Upper Roaring Fork Hydrological Decision Support System

A product of the

Roaring Fork River Management Plan

City of Aspen | Pitkin County November, 2017

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Table of Contents

1. Introduction

The structural form and functional integrity of a riverine system is described by a suite of hydrological, physiochemical, biological, geomorphological, and hydraulic processes. Complex bi-directional interactions occur between each, complicating evaluation of any one component of the system in isolation from the others. However, the overall form and function of a river is significantly influenced by its climate, geology, and hydrology. The Natural Flow Paradigm postulates that hydrology represents the key driver of riverine structure and function and fluvial ecologists often treat steamflow as the “master variable” exerting the largest influence on riverine ecosystem form and function (Poff et al., 1997). The daily, seasonal, and inter-annual variations in flows make up its *hydrologic regime*. Changes in the timing and magnitude of various elements of the hydrological regime can produce cascading effects—or positive feedback loops—between structural and biological components of the ecosystem.

River systems subject to hydrological alteration due to changing climate or human management actions are vulnerable to degradation in measures of river health. Activities that deplete or augment streamflow have the potential to impact important regime characteristics, including: total annual volume, magnitude and duration of peak and low flows, and variability in timing and rate of change. Changes to total annual volume and peak flows may impact channel stability, riparian vegetation, and floodplain functions. Impacts to base flows frequently alter water quality and the quality and availability of aquatic habitat. Alterations to natural patterns of flow variability (e.g. the frequency and timing of floods) impact fish, aquatic insects and other biota with life history strategies tied to predictable rates of occurrence or change (Johnson et al., 2016).

2. Water Budget for the Upper Roaring Fork

The balance of water flowing into streams from snowmelt and rainfall, getting diverted for human uses, being consumed or evaporating, and returning to the river via surface or groundwater (Figure 1), creates the components of a *water budget*. The responses of physical and legal water demands to hydrological conditions determine the allocation of water among the various uses present in the system. The diversity of, and competition among, these water uses in the Roaring Fork watershed produces gaps between existing supply—both in time and in place—and the supply needed to satisfy both consumptive and environmental and recreational use needs.

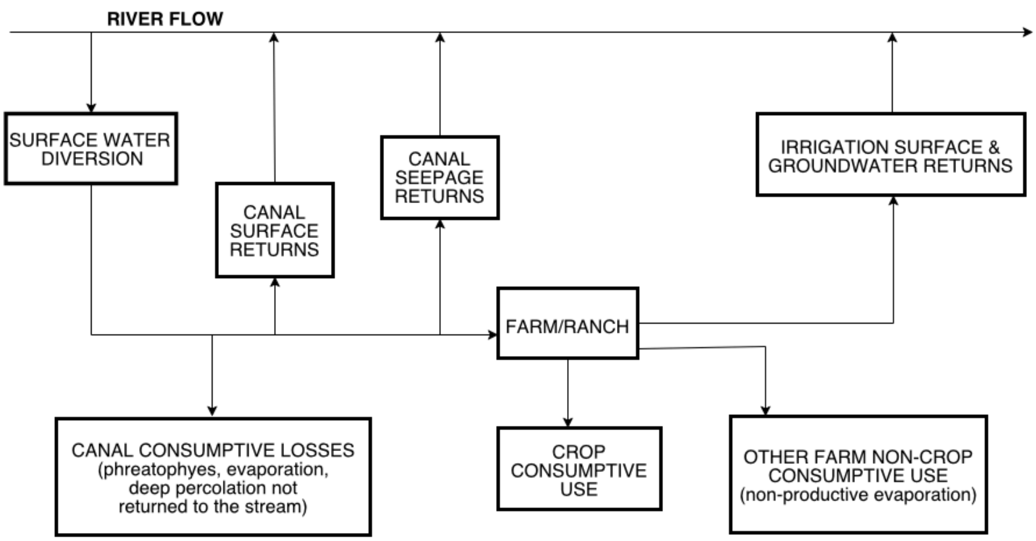

Figure 1: Conceptual model indicating the various pathways water travels along between a stream or river and a typical point of agricultural use on Colorado streams and rivers.

Hydrologic characteristics of interest for streams in the Roaring Fork watershed include the duration, frequency, and magnitude of different flows states on the mainstem Roaring Fork River and its major tributaries. Surface water diversions and reservoir operations strongly alter the longitudinal (upstream-downstream) and temporal (day-to-day or seasonal) patterns of flow in many stream segments throughout the watershed. Additionally, long-term hydrological conditions like drought or wet periods can impart both obvious and subtle changes in regime behavior. Stakeholders in the Roaring Fork watershed recognize that understanding human and natural controls on hydrology is a critical first step for effective resource management. To this end, the Roaring Fork River Management Plan sought to produce data and modeling tools capable of characterizing the hydrological regime at numerous locations throughout the watershed under a range of climatic or human management conditions.

Directly characterizing patterns of daily streamflow across a range of hydrological conditions and under different management regimes in the upper Roaring Fork watershed is possible at several locations where United States Geological Survey (USGS) gauges exist and maintain long data records (Table 1, Figure 2). On the mainstem and on some tributaries, satisfactory streamflow records are somewhat sparse both in geographic coverage and length of observations. Without some amount of data processing or analysis, observed streamflow records are, thus, inadequate to describe daily flow conditions at a sufficient spatial resolution to inform water management decisions at all locations where stakeholders desire. Even in cases were streamflow records can be extended using statistical data filling techniques, water abstractions and tributary inflows upstream and downstream from gauge locations makes reliance on fixed measurement locations implausible for the types of questions germane to this planning effort.

Table 1. Historical and current streamflow gauging stations in the upper Roaring Fork watershed considered in this assessment.

Provider	Site ID	Drainage Area (sq mi)	Site Name
USGS	09072550	9.03	ROARING FORK RIVER ABV LOST MAN CR NEAR ASPEN, CO
USGS	09073005	15.1	LINCOLN CREEK BELOW GRIZZLY RESERVOIR NR ASPEN, CO
USGS	09073300	75.8	ROARING FORK RIVER AB DIFFICULT C NR ASPEN, CO
USGS	09073400	106.0	ROARING FORK RIVER NEAR ASPEN, CO
USGS	09074500	43.1	HUNTER CREEK AT ASPEN, CO
USGS	09074000	41.7	HUNTER CREEK NEAR ASPEN, CO
USGS	09074800	32.3	CASTLE CREEK ABOVE ASPEN, CO
USGS	09075700	35.4	MAROON CREEK ABOVE ASPEN, CO
CDWR	ROABMCCO	289.0	ROARING FORK RIVER BELOW MAROON CREEK NEAR ASPEN, CO

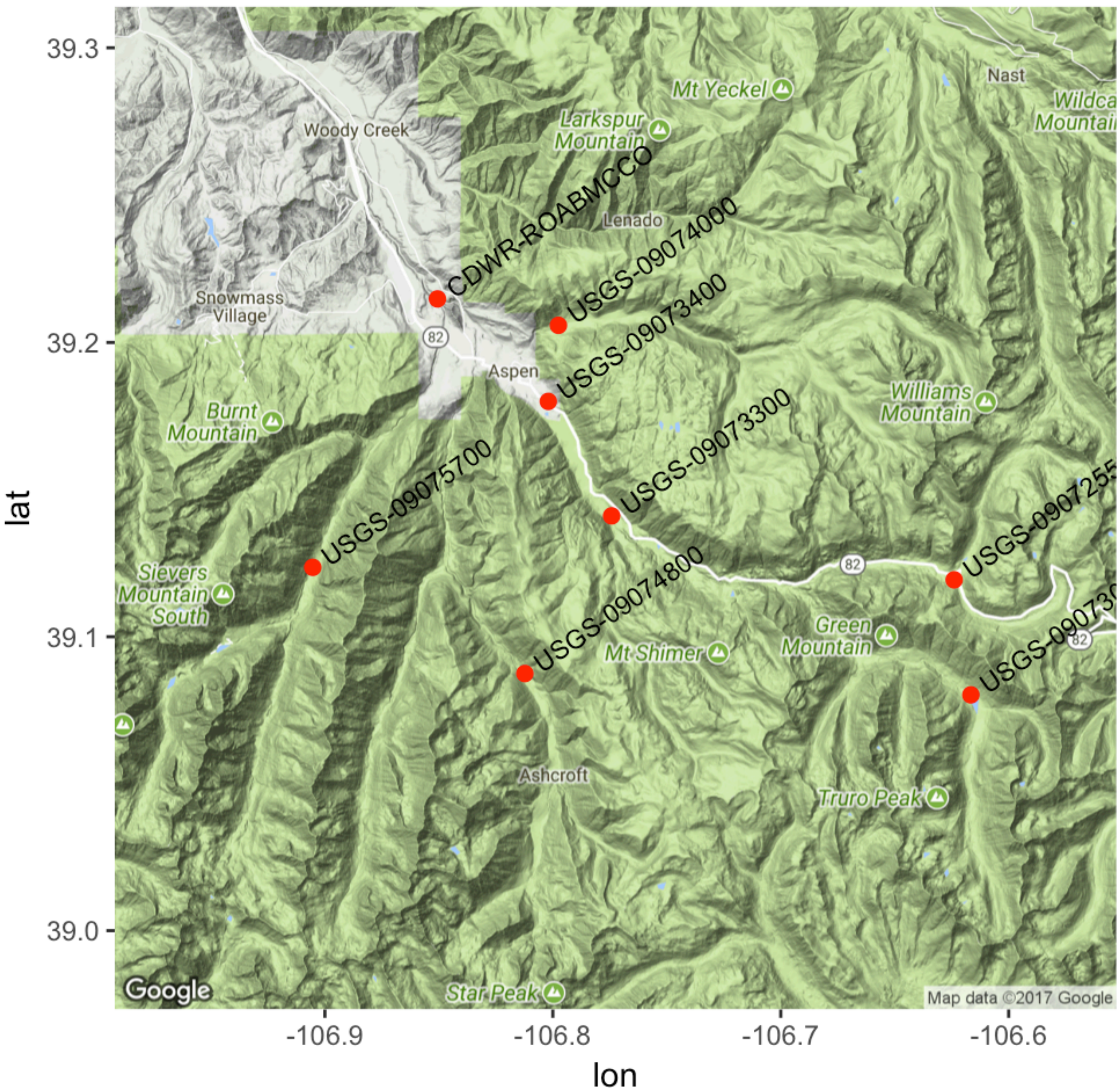

Figure 2. Locations of historical and current streamflow gauging locations in the upper Roaring Fork watershed.

The presence of human management activities in the upper Roaring Fork watershed means that any useful hydrological decision support tool must explicitly account for the operation and administration of transmountain diversions; reservoirs; surface water diversions (and associated return flows) supporting agriculture, landscaping, municipal use, snowmaking; and hydropower diversions (Table 2). The most significant water diversion structures and projects in the upper watershed are discussed briefly below.

Table 2. Surface water diversion structures and locations considered by this assessment.

WDID	Water Source	Structure Name	Total Decreed Rate (cfs)
3804617	Lincoln Creek	Twin Lakes Tunnel #1	625
3801763	Roaring Fork River	Twin Lakes Tunnel #2	486.16
3800981	Roaring Fork River	Salvation Ditch	59
3801091	Roaring Fork River	Wheeler Ditch	10
3800963	Roaring Fork River	Riverside Ditch	3
3800904	Roaring Fork River	Nellie Bird Ditch	4.94
3801594	Hunter Creek	Fry-Ark PR Hunter Tunnel	270
3801790	Hunter Creek	Red Mountain Ditch	27.34
3801026	Maroon Creek	Stapleton Brothers Ditch	16.01
3800749	Maroon Creek	Herrick Ditch	64.86
3800854	Maroon Creek	Maroon Ditch	68.4
3801101	Willow Creek	Willow Creek Ditch	40
3800869	Castle Creek	Midland Flume Ditch	160
3800755	Castle Creek	Holden Ditch	30
3800853	Castle Creek	Marolt Ditch	18.6
3800992	Castle Creek	SI Johnson Ditch	5.5

2.1 Overview of Water Rights Considerations

There are three diversion structures or systems that have historically had the greatest effects on stream flows in the Upper Roaring Fork upstream and through the City of Aspen: the Independence Pass Transmountain Diversion System, the Salvation Ditch and the Hunter Creek portion of the Frying Pan/Arkansas Project collection system. Several other diversions significantly affect stream flows in other portions of the Upper Roaring Fork and its tributaries above Brush Creek. The Wheeler Ditch has occasionally reduced flows in the Roaring Fork downstream from its headgate near the center of Aspen. The Red Mountain Extension Ditch has reduced flows in the lower portion of Hunter Creek and in the Roaring Fork downstream of the Hunter Creek confluence. The City of Aspen's municipal diversions from Castle Creek have reduced flows in Castle Creek and the Upper Roaring Fork downstream of the Castle Creek confluence.

2.1.1 Independence Pass Transmountain Diversion System

The Independence Pass Transmountain Diversion System (IPTDS) is owned and operated by the Twin Lakes Reservoir and Canal Company (Twin Lakes). The IPTDS diverts from several Roaring Fork headwater tributaries. Diverted water is collected by pipelines and flows by gravity through Twin Lakes Tunnel #1 to the Arkansas basin, where it is used for municipal and irrigation (M&I) purposes by Twin Lakes shareholders. Grizzly Reservoir, with a 400 AF storage capacity, acts as a point of diversion, central collection point, and forebay for Tunnel #1. Diversions by the IPTDS have historically occurred year-round and have ranged from as low as 9,000 AF per year to as high as 66,000 AF per year, averaging approximately 43,000 AF per year over the most recent 20 years (Figure 3).

