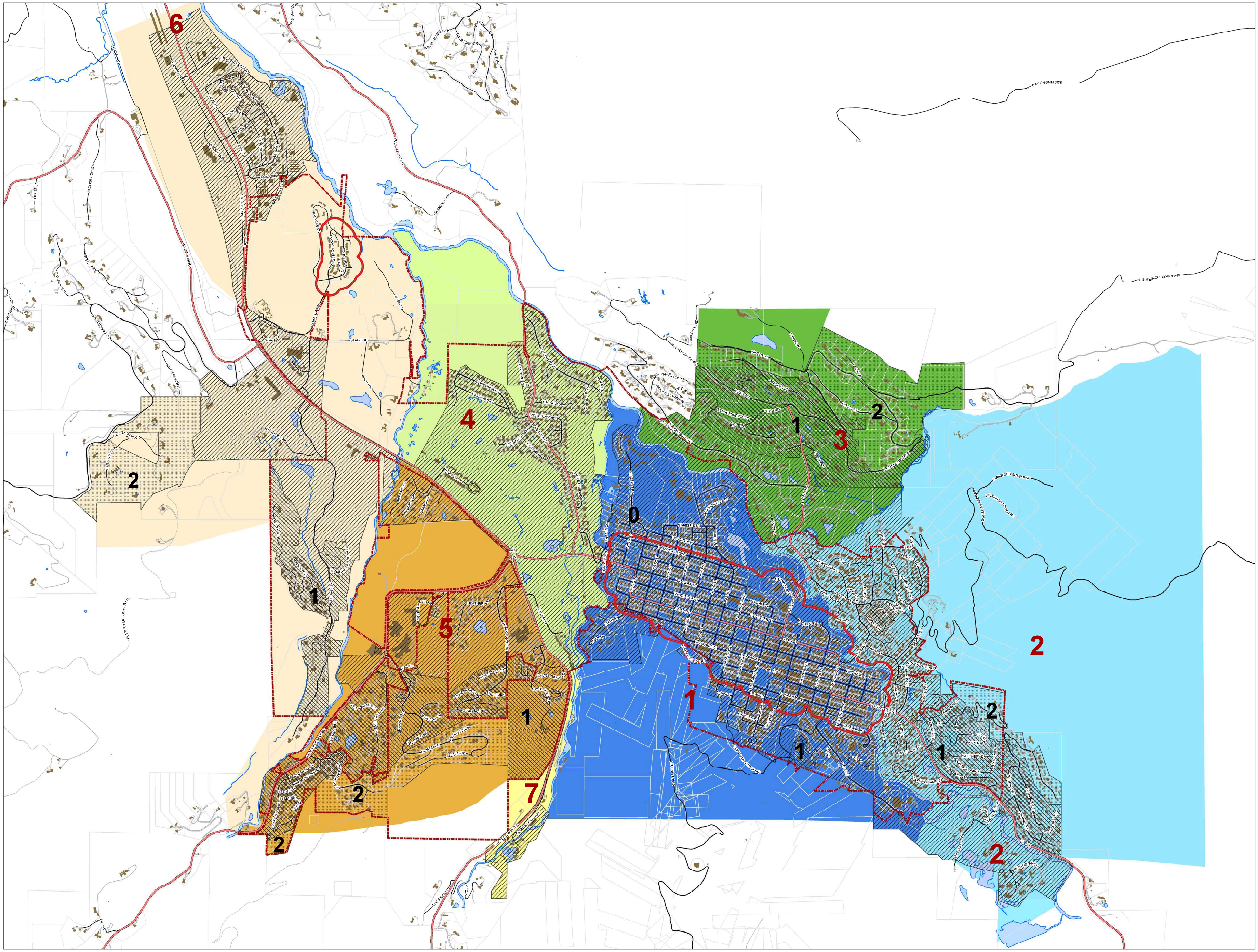
Figure B-6. Screen shot of estimated impacts to instream flows with expected values for demand, flow adjustments, and climate change

Note: Monte Carlo simulation examined about 10,000 different combinations of plausible demands, flow adjustment factors, and climate change impacts. The following graphic represents the results from a single combination.

Figure 13. Spells Plot - Periods when Combined Castle Creek + Maroon Creek Flow <=27.3 cfs after Meeting all but ISF Demands

	Jan				Feb				Mar					Apr				May					Jun				Jul				Aug					Sep				Oct				Nov					Dec			
CY Wk	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
WY Wk	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	1	2	3	4	5	6	7	8	9	10	11	12	13
1969																																								21	16		26						27	26	27	25
1970		27		27	24	24	24	25	25																																											
1971										26																												25	19	22	17										27	25
1972	25	27	27	26	25	24	24	24	25	27																			22	15	16	12	18	14	13	22	16	21	16	16	18											27
1973	26		24	23	23	21	20	18	20	22	23																											21	17	19	13	26	24						26	27	25	26
1974	27	26	26	25	24	22	21	20	20	21	26																				22	21	18	8	1.7	4.2	1.2	0.8	-1.8	4.4	3.2	19	20								26	25
1975	26	23	23	24	23	23	23	21	22	25	24																											24	16	15	13	27	25							27	26	26
1976	25	23	24	24	23	22	25	23	25	25																						20	20	18	14	12	8.6	7.7	14	17	12	24	21			26	25	23	23	23	22	22
1977	21	20	20	19	18	17	16	16	17	18	20	25													16	-11	-11	-19	-18	-14	-15	-15	-11	-8.4	-10	-7	-4.3	-9	-11	-6	-6.8	8	8	19	17	16	16	15	14	15	14	15
1978	15	16	15	15	15	14	15	15	15	17	18	24																						16	11	14	10	7.3	3.7	5	1.7	16	17	26	26	26	25	23	21	22	22	20
1979	19	18	18	18	18	18	18	18	19	20	23																										20	15	13	14	11	26	25					26	25	23	22	23
1980	23	23	23	23	23	22	23	23	24	25	27																											25	20	22	18											
1981			26	23	22	21	19	19	19	20	22																	23	16	13	6.1	4.9	10	4.5	5.8	14	14	8.6	5.8	8.3	7	23	20				27	25	23	23	20	15
1982	13	14	17	23	24	23	22	25	26	25																																										
1983						26	26	26	26																														26		26											
1984																																																				
1985																																																				
1986																																																				
1987									27																												19	17	14	16	14								27	25		27
1988			27	25	27	27	27																					23	13	12	22	14	14	14	12	11	17	16	13	14	9	21	18					26	24	25	25	24
1989	24	23	25	27	27	24	26	27	24	23																								17	9.3	12	9.3	11	9.4	12	6.5	19	17	26	25	25	25	23	23	21	20	18
1990	17	18	16	17	18	19	19	21	24	24	26																			20	12	6.1	16	7.2	3.6	7.8	0.7	8.9	6.2	15	13	26	24					25	25		22	22
1991	22	22	21	19	19	19	20	18	19	21	22	27																						18	18	26			18	26	18		26									
1992	26	25	26	23	23	24	24	24	25	24																											19	24	21	20	16											
1993																																																				
1994					24	26	25	26	26	25	27																			25	25	21	26	15	13	25	13	12	9.2													

Appendix C: Service Area Map of the Aspen Water System



Aspen Water Billing, Pump Zones & Electric Service Area

For internal use only

Legend

1 inch = 887 feet

When printed at 24"x36"

Date: 5/4/2016

City of Aspen

Utilities

Geographic Information Systems

THE CITY OF ASPEN

This map/drawing/image is a graphical representation of the features depicted and is not a legal representation. The accuracy may change depending on the enlargement or reduction.