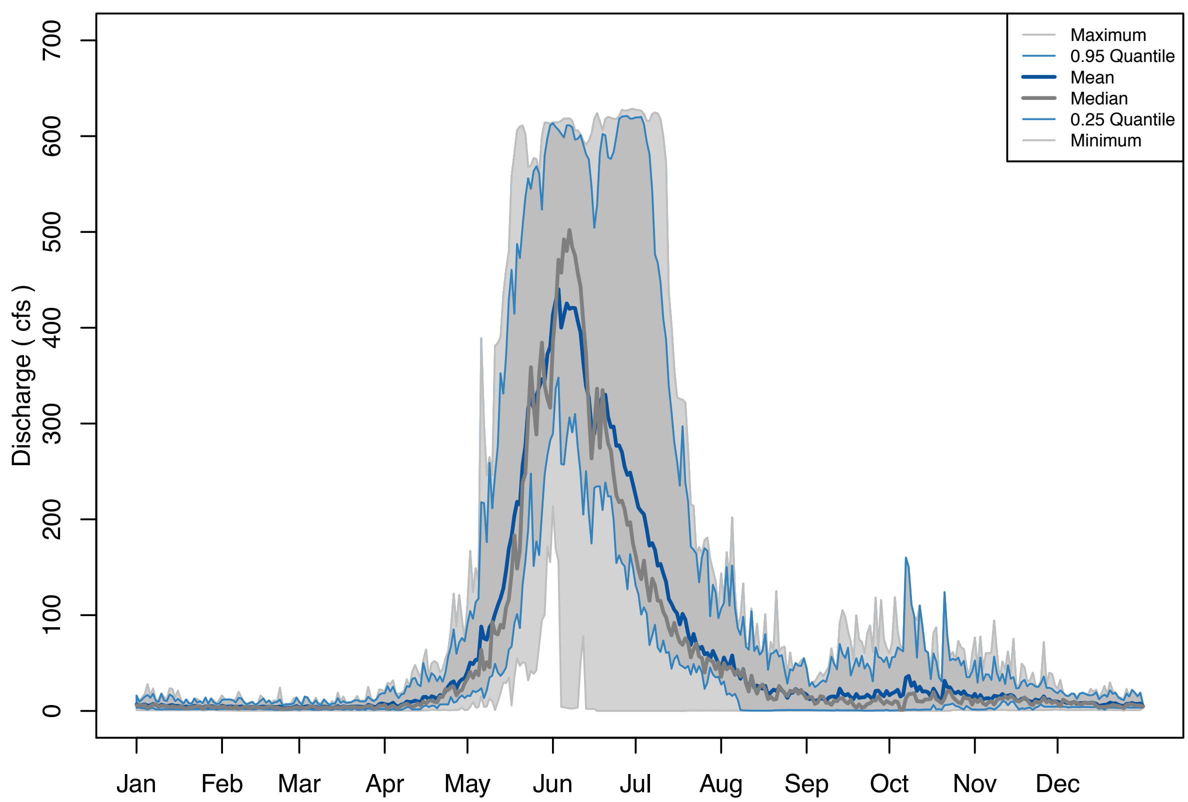

Figure 3. Historical diversion patterns reported for Twin Lakes Tunnel #1.

During the peak runoff season (typically late May through June) of wet years, the physical supplies at the IPTDS points of diversion typically exceed the system's diversion and collection capacities and spills occur at those locations. At other times, the IPTDS generally diverts the entire physical supply whenever the IPTDS rights are in priority, subject to the terms of the IPTDS decrees and the Twin Lakes Exchange.

The IPTDS operates under its original 1936 priority water rights and its supplemental 1994 priority rights. The 1936 priority rights were decreed in Civil Action No. 3082 for irrigation use and were subsequently changed to include municipal & industrial (M&I) uses in Case No. W-1901. Those decrees imposed several limits on Twin Lakes' diversions under the 1936 priority rights, including: (1) no more than 68,000 AF of diversions in any year, (2) no more than 570,000 AF of diversions in any ten-year period, and (3) no diversions at times when Twin Lakes Reservoir has stored its decreed capacity of 54,452 AF for the year and there is 726.28 cfs available in priority to the Colorado Canal June 9, 1890 irrigation right. In the 95CW321 decree, Twin Lakes obtained its supplemental 1994 priority rights, which allow Twin Lakes to divert at times when the 1994 rights are in priority and limit #3 above would otherwise curtail Twin Lakes' diversions under its 1936 priority rights. The 1995 priority rights are decreed for direct flow and storage for irrigation and M&I uses. Twin Lakes' combined diversions under the 1936 and 1994 priority rights are constrained by the same 68,000 AF annual and 570,000 AF ten-year volumetric limits. Diversions under the 1994 priority rights alone are limited to no more than 30,000 AF in any year and no more than 46,500 AF in any ten-year period.

The Twin Lakes Exchange was initially described in the Operating Principles for the Frying Pan/Arkansas (FryArk) Project and is the subject of several subsequent agreements. Under the Twin Lakes Exchange, up to 3,000 AF per year of water is diverted from FryArk points of diversion in the Hunter Creek basin and is delivered to Twin Lakes via FryArk project facilities in exchange for an equivalent amount of bypass of water at the IPTDS points of diversion that would otherwise be divertible under the IPTDS 1936 priority rights. The 95CW321 decree and stipulations to that decree impose several conditions on Twin Lakes' diversions under the 1994 priority rights. The conditions that provide additional water for the Roaring Fork can be generally summarized as follows[1].

- The first 40 AF of water available each year to the 1994 priority right is stored in a 40 AF Grizzly Reservoir Mitigation Account, for release during the current year to help meet instream flows on the Roaring Fork. Any leftover water in this account reverts to Twin Lakes.

- One third of the next 2,360 AF available each year to the 1994 priority right each year (up to 787 AF) is allocated to the Colorado River Water Conservation District for the benefit of West Slope water users.

- Up to 200 AF of the River District's annual allocation is stored in a 200 AF River District Grizzly Reservoir account. Water can be released from the River District Grizzly Reservoir account for several purposes including satisfying deficits to the CWCB's instream flow right upstream of Maroon Creek. Releases from the River District Grizzly Reservoir account are limited to 150 AF in any one year. Any water left over in the River District Grizzly Reservoir account is carried over to the next year.

- Under a separate agreement, Pitkin County has the right to use up to 20 AF per year from the River District Grizzly Reservoir account for replacement and other purposes. The County's use of this water for replacement generally results in the released water supporting instream flows on the Roaring Fork.

- The balance of the River District's 787 AF annual allocation is stored in available space in Arkansas River basin reservoirs and is generally used to meet the repayment obligations of certain West Slope water users to Aurora and Colorado Springs or can be substituted

[1] It should be noted that this is just a summary. The 95CW321 decree and its stipulations should be read for more detailed descriptions. Also, allocations of water from the 1994 priority water rights for West Slope uses, including releases to support instream flows in the Roaring Fork, continue to be the subject of ongoing negotiations between the several parties.

for additional bypasses of water at the IPTDS diversions in the Roaring Fork (beyond the bypasses comprising the 3,000 AF FryArk Exchange).

- Releases from the River District Grizzly Reservoir account, along with any additional IPTDS bypasses, are generally used for satisfying deficits to the CWCB's instream flow rights on the Roaring Fork upstream of Maroon Creek, with successive use of the released water downstream of Maroon Creek.

The combined benefit of the 95CW321 conditions to instream flows in the Roaring Fork are potentially significant: up to 210 AF of Grizzly Reservoir releases and up to 787 AF of additional bypasses at IPTDS points of diversion in a given year. However, these potential benefits are dependent upon the yield of Twin Lakes' 1994 priority IPTDS water rights, which are not reliable because the 1994 priority water rights are not available or needed for diversion in all years. In some below average years, the conditions imposed on the 1936 priority rights may not come into play and all IPTDS diversions would occur under the 1936 priority rights. In some wet years, Twin Lakes may not need to divert under the 1994 priority rights because of lack of demand in the Arkansas basin.

From a basin-wide administration perspective, the IPTDS 1936 priority water rights are senior to the ISF rights on the Roaring Fork but are junior to most of the in-basin Roaring Fork ditch rights, including those of the Salvation and Wheeler ditches. The IPTDS 1936 priority water rights are also junior to the Cameo rights (a group irrigation rights associated with the Grand Valley Canal and the Grand Valley Project) and must be curtailed when there is a call from the senior Cameo rights. While the IPTDS 1936 priority water rights are junior to most of the in-basin Roaring Fork ditch rights, diversions by the IPTDS have not normally been called out by in-basin Roaring Fork ditch rights because intervening flows from Roaring Fork tributaries downstream of the IPTDS points of diversion have historically been sufficient to satisfy downstream senior Roaring Fork rights. This is evidenced by the lack of recorded historical calls by Roaring Fork ditch rights and was confirmed by discussions with the District 38 Water Commissioner. However, the IPTDS has been called out by the senior Cameo call, which typically occurs in an intermittent manner during July through August of below-average years, (Figure 4).

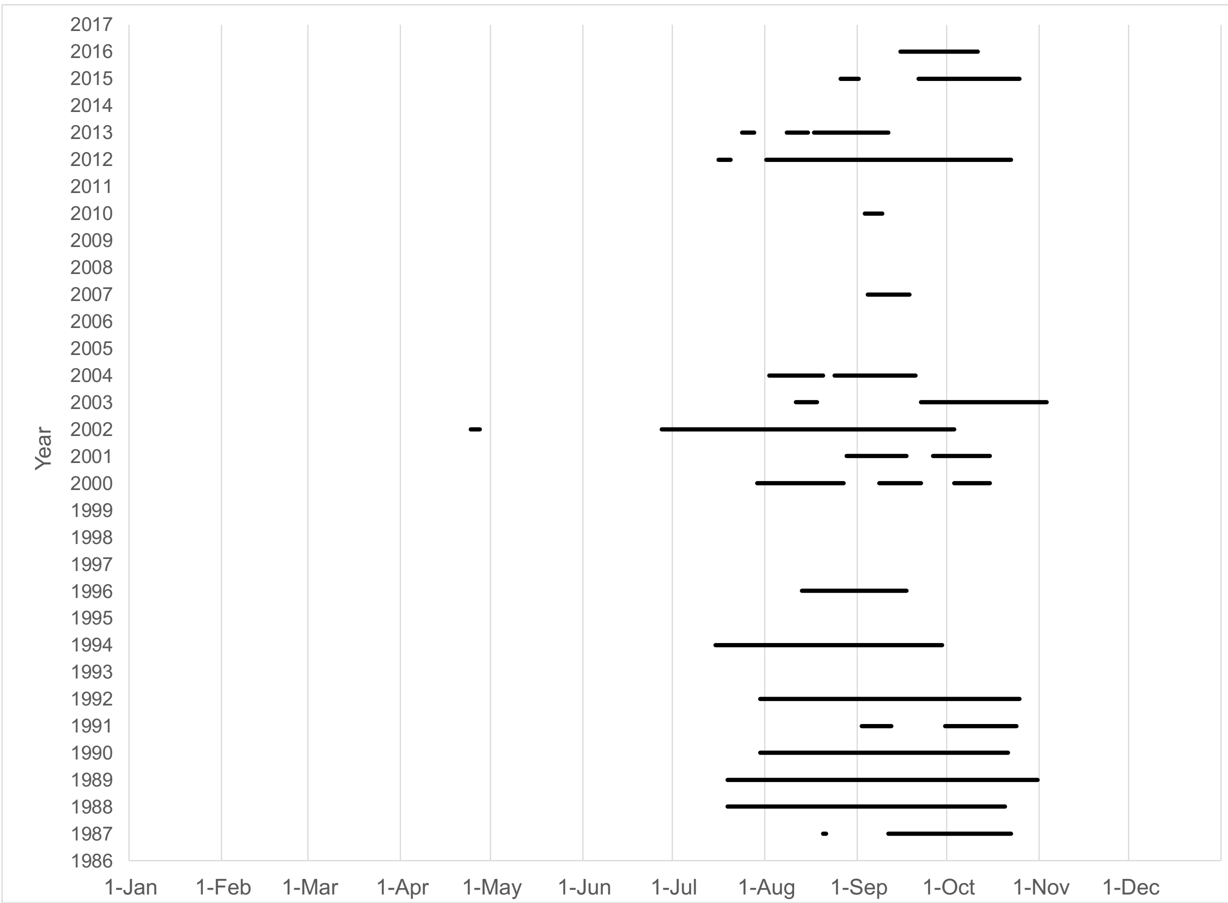

Figure 4: Historical occurrence of the Cameo Call, a collection of water rights near Grand Junction senior to IPTDS water rights

Diversions by the IPTDS are the primary cause of human-caused shortages, or aggravations to natural shortages, to the CWCB's 32 cfs instream flow right on the Upper Roaring Fork as measured as the Roaring Fork Near Aspen gage (09073400) during November through March, although most of the shortages during November through March are natural shortages, which are aggravated by IPTDS diversions. During these months, Roaring Fork ditches are not diverting and natural flows are already relatively low, typically close to the 32 cfs ISF right for the Upper Roaring Fork.

2.1.2 Grizzly Reservoir

Grizzly Reservoir is located on Lincoln Creek and is operating by Twin Lakes as part of the IPTDS collection system. The reservoir has a storage capacity of approximately 400 AF. It provides storage for water available to the Colorado River Water Conservation District and Pitkin County pursuant to the 95CW321 decree and several related agreements. It is also used by the public as a recreational reservoir. Water available from Grizzly Reservoir for West Slope uses, including releases to maintain minimum stream flows, comes from diversions made under Twin Lakes' IPTDS 1994 priority water rights, which do not divert reliably in every year, as mentioned above.

2.1.3 Salvation Ditch

The Salvation Ditch is owned and operated by the Salvation Ditch Company and diverts water from the Upper Roaring Fork for irrigation uses on McClain Flats. The point of diversion is approximately 100 feet downstream of the USGS stream gauge above Aspen. The Salvation Ditch's water right has an appropriation date of August 2, 1902, which is senior to the IPTDS water rights and the Cameo rights but is junior to the downstream Wheeler Ditch water right. The Ditch normally diverts from May through October. Diversions have ranged from as low as 3,400 AF per year to as high as 8,400 AF per year, averaging approximately 5,000 AF per year over the most recent 20 years (Figure 5).

Because of the relatively senior priority of its water right and the relatively large inflows to the Roaring Fork downstream of the Salvation Ditch's headgate, the Ditch's diversions are normally not limited by the Cameo call or by the demands of downstream Roaring Fork ditches, including demands of the Wheeler Ditch, a senior right located approximately 1.5 miles downstream of the Salvation Ditch's headgate. The Roaring Fork typically gains sufficient flow between the Salvation and Wheeler Ditch headgates that the Wheeler Ditch does not normally call out the Salvation Ditch. Salvation Ditch representatives have reported that the Ditch occasionally voluntarily reduces its diversions during critical dry spells to help support instream flows and downstream junior water users. Diversions by the Salvation Ditch are the primary cause of shortages to the Upper Roaring Fork between the Salvation Ditch headgate and the confluence with Castle Creek, although diversions by the Wheeler Ditch have caused aggravations to shortages in this reach.

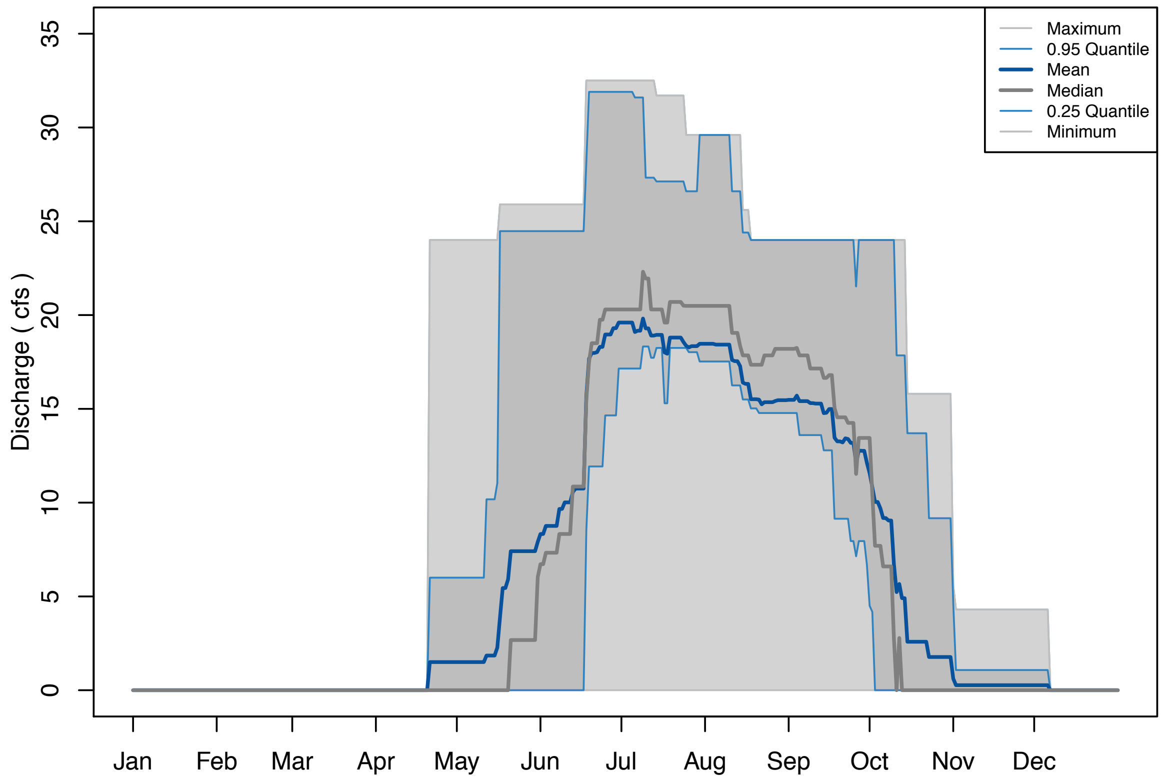

Figure 5. Historical reported diversion patterns for the Salvation Ditch.

2.1.4 Hunter Creek Collection System – Frying Pan Arkansas Project

The Hunter Creek Collection System portion of the Frying Pan Arkansas (FryArk) project is comprised of diversion dams at three locations - Hunter Creek, No Name Creek and Midway Creek. A series of tunnels convey the diverted water to the Boustead Tunnel, which delivers FryArk project diversions to Turquoise Lake in the Arkansas basin. FryArk diversions from the Hunter Creek system are subject to bypass requirements as needed to meet the CWCB's instream flow rights on Midway Creek, No Name Creek and on several segments of Hunter Creek. While the water rights of the FryArk project are junior to the Cameo rights, they are insulated from Cameo calls by replacement releases from Ruedi Reservoir. Daily diversions typically occur from mid-May through early July and typically peak at around 200 cfs (Figure 6). Annual diversions have averaged approximately 10,000 AF per year and have ranged from a low of approximately 2,800 AF (2002 and 2012) to a high of approximately 16,500 AF (2011).

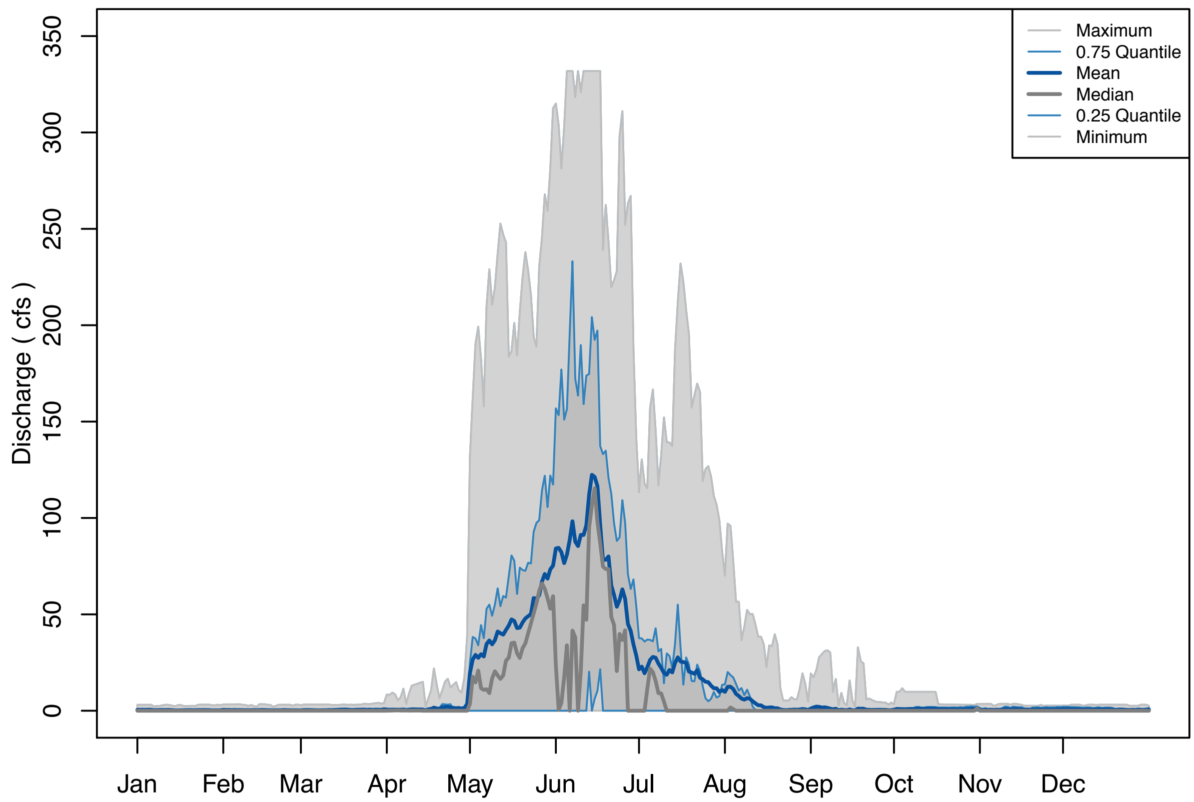

Figure 6. Historical reported diversion patterns for the Hunter Tunnel.

2.1.5 Wheeler Ditch

The Wheeler Ditch diverts from the Roaring Fork within the City of Aspen at a point about 1.5 miles downstream of the Salvation Ditch. It is owned by the City of Aspen and is used to irrigate lands associated with Aspen's storm water management facilities. The Wheeler Ditch is senior to the Salvation Ditch and to the Cameo rights and has never been called out by downstream Roaring Fork irrigation rights. Diversions have averaged about 4 cfs (Figure 7) and typically run from early May through late October (annual average ~1300 AF). Beginning in 2013, the City of Aspen has operated the Ditch to reduce diversions at times during the irrigation season when the CWCB's instream flow reach is not satisfied in the reach immediately below the Wheeler Ditch headgate.

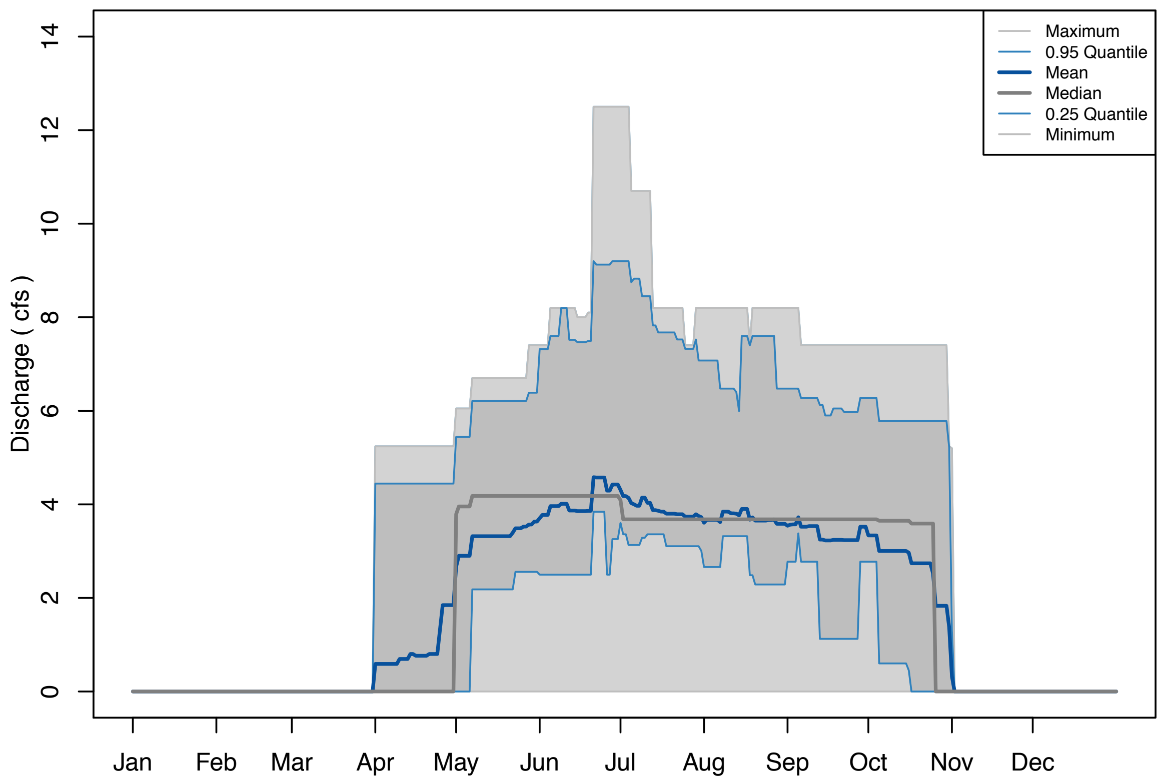

Figure 7. Historical reported diversion patterns for the Wheeler Ditch.

2.1.6 Red Mountain Extension Ditch

The Red Mountain Extension Ditch diverts from the lower reach of Hunter Creek and supplies water for irrigation to parcels located mainly on McClain Flats. The ditch diverts from early May to mid-October and a typical rate of 12 cfs (Figure 8). Historical annual diversions average about 3,600 AF per year and have ranged from about 800 AF to about 5,600 AF. The Red Mountain Extension Ditch's water rights are senior to the Cameo call.

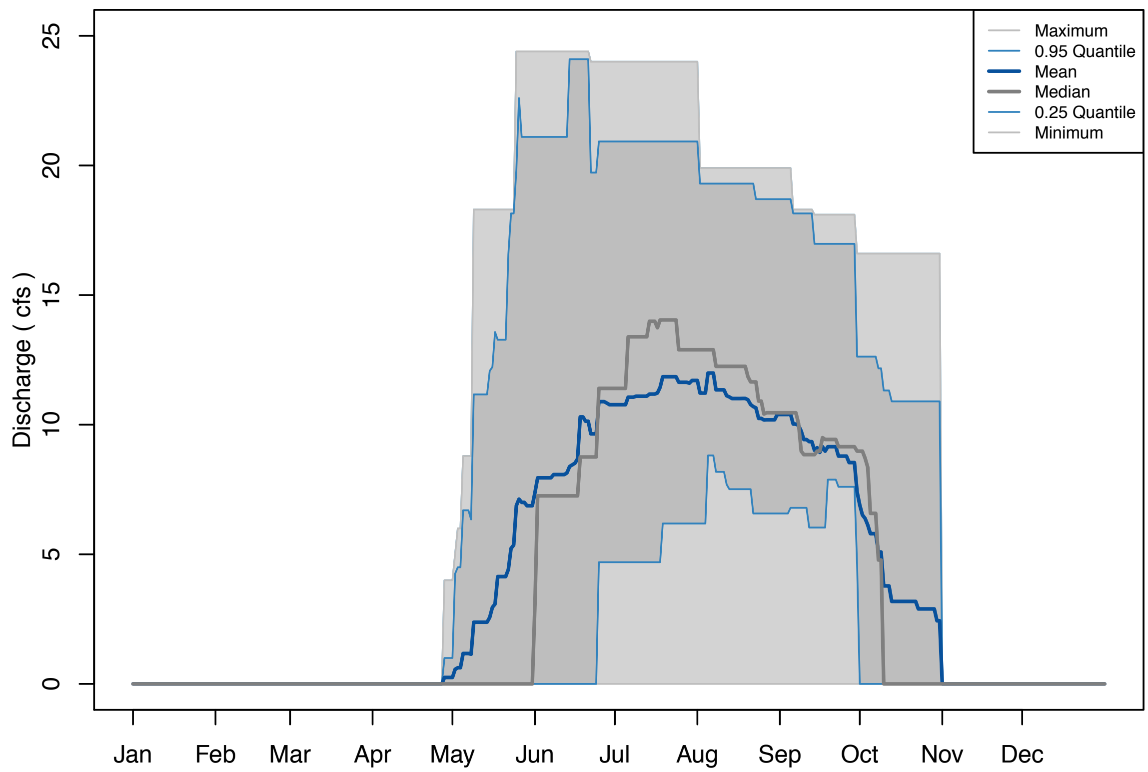

Figure 8. Historical observed diversion patterns into the Red Mountain Extension Ditch.

2.1.7 City of Aspen Water Supply System

The City of Aspen owns and operates its own water utility. The utility provides both treated and raw water supply to customers within its service area, as to other users via service contracts. Aspen's treated water system is supplied primarily by surface diversions from Castle Creek (Figure 9), supplemented by diversions from Maroon Creek and pumping of three municipal wells situated in the downtown Aspen area. These supplemental sources are used at times when surface supplies from Castle Creek are insufficient to meet Aspen's demands while maintaining minimum stream flows below Aspen's Castle and Maroon Creek diversions. Aspen's diversions from Castle and Maroon Creek are conveyed by pipelines to Thomas Reservoir (13 AF capacity), which provides short-term storage and supplies Aspen's water treatment plants located adjacent to the reservoir. Some of the water delivered to Thomas reservoir is released for raw water irrigation and snowmaking. Aspen has committed to operating its diversions to support the CWCB's instream flow rights below its points of diversion in all but extraordinary circumstance.

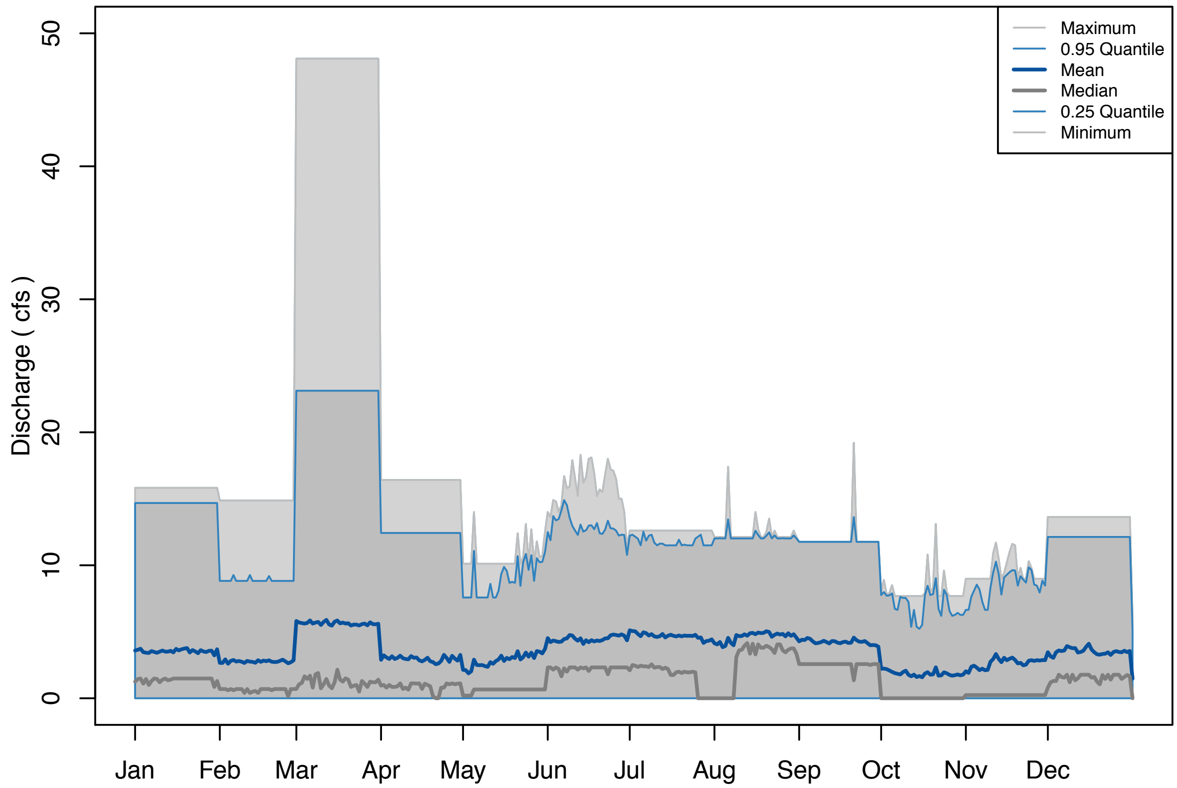

Figure 9. Historical reported diversion patterns into the Midland Flume, which carries water to Thomas Reservoir.

The City of Aspen also operates the Maroon Creek hydropower project (Figure 10), a run-of-river project that diverts water from Maroon Creek above Willow Creek and returns the diverted water to Maroon Creek at a downstream location without depletion.

Several ditch systems that divert from the Roaring Fork and Castle Creek to provide raw water for the downtown mall, fountains, aesthetic features, irrigation of street trees and private properties, the municipal golf course, Marolt Open Space and the Red Butte cemetery. Aspen's combined diversions from Castle and Maroon Creek for uses other than Maroon Creek hydropower have averaged about 5,200 AF per year.

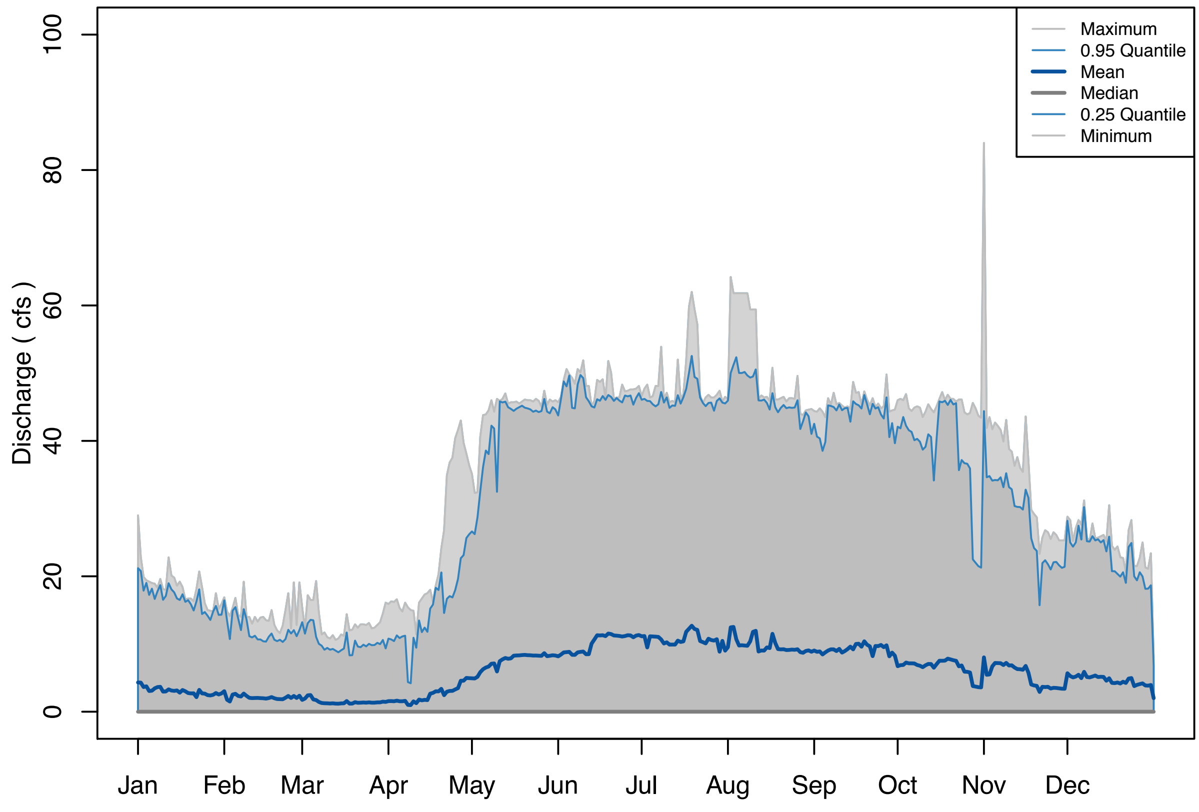

Figure 10. Historical diversion patterns reported for the Maroon Ditch, which supplies flow to the Maroon Hydropower Plant.

Aspen's municipal water supply system operates without a significant amount of available surface storage, which is unusual for municipal water supply systems of similar size. Aspen owns conditional storage rights on Castle and Maroon Creek, which Aspen is considering developing. In recognition of the problematic aspects of building a significant new reservoir on Castle or Maroon Creek, Aspen has contracted to purchase two adjoining parcels of land near Woody Creek for potential use as an alternate off-channel water storage reservoir for its conditional water rights.

3. Decision Support Tool Development

To provide estimates of streamflow at additional points intermediate to or above locations where historical data is available and at points above and below surface water diversions, this project employed a variety of methodologies. Regression models, point-flow spreadsheet models, and water rights simulation models were created to provide different types of information about patterns of streamflow. Development of each required approximating the administration of Colorado Water Law in order to produce daily timestep estimates of water availability, water demand, patterns of local use, and discrepancies between use needs and water supply. These decision support tools enable retrospective analysis of surface water hydrology in the upper Roaring Fork and will allow City and County staff and their consultants to test "what-if" water use and management scenarios in a consistent and data-driven manner in the future. Notably, daily hydrological simulation models may be useful to the City's ongoing efforts to understand impacts of climate change on its water supplies and its future ability to simultaneously meet municipal demands, contract obligations, and the needs of the environment.

3.1 Point Flow Model Development

The simplest method for estimating streamflows at locations where observed data records do not exist is to create an additive water balance model in a spreadsheet. This approach, sometimes termed 'point-flow' modeling relies on observed streamflows, reported surface water diversions, and some knowledge of network structure, stream gains and losses, and return flow timing and allocation. In the upper Roaring Fork watershed, this modeling approach was used to characterize hydrological regime behavior on 13 stream segments. The model estimated daily streamflows using only historical streamflow observations from USGS and CDWR and records of daily water diversion available from CDWR in the HydroBase system. This approach yielded streamflow time series of different lengths, covering different periods of time at different locations in the watershed. The long streamflow records available on the Roaring Fork River above Aspen and on Hunter Creek above the Red Mountain Ditch enabled computation of streamflow at upstream and downstream points between 1975 and 2013. Limited streamflow records on Castle Creek and Maroon Creek, conversely, limited estimates of streamflow in those drainages to the period between 1975 and 1995. The spreadsheet model computes daily flow percentiles for each day in the calendar year using the full record of estimated flows on each reach. Users may define different drought or flood conditions of interest by selecting daily flow percentiles for model output that correspond to 'Dry', 'Average', and 'Wet' conditions.

The primary purpose of point flow model development is to allow stakeholders and water managers to understand how historical patterns of streamflow and water use impacted water availability for environmental needs in low-flow periods. To do this, the model allows users to assign low-flow thresholds for each reach. Thresholds may correspond to CWCB ISF rights, to Fryingpan-Arkansas Project Operating Principals, to recommendations made in special studies, or to user-defined values. Daily flows on each reach are compared against thresholds to calculate the magnitude, timing and duration of environmental water use shortages under the selected hydrological year types. The model generates estimates of shortages under natural (no-use) conditions, and existing (historical-use) conditions. Calculating both provides users with important information for placing estimates of environmental use shortages in context with limitations imposed by natural water availability.

Total Dry Year Shortages:	Roaring Fork River below Lost Man Creek	Lincoln Creek below New York Creek	Roaring Fork River above Difficult Creek	Roaring Fork River at North Star	Roaring Fork River below Wheeler Ditch	Hunter Creek below Red Mountain Ditch
Total Days Below Threshold (Count)	301	195	196	176	262	304
Total Days Above Threshold (Count)	64	170	169	189	103	61
Summer Days Below Threshold (Count)	150	44	45	25	111	153
Total Shortage (af)	3418	1144	2780	2776	6107	14193
Summer Shortage (af)	1145	97	1693	145	3330	6691

Figure 11. Example output from the point flow spreadsheet model.

The largest limitations of the point-flow model are its reliance on historical records and its focus on low-flow thresholds. This is particularly true where patterns of water use changed significantly over the last 40 years and where historical water management is no longer an appropriate proxy for understanding current or future use. It is also problematic on reaches where the primary question of interest involves the impact of water management on peak flow timing, duration, and magnitude. Therefore, outputs from the point flow model are best suited for understanding the historical context that shapes the current condition of riparian areas, aquatic biota, and other elements of riverine landscapes impacted by low-flow alteration. Different tools are required to help managers and stakeholders understand the impact of current or future water management actions (or climate change) on all components of hydrological regime behavior.

3.2 Water Rights Simulation Model Development

Understanding the complex interplay between inflow hydrology and the exercise of surface water diversion rights under Colorado water law requires a water rights allocation and accounting model. Gauge records, diversion histories, and, optionally, rainfall/runoff simulations provide the inputs necessary to build a functioning simulation model for local streams and rivers. Hydrological simulations for the Roaring Fork River and its tributaries were initially produced by modifying the State of Colorado Stream Simulation Model (StateMod) developed by the Colorado Water Conservation Board (CWCB) for the Colorado River Basin.[12] The basic CWCB StateMod model simulates inflows, surface water diversion, crop usage, ground- and surface-water return flows, reservoir operations, in-stream demands, reservoir operations, and augmentation plans on a monthly time step. For computational efficiency, the model combines multiple simulation objects (such as diversions or instream flow points) into aggregated modelling nodes.

The CWCB model was refined for this project. Aggregated simulation nodes in the upper Roaring Fork watershed were disaggregated (or split apart into separate objects) and the simulation time step was refined downward from monthly to daily. Updated data records provided by Colorado Decision Support System (CDSS) databases, the local Water Commissioner, and municipal water managers were integrated into the model to produce a more robust and accurate simulation of local water allocation and accounting. Diversions were updated with ditch capacities, return flow locations, and estimates of ditch loss. The refined StateMod model characterized the impacts of management actions and changing hydrological conditions on average daily streamflow at numerous locations across the watershed (Figure 12). In order to accommodate important administrative actions on the mainstem Colorado River, the model actually includes rivers and diversion locations across the entire Colorado River basin.

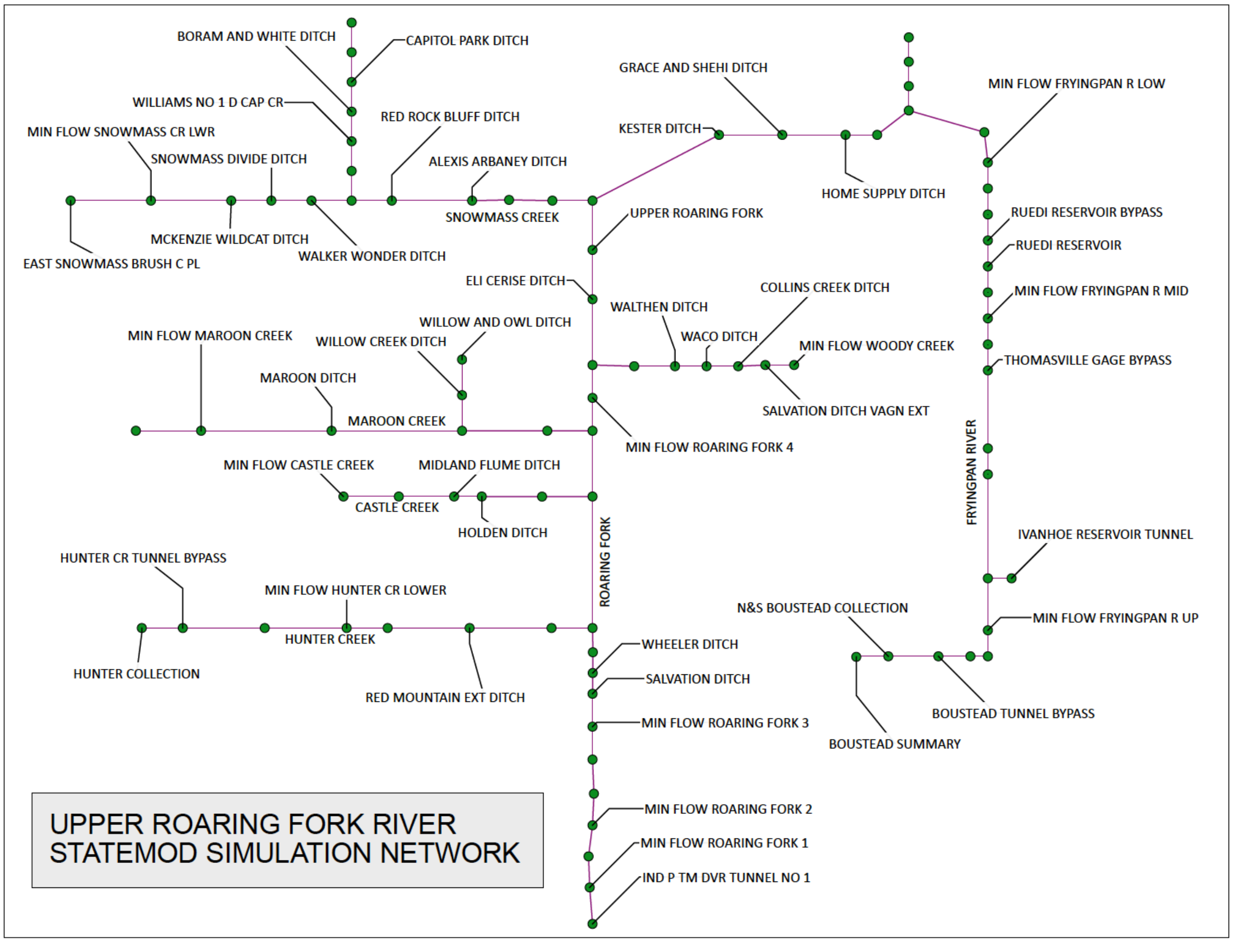

Figure 12. Portion of the StateMod simulation network covering the upper Roaring Fork watershed.

Several conversations with local water managers and City of Aspen staff subsequent to refinement of the StateMod model indicated some dissatisfaction with complexities and steep learning curve associated with use of StateMod. These potential users of the decision support tools developed under the Roaring Fork River Management Plan indicated a strong preference for more user-friendly modeling environment. In response, we developed a MODSIM-DSS model for the upper Roaring Fork watershed. The MODSIM model network included the mainstem Roaring Fork River, major tributaries, and major surface water diversions (Figure 13). Simulations covered the period between 1975 and 2013. The hydrological variability observed over this period provides a baseline for expected hydrological behavior on top of which climate change or water management scenarios can be built.

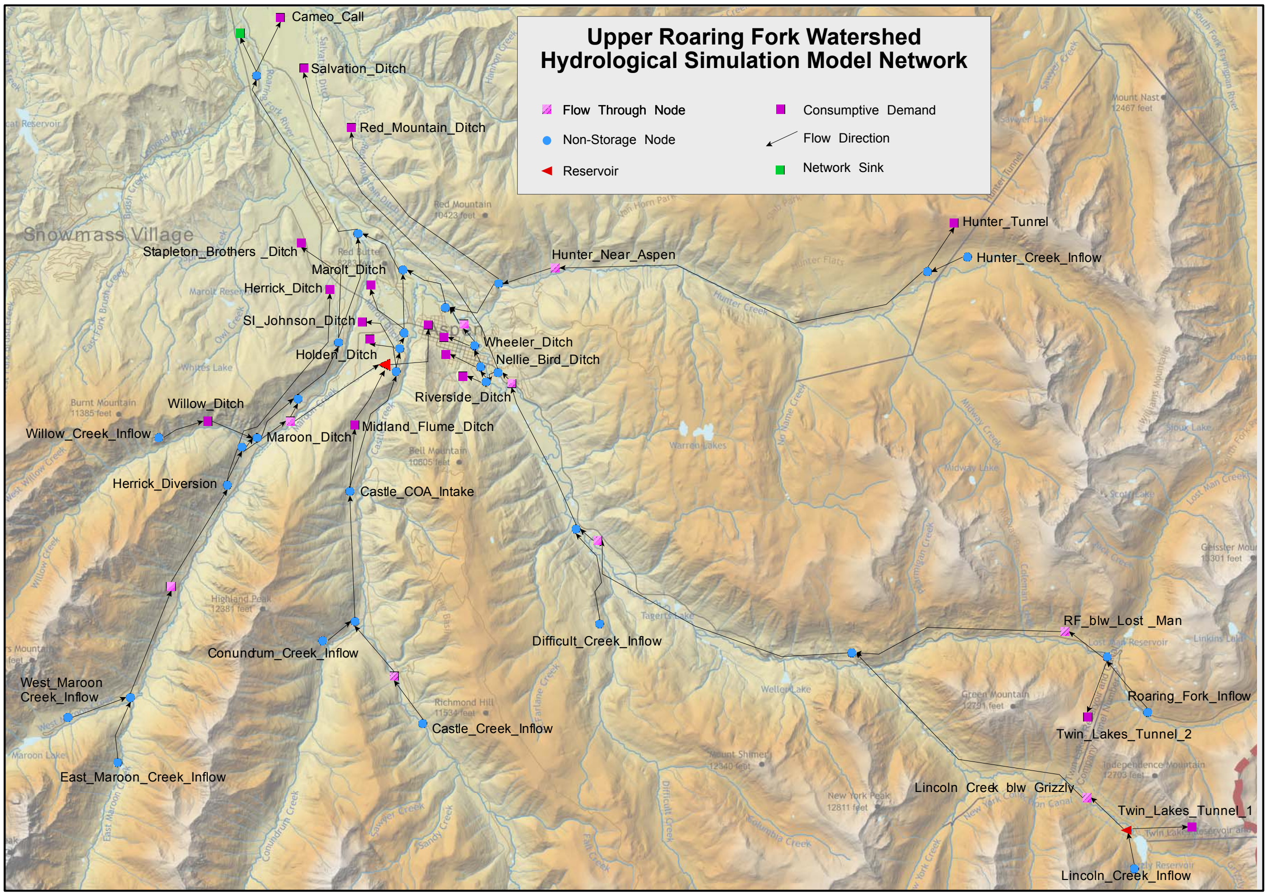

Figure 13. MODSIM-DSS simulation network for the upper Roaring Fork Watershed

3.2.1 Inflow Hydrology

Where suitable diversion records and long observed streamflow data sets exist, inflow hydrology over the period of interest can be computed directly. This is the case on Hunter Creek above Red Mountain Ditch and on the Roaring Fork River at the North Star Preserve. At both of these locations, calculating natural flows involved adding historical transmountain diversion records to the observed streamflows. Flows were then distributed among the upstream tributaries and contributing basins using the watershed area ratio approach. On the Roaring Fork River, 16% of the flows were allocated to the mainstem above the IPTDS diversion, 11% to the confluence with Ptarmigan Creek, 26% to Lincoln Creek and its tributaries above the

IPTDS collection system, 4% to lower Lincoln Creek, 15% to the segment tributaries near Tagert Lakes, and 28% to Difficult Creek. In the Hunter Creek drainage, 40% of the naturalized flow was allocated to Hunter Creek and its tributaries above the FryArk collection system and 60% was allocated between those collection points and the downstream USGS gauge.

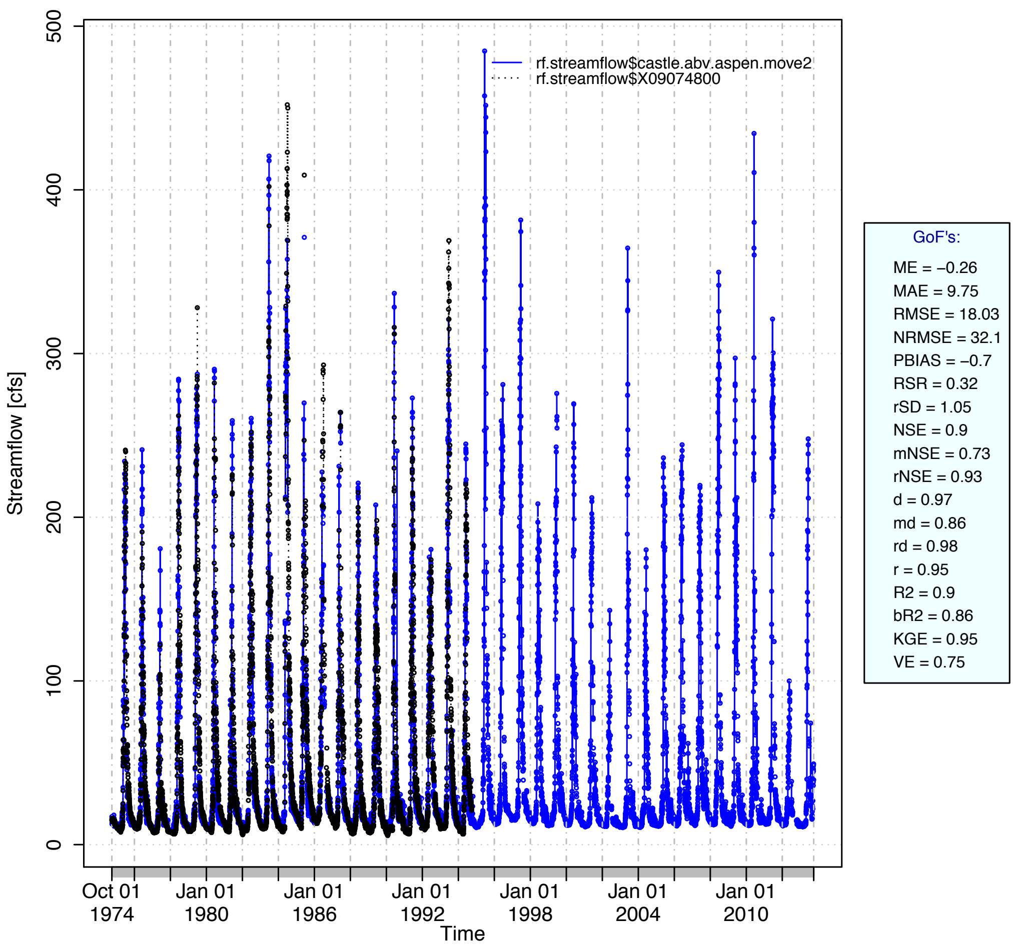

Figure 12. MOVE.2 model for streamflows at USGS gauge on upper Castle Creek. Black line is observed data, blue is simulated.

Calculation of natural flows on Castle Creek and Maroon Creek over the period of interest required extension of the observed records at the historical USGS gauges on each creek. Records on Castle Creek (USGS-09074800) were extended by applying the Maintenance of Variance 2 (MOVE.2) function in the smwrStats package in the R statistical computing environment. The naturalized flow records from the USGS gauge at North Star Preserve was selected as the reference data set. The function was applied using a lognormal distribution and a lag of 3 days. Flows on Maroon Creek were also filled by applying the MOVE.2 methodology. Prior to filling, diversions at the Herrick Ditch were added to the observed flows at the Maroon Creek gauge (USGS-09075700). The naturalized flow records from the USGS gauge at North Star Preserve was selected as the reference data set. The function was applied using a lognormal distribution and a lag of 5 days. The fitted streamflows for each location (Figure 12, 13) (Table 3) were deemed suitable for inclusion in the model and were subsequently used as the upstream boundary condition for each creek.

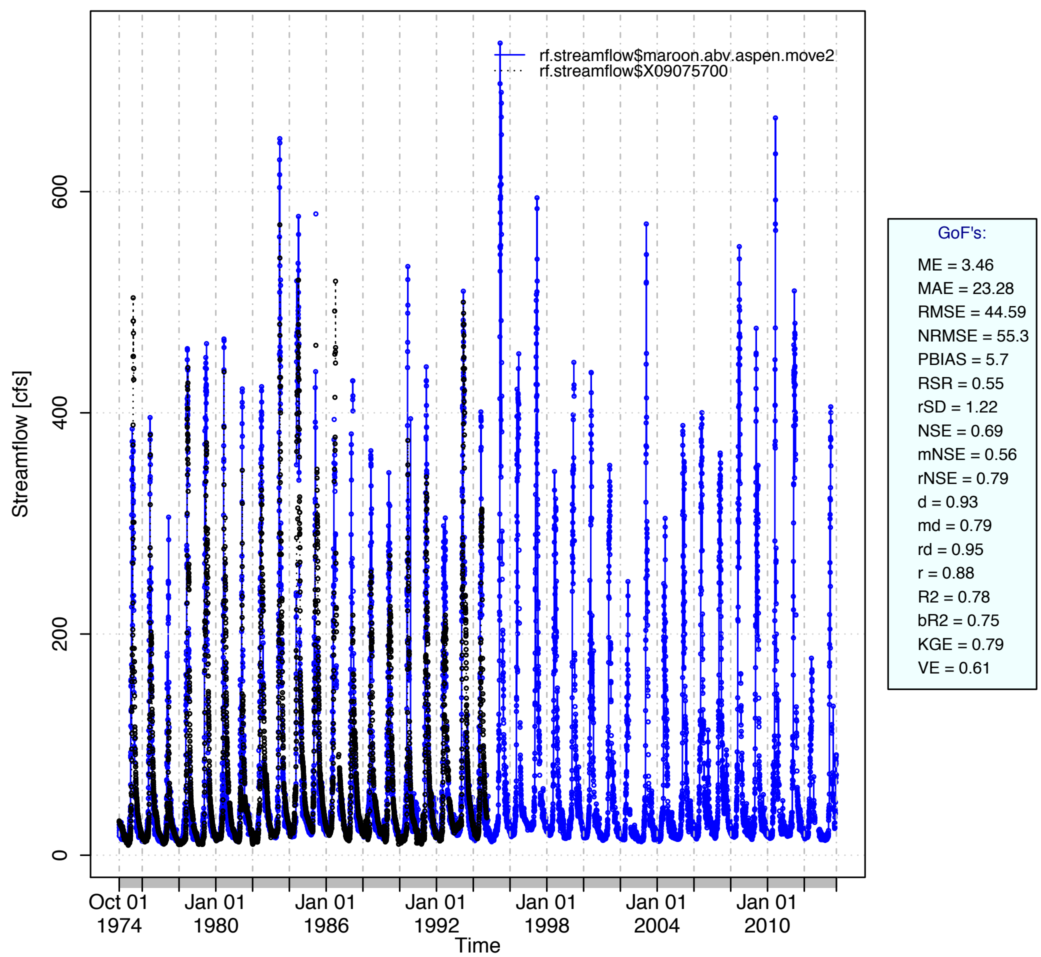

Figure 13. MOVE.2 model for streamflows at USGS gauge on upper Maroon Creek. Black line is observed data, blue is simulated.

Table 3. Goodness-of-fit measures applied to assess model fit.

Abbreviation	Measure Description
me	Mean Error
mae	Mean Absolute Error
rmse	Root Mean Square Error
nrmse	Normalized Root Mean Square Error
PBIAS	Percent Bias
pbiasfdc	PBIAS in the slope of the midsegment of the Flow Duration Curve
RSR	Ratio of RMSE to the Standard Deviation of the Observations, RSR = rms / sd(obs). (0 <= RSR <= +Inf)
rSD	Ratio of Standard Deviations, rSD = sd(sim) / sd(obs)
NSE	Nash-Sutcliffe Efficiency (-Inf <= NSE <= 1)
mNSE	Modified Nash-Sutcliffe Efficiency
rNSE	Relative Nash-Sutcliffe Efficiency
d	Index of Agreement (0 <= d <= 1)
md	Modified Index of Agreement
rd	Relative Index of Agreement
cp	Persistence Index (0 <= PI <= 1)
r	Pearson product-moment correlation coefficient (-1 <= r <= 1)
r.Spearman	Spearman Correlation coefficient (-1 <= r.Spearman <= 1)
R2	Coefficient of Determination (0 <= R2 <= 1). Gives the proportion of the variance of one variable that is predictable from the other variable
bR2	R2 multiplied by the coefficient of the regression line between sim and obs (0 <= bR2 <= 1)
KGE	Kling-Gupta efficiency between sim and obs (0 <= KGE <= 1)
VE	Volumetric efficiency between sim and obs (-Inf <= VE <= 1)

Stream gains and tributary contributions below the inflow locations on Castle Creek and Maroon Creek were estimated using the watershed area ratio approach. Total surface water flows for the Maroon Creek watershed were estimated as 165% of the filled gauge record from upper Maroon Creek. Seventy percent of this flow was allocated back to Maroon Creek above the Herrick Ditch, 25% for Willow Creek above the Willow Ditch, 3% above the Maroon Hydropower Plant outfall, and 2% on the short segment above the confluence with the Roaring Fork River. A limited streamflow record on lower Castle Creek (USGS-09075400) provided opportunity for a more refined approach to distributing flows in that drainage. Flows for the entire Castle Creek drainage were first estimated as 230% of the filled record from the gauge on upper Castle Creek. These flows were then modified to match downstream flow records by raising them to the 0.94 power. The final estimated flows were distributed back to points in the

Castle Creek drainage such that 96% accrued to Castle Creek above the Midland Flume and 4% accrued at the confluence with Keno Gulch.

Synthetic regional groundwater inflows contributing to streamflows on the Roaring Fork River and its tributaries above Brush Creek were computed by conducting a baseflow separation on the time series of naturalized streamflows on the Roaring Fork River at North Star Preserve. Daily baseflow values over the period of interest were estimated by applying a Lynne-Hollick (LH) baseflow filter from the hydroStats package in the R statistical computing environment. The LH filter was set to 0.985 and the number of burn-in days was set to 30. Estimated baseflows were distributed to the major tributary watersheds in the upper Roaring Fork located below the USGS gauge above Aspen using the watershed area ratio approach such that 40% of the flows accrued to the mouth of Castle Creek, 30% to the mouth of Maroon Creek, 20% to the mouth of Hunter Creek, and 10% to the Roaring Fork below the Wheeler Ditch. Groundwater contributions to streamflow are notoriously difficult to measure directly. However, first principals in watershed hydrology and limited direct measurement of streamflow gains on the Roaring Fork River through the City of Aspen suggest that inclusion of some estimate of groundwater contribution to streamflow should make simulations more accurate. In fact, inclusion of these baseflows as a proxy for regional groundwater contributions greatly assisted in calibration of simulated low flows to observed streamflows at the CDWR gauge in the Roaring Fork Gorge (CDWR-ROABMCCO).

Using the approaches outlined above, estimates of regional groundwater and flow on Castle Creek and Maroon Creek require only the naturalized flow record from the USGS streamgauge in the North Star Preserve (USGS-09073400). Use of this gauge as the index station was intentional, as this gauging station is included in numerous regional and state-sponsored assessments of the impact of climate change on streamflows. Incorporating climate change impacts in future application of the model is thus simplified. Impacts on groundwater and tributary flows (excepting Hunter Creek) may be rapidly estimated through reapplication of the above methodologies to the predicted streamflow timeseries for USGS-09073400.

3.2.2 Water Demands

Water demands for transmountain diversions were set equal to the 95th percentile of weekly historical diversions measured between 2000-2015. The same approach was used for the Wheeler Ditch, Nellie Bird Ditch, Salvation Brothers Ditch and Riverside Ditch where diversions are not strongly tied to crop water requirements. A special study commissioned by the City of Aspen (Wilson Water Group, 2016) provided water demands at the Midland flume for treated municipal supply, snowmaking, etc. Hydropower demands on Maroon Creek were assumed equal to the absolute decreed rate for the Maroon Ditch. Irrigation water demands associated with most other diversions in the system were extracted from StateCU and the StateMod model described previously. The general approach calculated Irrigation Water Requirement (IWR) based on the irrigated acreages associated with each diversion structure, observed precipitation and air temperature between 1975-2013, and the type of crop irrigated at each location. The efficiency of water conveyance and delivery system was then estimated by comparing the IWR to the historical diversion record (Table 4). Infiltration fractions were then estimated by subtracting the irrigation efficiency from 1.0 (Table 5). The maximum diversion rate for each structure was set equal to the absolute adjudicated water right.

Table 4. Irrigation efficiencies evaluated for MODSIM diversion nodes. Values calculated as [Irrigation Water Requirements] – [Historical Diversions].

Month	Salvation Ditch	Red Mountain Ext. Ditch	Midland Flume	Holden Ditch	Herrick Ditch	Willow Creek Ditch
Oct	0.03	0.06	0.26	0	0.01	0.02
Nov	0	0	0	0	0	0
Dec	0	0	0.1	0	0	0
Jan	0	0	0.1	0	0	0
Feb	0	0	0.12	0	0	0
Mar	0	0	0.14	0	0	0
Apr	0.34	0.6	0.44	0	0.17	0
May	0.19	0.35	0.55	0.01	0.16	0.24
Jun	0.13	0.19	0.62	0.07	0.07	0.15
Jul	0.11	0.16	0.61	0.07	0.05	0.14
Aug	0.06	0.09	0.56	0.05	0.02	0.07
Sep	0.05	0.1	0.44	0.01	0.02	0.04

Table 5. Infiltration fractions applied to MODSIM diversion nodes calculated as 1 – [Irrigation Efficiency].

Month	Salvation Ditch	Red Mountain Ext. Ditch	Midland Flume	Holden Ditch	Herrick Ditch	Willow Creek Ditch
Oct	0.97	0.94	0.74	1	0.99	0.98
Nov	1	1	1	1	1	1
Dec	1	1	0.9	1	1	1
Jan	1	1	0.9	1	1	1
Feb	1	1	0.88	1	1	1
Mar	1	1	0.86	1	1	1
Apr	0.66	0.4	0.56	1	0.83	1
May	0.81	0.65	0.45	0.99	0.84	0.76
Jun	0.87	0.81	0.38	0.93	0.93	0.85
Jul	0.89	0.84	0.39	0.93	0.95	0.86
Aug	0.94	0.91	0.44	0.95	0.98	0.93
Sep	0.95	0.9	0.56	0.99	0.98	0.96

3.2.3 Water Rights Administration

The water rights extension in MODSIM was used to simulate administration of water in the upper Roaring Fork watershed according to Colorado water law. Each water right at each diversion structure was given a negative cost value corresponding the administration number assigned by DWR such that increasing negative values represent more senior water rights (Table 6). Bypass flows maintained by the City of Aspen at the Maroon Ditch and Midland Flume for environmental benefit were included as separate water demands and given a slightly higher priority than the most senior right at the corresponding structure, even though these bypasses are not decreed uses of water and cannot, technically, be administered with the same priority as the diversion right. Therefore, use of the model for evaluating some scenarios may require modification of this priority setting; particularly where upstream junior water rights have claim to bypassed flows. Bypass requirements at TMDs were treated as water demands with a higher priority than the associated structure to ensure they are always met (to the degree that they can be given native inflow hydrology). Effects of administration of the Cameo Call on the IPTDS was handled by extracting the simulated call for water in the StateMod model described previously. In this way, the impacts of 'big-river' administration are accounted for in the model without requiring simulation of streamflows, reservoir operations, diversions, etc. across the entire Colorado River basin directly.

Table 6. Diversion structures and water rights included in the MODSIM model.

Structure WDID	Absolute Rate	Unit	Adjudication Date	Admin. Number	MODSIM Cost
3800749	9	cfs	10/1/1890	31648.1488	-295
3801790	1	cfs	5/15/1884	12554.0000	-480
3800981	58	cfs	8/2/1902	20041.1921	390
3801091	10	cfs	9/1/1882	11932.0000	-490
3800963	3	cfs	6/1/1888	30941.1403	-340
3800904	4	cfs	6/9/1885	30941.1294	-350
3800755	4	cfs	1/10/1926	30941.2777	-320
3800755	19	cfs	3/1/1902	30845.1905	-360
3800755	30	cfs	8/27/1950	36763.0000	-280
3800854	3	cfs	7/10/1889	15799.1444	-410
3801026	8	cfs	6/30/1904	30523.1990	-370
3801101	3	cfs	7/1/1885	12966.0000	-470
3804617	625	cfs	8/23/1930	30941.2945	-310
3800869	60	cfs	11/16/1885	15515.1310	-430
3800869	100	cfs	5/11/1889	15515.1438	-420
3801101	3	cfs	5/1/1887	13635.0000	-460
3801101	30	cfs	4/15/1891	15514.1508	-440
3801101	4	cfs	12/22/1989	51125.0000	-120
3800749	52	cfs	8/1/1951	37552.3710	-270
3800749	4	cfs	12/22/1989	51125.0000	-120
3800904	1	cfs	4/30/1989	52230.5089	-100
3800755	2	cfs	5/1/1932	30941.3007	-300
3801026	6	cfs	9/22/1960	40442.0000	-250
3801026	2	cfs	6/1/1977	46751.4654	-170
3801790	13	cfs	11/27/1888	14211.0000	-450
3801790	6	cfs	4/3/1909	25618.2164	-380
3801790	4	cfs	9/3/1915	30941.2399	-330
3801790	1	cfs	6/11/1990	51296.0000	-100
3801790	1	cfs	12/11/2001	56247.5550	-90
3801790	1	cfs	10/15/2004	56536.0000	-80
3800981	1	cfs	12/26/1989	51129.0000	-110
3800854	65	cfs	8/12/1892	32907.1557	-290
3801594	270	cfs	7/29/1957	39291.0000	-260
3802049	32	cfs	1/14/1976	46034.0000	-220
3802023	8	cfs	1/14/1976	46034.0000	-220
3802050	10	cfs	1/14/1976	46034.0000	-220
3802015	12	cfs	1/14/1976	46034.0000	-220
3802027	14	cfs	1/14/1976	46034.0000	-220
3802111	55	cfs	11/8/1985	49620.0000	-150
3802000	14	cfs	2/26/1975	45712.0000	-240
3802000	16	cfs	1/31/1979	47147.0000	-160
3802039	15	cfs	1/14/1976	46034.0000	-220
3801763	322	cfs	8/25/1936		-310

3.2.4 Baseline simulation Model Performance

Simulations yielded a 38-year data set extending from 1975 to 2013. Model performance was evaluated by comparing simulation results against measured streamflows at several gauging stations (Figure 14). Goodness-of-fit measures provided indications of times and locations where simulation results most accurately reflected observed conditions (Table 3). The revised model performed well at mainstem Roaring Fork River locations, particularly during low flows. A lack of long-term historical records and difficulty in simulating the operation of the IPTDS produced some uncertainty below the IPTDS diversion point on the upper Roaring Fork River near Lost Man Creek. Difficulty simulating IPTDS and FryArk responses to reservoir operations on in the Arkansas Basin may cause artificially high peak flows in some years in the simulation model.

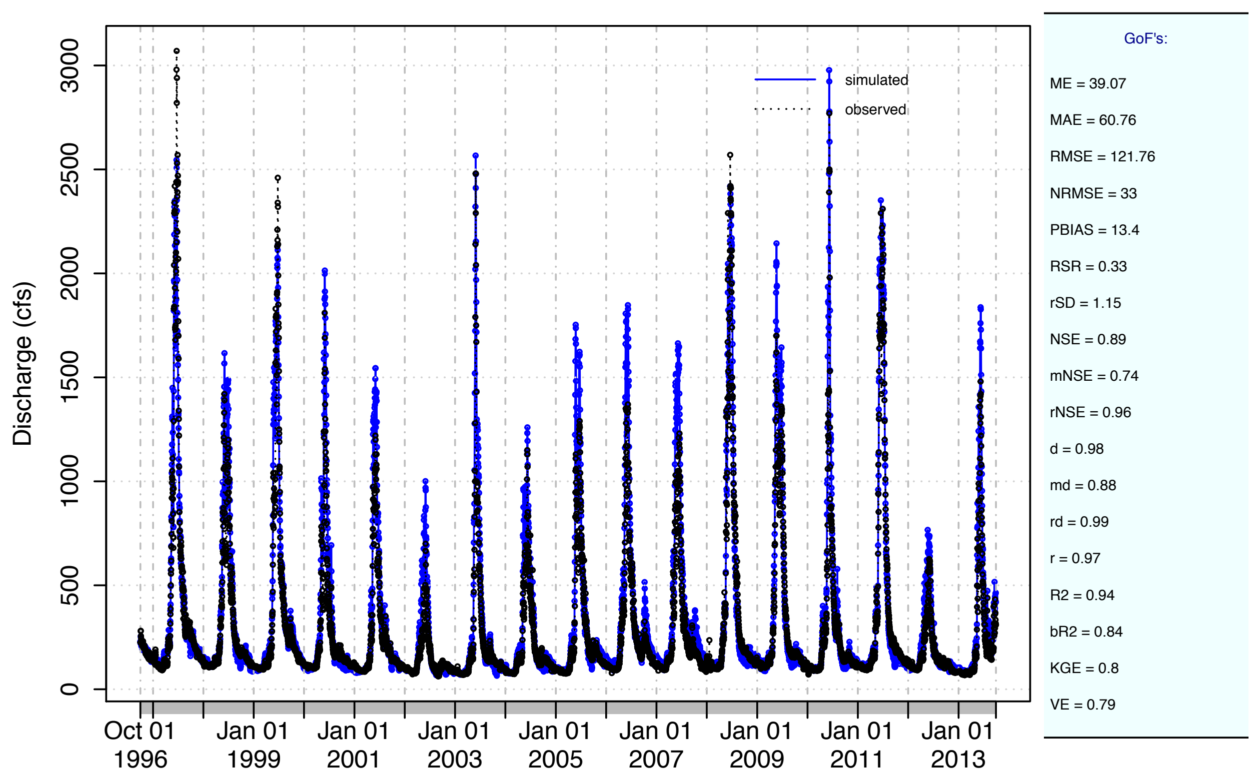

Figure 14. Simulated and observed streamflows in the Roaring Fork Gorge at CDWR-ROABMCCO.

3.2.5 Scenario Development

The most appropriate application of the decision support tools developed here requires development of paired pre- and post-condition simulations. The pre- and post-condition scenarios discussed here represent: 1) the 'natural' condition that would exist in the absence of human water use or management activities, and 2) the 'current' condition as it is affected by existing patterns of water use and administration. In the context of the Roaring Fork River Management Plan, these two scenarios provide useful information for understanding the degree to which water management activities altered the natural hydrological template—an important driver of ecological and geomorphological conditions. Appropriate application of simulation results relies on comparative analysis of the modeled pre- and post-condition scenario results and not their individual characterization as precise estimates of historical or future conditions. In the future, local stakeholders and water managers may build upon these scenarios as a means for developing simple or complex impact assessments of climate change, reservoir development, water rights leasing, etc. on patterns for flow throughout the upper Roaring Fork watershed.

4. Hydrological Regime Behavior

Hydrology in the upper Roaring Fork watershed is dominated by snowmelt runoff and impacted by patterns of water use at all times of the year. Peak flows increase with increasing watershed size. The summer and fall are typically characterized by a short recession of peak flows followed by a period of stable low flows between early fall and late spring. The IPTDS and the Fryingpan-Arkansas Project impact peak flow timing and magnitude on downstream river segments. The IPTDS completely dewaters portions of the upper Roaring Fork River for significant periods each year. Late summer water depletions in the lower watershed on the mainstem Roaring Fork create some discontinuities in longitudinal patterns in flow magnitude and low-flow duration. The effects are most prominent on lower Hunter Creek and on the Roaring Fork River between the North Star Preserve and the confluence with Castle Creek. Identification of locations across the watershed where management activities appear to impact the hydrological regime most significantly provides indication of stream reaches where additional management actions may propagate positive or negative changes to measures of river health and resiliency.

4.1 Hydrological Alteration

Hydrological simulation results elucidate the convergence of climate, stream network structure, and patterns of water use that dictate the ability of local streams and rivers to meet the full array of existing uses in different year types. Understanding the ability of the Roaring Fork River and its tributaries to meet both human and ecosystem begins with characterization of the range of hydrological conditions throughout the watershed and the degree to which these conditions are impacted by management activities.

An analysis of hydrological regime behavior at locations throughout the Roaring Fork watershed considered 30 measures of hydrological behavior (Table 7). Metrics characterizing flow magnitude, duration, and rate of change were derived through statistical examination of the entire 38-year simulation period at each node in the modelling network. Results covered a range of wet, average, and dry hydrological conditions. Three flow percentiles (0.75, 0.5, 0.25) were selected to approximate moderate-wet, average, and moderate-drought conditions. Indices of hydrological alteration were computed by first characterizing hydrological regime behavior under each scenario at each simulation node using the IHA package in the R statistical computing environment. Output yielded measures of the metrics presented in Table 7 for each year in the simulation period. Annual values where then summarized into three aggregated sets corresponding to each of the threshold flow percentiles identified above. The percent change in each measure of hydrological behavior was subsequently derived by comparing results from the existing conditions scenario to the results from the natural conditions scenario (Table 8, 9, 10).

Table 7. Measures of hydrological regime behavior assessed throughout the upper Roaring Fork watershed.

Variable	Units	Description
April	cfs	April mean daily discharge
August	cfs	August mean daily discharge
December	cfs	December mean daily discharge
February	cfs	February mean daily discharge
January	cfs	January mean daily discharge
July	cfs	July mean daily discharge
June	cfs	June mean daily discharge
March	cfs	March mean daily discharge
May	cfs	May mean daily discharge
November	cfs	November mean daily discharge
October	cfs	October mean daily discharge
September	cfs	September mean daily discharge
1 Day Max	cfs	Daily mean dischage, maximum daily obs of daily mean discharges
1 Day Min	cfs	1 day minimum for daily mean discharge
3 Day Max	cfs	Maximum of 3-day means of daily discharge
3 Day Min	cfs	Minimum of 3-day means of daily discharge
7 Day Max	cfs	Maximum of 7-day means of daily discharge
7 Day Min	cfs	Minimum of 7-day means of daily dischrage
30 Day Max	cfs	Maximum of 30-day means of daily discharge
30 Day Min	cfs	Minimum of 30-day means of daily discharge
90 Day Max	cfs	Maximum of 90-day means of daily discharge
90 Day Min	cfs	Minimum of 90 day means of daily discharge
Base index	ratio	Ratio of 7-day minimum flow to mean annual flow (7 day min / mean annual)
Zero flow days	count	Number of no-flow days
Max	Julian day	Date of peak flow, in Julian days 1-365 from January 1
Min	Julian day	Date of minimum flow, in Julian days 1-365 from January 1
High pulse length	days	Mean duration of high pulses
High pulse number	count	Mean number of high pulses within each water year
Low pulse length	days	Mean duration of low pulses
Low pulse number	count	Mean number of low pulses within each water year
Fall rate	cfs/day	Mean of all negative differences between consecutive daily flow values
Reversals	count	Number of hydrologic reversals (dropping flow changing to rising and vice-versa)
Rise rate	cfs/day	Mean of all positive difference between consecutive daily flow rates

Table 8. Simulated hydrological alteration during moderately dry conditions

25th Flow Percentile (Dry Year)	Lower Lincoln Creek	Roaring Fork above Lincoln Creek	Roaring Fork at Tagert Lakes	Roaring Fork at North Star Preserve	Roaring Fork at Aspen Club	Roaring Fork at Mill Street	Roaring Fork below Maroon Creek	Hunter Creek below No Name Creek	Lower Hunter Creek	Castle Creek at Keno Gulch	Lower Castle Creek	Maroon Creek above Willow Creek	Maroon Creek below Willow Creek	Lower Maroon Creek
Mean January Flow	-45%	-62%	-53%	-29%	-29%	-29%	-8%	0%	0%	-30%	-25%	0%	-18%	0%
Mean February Flow	-43%	-60%	-51%	-28%	-29%	-29%	-9%	0%	0%	-26%	-24%	0%	-16%	0%
Mean March Flow	-47%	-62%	-54%	-29%	-29%	-29%	-8%	0%	0%	-26%	-21%	0%	-14%	0%
Mean April Flow	-60%	-58%	-60%	-29%	-33%	-40%	-8%	0%	0%	-27%	-27%	0%	-20%	0%
Mean May Flow	-78%	-52%	-66%	-31%	-39%	-37%	-20%	-11%	-16%	-8%	-8%	-5%	-52%	-2%
Mean June Flow	-85%	-58%	-72%	-41%	-46%	-46%	-26%	-28%	-38%	-3%	-7%	-4%	-22%	-2%
Mean July Flow	-75%	-53%	-64%	-30%	-53%	-50%	-18%	0%	-50%	-7%	-23%	-11%	-50%	-6%
Mean August Flow	-68%	-53%	-61%	-31%	-44%	-47%	-16%	0%	-100%	-13%	-34%	-11%	-65%	-7%
Mean September Flow	-62%	-58%	-60%	-29%	-37%	-41%	-16%	0%	-100%	-16%	-56%	-21%	-63%	-15%
Mean October Flow	-59%	-60%	-60%	-30%	-41%	-46%	-12%	0%	-66%	-19%	-19%	-18%	-50%	-14%
Mean November Flow	-56%	-59%	-57%	-30%	-30%	-30%	-7%	0%	0%	-23%	-23%	0%	-36%	-3%
Mean December Flow	-50%	-57%	-53%	-27%	-27%	-27%	-7%	0%	0%	-26%	-26%	0%	-26%	-1%
Annual 1 Day Max	-85%	-59%	-72%	-41%	-44%	-44%	-26%	-35%	-39%	-2%	-5%	-2%	-14%	-1%
Annual 1 Day Min	-42%	-60%	-45%	-24%	-26%	-28%	-8%	0%	-100%	-13%	-68%	0%	-18%	0%
Annual 3 Day Max	-85%	-59%	-73%	-41%	-44%	-44%	-25%	-35%	-39%	-2%	-5%	-2%	-14%	-2%
Annual 3 Day Min	-39%	-59%	-47%	-25%	-26%	-28%	-7%	0%	-100%	-16%	-65%	0%	-18%	0%
Annual 30 Day Max	-85%	-59%	-73%	-41%	-45%	-44%	-26%	-32%	-37%	-2%	-5%	-3%	-18%	-2%
Annual 30 Day Min	-40%	-59%	-49%	-27%	-28%	-28%	-9%	0%	-99%	-19%	-32%	-0%	-13%	-0%
Annual 7 Day Max	-85%	-59%	-73%	-41%	-44%	-44%	-27%	-34%	-39%	-2%	-5%	-2%	-14%	-1%
Annual 7 Day Min	-38%	-59%	-48%	-26%	-28%	-28%	-9%	0%	-100%	-16%	-61%	0%	-17%	0%
Annual 90 Day Max	-83%	-59%	-71%	-40%	-46%	-45%	-24%	-26%	-34%	-4%	-13%	-5%	-29%	-3%
Annual 90 Day Min	-44%	-59%	-51%	-28%	-28%	-29%	-9%	0%	-13%	-22%	-18%	-0%	-17%	-0%
Baseflow Index	+147%	-4%	+57%	+16%	+27%	+24%	+16%	+30%	-100%	-1%	-49%	+5%	-1%	+2%
Fall Rate	-50%	-40%	-46%	-35%	-36%	-30%	-21%	-17%	0%	0%	0%	0%	-20%	+15%
High Pulse Duration	0%	0%	+25%	0%	+14%	+14%	+50%	0%	-33%	0%	-25%	-3%	-3%	+2%
High Pulse Count	-33%	-17%	-33%	+25%	+25%	+25%	0%	0%	0%	0%	0%	0%	0%	0%
Low Pulse Duration	-50%	-6%	-25%	+23%	+23%	-8%	+25%	0%	+67%	0%	+6%	+9%	-9%	+41%
Low Pulse Count	-100%	+13%	0%	0%	+13%	+50%	-50%	0%	+200%	+100%	+33%	+50%	0%	0%
Flow Reversals	-44%	-10%	-14%	-5%	-7%	-7%	-5%	0%	-7%	-2%	+1%	+11%	-6%	+19%
Rise rate	-33%	-33%	-40%	-17%	-29%	-21%	-14%	0%	+6%	0%	0%	0%	-50%	0%
Annual Volume	-77%	-59%	-67%	-38%	-45%	-44%	-21%	-21%	-35%	-8%	-15%	-6%	-34%	-3%

Table 9. Simulated hydrological alteration during average conditions.

50th Flow Percentile (Avg. Year)	Lower Lincoln Creek	Roaring Fork above Lincoln Creek	Roaring Fork at Tagert Lakes	Roaring Fork at North Star Preserve	Roaring Fork at Aspen Club	Roaring Fork at Mill Street	Roaring Fork below Maroon Creek	Hunter Creek below No Name Creek	Lower Hunter Creek	Castle Creek at Keno Gulch	Lower Castle Creek	Maroon Creek above Willow Creek	Maroon Creek below Willow Creek	Lower Maroon Creek
Mean January Flow	-53%	-60%	-56%	-31%	-30%	-30%	-9%	0%	0%	-26%	-26%	0%	-26%	0%
Mean February Flow	-50%	-60%	-55%	-30%	-30%	-30%	-9%	0%	0%	-27%	-27%	0%	-21%	0%
Mean March Flow	-53%	-60%	-56%	-31%	-30%	-30%	-9%	0%	0%	-27%	-27%	0%	-24%	0%
Mean April Flow	-63%	-59%	-61%	-33%	-33%	-41%	-10%	0%	0%	-20%	-20%	0%	-36%	0%
Mean May Flow	-79%	-55%	-67%	-40%	-45%	-44%	-22%	-24%	-28%	-5%	-12%	-2%	-47%	-2%
Mean June Flow	-85%	-59%	-73%	-41%	-45%	-45%	-24%	-32%	-39%	-2%	-6%	-3%	-17%	-2%
Mean July Flow	-80%	-57%	-68%	-39%	-52%	-50%	-23%	-7%	-36%	-5%	-9%	-6%	-32%	-4%
Mean August Flow	-73%	-57%	-64%	-31%	-57%	-61%	-24%	0%	-61%	-10%	-22%	-15%	-66%	-8%
Mean September Flow	-66%	-56%	-61%	-30%	-39%	-41%	-16%	0%	-77%	-15%	-23%	-19%	-61%	-9%
Mean October Flow	-60%	-57%	-58%	-26%	-34%	-39%	-11%	0%	-38%	-20%	-20%	-18%	-53%	-16%
Mean November Flow	-59%	-59%	-59%	-31%	-32%	-32%	-9%	0%	0%	-20%	-20%	0%	-40%	-2%
Mean December Flow	-55%	-59%	-57%	-30%	-30%	-30%	-8%	0%	0%	-24%	-24%	0%	-33%	0%
Annual 1 Day Max	-85%	-59%	-73%	-42%	-44%	-44%	-24%	-36%	-39%	-1%	-4%	-2%	-12%	-1%
Annual 1 Day Min	-38%	-58%	-48%	-26%	-27%	-27%	-7%	0%	-100%	-30%	-30%	-3%	-17%	-2%
Annual 3 Day Max	-85%	-59%	-73%	-42%	-44%	-44%	-25%	-36%	-39%	-1%	-5%	-2%	-12%	-1%
Annual 3 Day Min	-43%	-61%	-51%	-28%	-29%	-29%	-7%	0%	-100%	-26%	-32%	-3%	-18%	-3%
Annual 30 Day Max	-85%	-59%	-73%	-41%	-45%	-44%	-22%	-34%	-38%	-2%	-6%	-2%	-14%	-1%
Annual 30 Day Min	-50%	-59%	-54%	-30%	-30%	-32%	-9%	0%	-74%	-27%	-33%	0%	-20%	0%
Annual 7 Day Max	-86%	-59%	-73%	-41%	-44%	-44%	-24%	-36%	-37%	-2%	-4%	-2%	-12%	-1%
Annual 7 Day Min	-47%	-60%	-53%	-29%	-29%	-31%	-8%	0%	-100%	-24%	-33%	-1%	-19%	-2%
Annual 90 Day Max	-83%	-59%	-71%	-40%	-46%	-45%	-24%	-29%	-35%	-3%	-10%	-3%	-22%	-2%
Annual 90 Day Min	-52%	-59%	-55%	-30%	-30%	-30%	-9%	0%	-7%	-26%	-27%	0%	-23%	0%
Baseflow Index	+149%	-2%	+52%	+18%	+29%	+27%	+14%	+38%	-100%	-15%	-21%	+5%	+16%	+3%
Fall Rate	-33%	-50%	-50%	-33%	-25%	-25%	-17%	0%	0%	+20%	+20%	0%	-50%	0%
High Pulse Duration	0%	0%	+25%	0%	-50%	-50%	+1%	0%	0%	0%	-43%	-6%	-6%	-5%
High Pulse Count	-25%	0%	0%	+67%	+67%	+33%	0%	0%	+33%	0%	+50%	0%	0%	0%
Low Pulse Duration	-50%	0%	0%	-8%	+17%	0%	+162%	0%	+33%	-19%	+13%	+11%	-23%	-9%
Low Pulse Count	-100%	0%	-13%	+17%	+33%	+33%	0%	0%	+67%	+67%	+33%	0%	+50%	0%
Flow Reversals	-34%	-9%	-13%	-2%	-2%	-5%	-2%	0%	-5%	-4%	+2%	+6%	0%	+14%
Rise rate	-43%	-50%	-50%	-30%	-33%	-33%	-21%	0%	0%	+20%	+20%	0%	-40%	0%
Annual Volume	-78%	-58%	-69%	-38%	-44%	-43%	-21%	-25%	-36%	-8%	-14%	-5%	-28%	-3%

Table 10. Simulated hydrological alteration during moderately wet conditions.

75th Flow Percentile (Wet Year)	Lower Lincoln Creek	Roaring Fork above Lincoln Creek	Roaring Fork at Tagert Lakes	Roaring Fork at North Star Preserve	Roaring Fork at Aspen Club	Roaring Fork at Mill Street	Roaring Fork below Maroon Creek	Hunter Creek below No Name Creek	Lower Hunter Creek	Castle Creek at Keno Gulch	Lower Castle Creek	Maroon Creek above Willow Creek	Maroon Creek below Willow Creek	Lower Maroon Creek
Mean January Flow	-55%	-59%	-57%	-31%	-31%	-31%	-9%	0%	0%	-23%	-23%	0%	-33%	0%
Mean February Flow	-56%	-59%	-56%	-30%	-30%	-32%	-8%	0%	0%	-24%	-24%	0%	-29%	0%
Mean March Flow	-53%	-59%	-56%	-31%	-31%	-31%	-9%	0%	0%	-23%	-23%	0%	-31%	0%
Mean April Flow	-69%	-57%	-63%	-34%	-38%	-32%	-10%	0%	-1%	-17%	-17%	0%	-46%	0%
Mean May Flow	-83%	-58%	-71%	-41%	-44%	-43%	-26%	-29%	-32%	-4%	-8%	-2%	-28%	+1%
Mean June Flow	-86%	-59%	-73%	-41%	-44%	-44%	-24%	-35%	-39%	-2%	-4%	-2%	-12%	-1%
Mean July Flow	-84%	-59%	-72%	-40%	-49%	-48%	-19%	-23%	-37%	-3%	-9%	-4%	-18%	-2%
Mean August Flow	-74%	-55%	-65%	-37%	-61%	-57%	-20%	0%	-42%	-8%	-19%	-9%	-49%	-6%
Mean September Flow	-70%	-52%	-56%	-29%	-50%	-53%	-21%	0%	-61%	-11%	-18%	-13%	-69%	-10%
Mean October Flow	-69%	-56%	-63%	-35%	-42%	-45%	-13%	0%	-18%	-14%	-14%	-13%	-59%	-8%
Mean November Flow	-65%	-60%	-63%	-34%	-35%	-34%	-9%	0%	0%	-18%	-18%	0%	-49%	-2%
Mean December Flow	-59%	-60%	-60%	-31%	-32%	-32%	-9%	0%	0%	-21%	-21%	0%	-41%	-2%
Annual 1 Day Max	-82%	-59%	-73%	-42%	-44%	-43%	-27%	-37%	-38%	-1%	-3%	-2%	-10%	-1%
Annual 1 Day Min	-50%	-57%	-53%	-29%	-29%	-35%	-8%	0%	-100%	-27%	-29%	-4%	-27%	0%
Annual 3 Day Max	-85%	-59%	-73%	-42%	-44%	-43%	-27%	-37%	-38%	-1%	-4%	-1%	-10%	-1%
Annual 3 Day Min	-51%	-59%	-55%	-29%	-29%	-34%	-9%	0%	-89%	-26%	-28%	-1%	-27%	0%
Annual 30 Day Max	-86%	-59%	-73%	-41%	-44%	-44%	-24%	-35%	-39%	-2%	-5%	-2%	-12%	-1%
Annual 30 Day Min	-53%	-59%	-56%	-31%	-30%	-31%	-9%	0%	-31%	-25%	-28%	0%	-27%	0%
Annual 7 Day Max	-86%	-59%	-73%	-42%	-44%	-43%	-25%	-36%	-39%	-1%	-3%	-2%	-10%	-1%
Annual 7 Day Min	-53%	-60%	-56%	-30%	-30%	-34%	-8%	0%	-71%	-26%	-27%	0%	-27%	0%
Annual 90 Day Max	-85%	-59%	-73%	-41%	-45%	-45%	-23%	-31%	-37%	-2%	-6%	-3%	-18%	-2%
Annual 90 Day Min	-55%	-59%	-56%	-31%	-31%	-31%	-9%	0%	-0%	-24%	-24%	-0%	-31%	-0%
Baseflow Index	+136%	-5%	+48%	+14%	+26%	+20%	+16%	+28%	-61%	-19%	-19%	+7%	+20%	+3%
Fall Rate	-67%	-33%	-40%	-29%	-29%	-29%	-25%	0%	0%	0%	0%	+9%	-47%	0%
High Pulse Duration	+139%	+70%	+106%	-15%	-52%	-52%	-8%	0%	-36%	-6%	-6%	-4%	-1%	-2%
High Pulse Count	0%	0%	+8%	0%	0%	0%	0%	0%	+25%	0%	+17%	+100%	+100%	+50%
Low Pulse Duration	-71%	-7%	-11%	+7%	+2%	-7%	0%	0%	+65%	-50%	+34%	-32%	-59%	-35%
Low Pulse Count	-92%	0%	0%	-18%	+5%	+9%	-11%	0%	+17%	+27%	+27%	+14%	+14%	+14%
Flow Reversals	-31%	-7%	-10%	+0%	-3%	-1%	-2%	+1%	+3%	-2%	-0%	0%	-5%	+1%
Rise rate	-56%	-40%	-43%	-34%	-27%	-18%	-26%	-13%	-6%	0%	0%	+12%	-33%	0%
Annual Volume	-80%	-59%	-71%	-39%	-45%	-44%	-21%	-25%	-33%	-7%	-11%	-3%	-28%	-2%

5. Conclusions

Effective and informed discussions about water issues in future community and/or stakeholder groups settings must be supported by reliable data and communication tools that speak to a diverse audience. Furthermore, any discussion that contemplates a change to water use or management should be supported by conceptual models, data products and simulation tools that help participants understand the likely outcomes of any given action. To this end, the project team developed a pair of hydrological and water rights simulation tools. These tools will allow City and County staff and their consultants to test “what-if” water use and management scenarios in the upper watershed. Consideration of simulation results using an ecological evaluation framework, also developed for this effort by the project team, will help place hydrological change in the appropriate ecological context and help users predict the degree to which any management action will impact river health.

In addition to their use to further assess and refine the management opportunities listed previously, simulation tools may be used to inform other parallel efforts. The daily hydrological simulation models may be useful to the City’s ongoing efforts to understand impacts of climate change on its water supplies and its future ability to simultaneously meet municipal demands, contract obligations, and the needs of the environment. Any effort to build climate change scenarios into the hydrological simulation models would also benefit future discussions about water management for river health but must be proceeded by an agreement among City departments regarding the types of and theoretical basis for selected climate change scenarios.

6. References

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