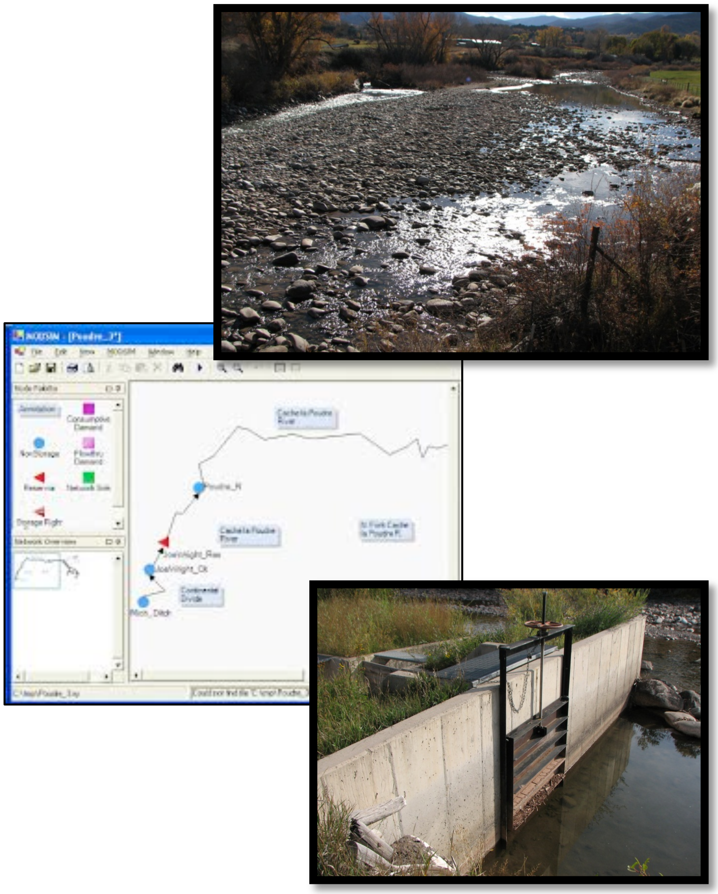
Technical Report

Water Rights Allocation and Accounting Model Development for the Lower Crystal River

lōtic
hydrological
consulting services



ROARING FORK WATERSHED PLAN
at work

SUBMITTED: 4/15/14

Prepared For:

Roaring Fork Conservancy
P.O. Box 3349
Basalt, Colorado 81621

Prepared By:

Lotic Hydrological, LLC
PO Box 1524
Carbondale, CO 81623

ACKNOWLEDGEMENTS

Generous grants from the Colorado Healthy Rivers Fund and Public Council of the Rockies provided support for this work. University of Michigan graduate students Kara Steeland and Charlotte Jameson provided valuable support through GIS analysis, interpretation of results, and their interactions with staff from the Town of Carbondale. Local landowners and water users Bill Fales and Tom Turnbull guided the refinement of water rights information available from the State of Colorado and greatly improved the accuracy and performance of the model. Jake DeWolfe, the Colorado Division of Water Resources, Water Commissioner for the Crystal River, provided a great deal of support, time, and expert knowledge during the model development and calibration phase. Colorado River District staff, Mike Eytel and Don Meyer, provided feedback and recommendations on model structure.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

APPENDICES

Appendix A. Plots of linear models relating streamflows in the Crystal River to tributaries

DEFINITION OF TERMS

AF: Acre Feet

AWAS: Alluvial Water Accounting System

CDSS: Colorado Decision Support System

CDWR: Colorado Division of Water Resources

CPW: Colorado Parks and Wildlife

CWCB: Colorado Water Conservation Board

GIS: Geographic Information System

IDS AWAS: Integrated Decision Support Group's Alluvial Water Accounting System

ISF: Instream Flow

RFC: Roaring Fork Conservancy

TOC: Town of Carbondale

USGS: United States Geological Survey

1. INTRODUCTION

The work presented here supports ongoing efforts by conservation groups as they endeavor to identify water conservation opportunities in the Crystal River watershed. Roaring Fork Conservancy (RFC) requires results from the hydrological simulations compiled in this technical report to determine the impact of various water conservation management scenarios on spatial and temporal patterns of in-channel flows in the lower Crystal River.

This project utilized data from the State of Colorado's Division of Water Resources (CDWR), the United States Geological Survey (USGS) and other sources to construct a surface water model that simulated water allocation and accounting according to the Prior Appropriation Doctrine in the lower Crystal River watershed. A MODSIM-DSS model constructed for the lower Crystal River simulated baseline streamflow conditions (in the absence of active management of surface water and groundwater resources) and streamflows as affected by surface water rights allocations across a range of hydrological conditions. Simulations incorporated three alternative water resource management scenarios developed by RFC and Town of Carbondale (TOC).

The constructed water allocation and accounting model simulated surface water flows within the Crystal River network, extending from Avalanche Creek to the confluence of the Crystal River with the Roaring Fork River. Simulation runs characterized spatial and temporal patterns in streamflow on the mainstem Crystal River under various water resource management scenarios: 1) baseline conditions: no active consumptive or non-consumptive use affecting streamflow, 2) active water rights allocation and accounting according to the Prior Appropriations Doctrine, and 3) active water rights allocation and accounting according to three potential municipal water conservation management plans. Simulation runs utilized a daily time step and spanned a period of six years (2007-2013). The selected simulation time period allows users to analyze and interpret the effects of varied hydrological conditions on the efficacy/impact of the tested resource management scenarios.

Results from water rights allocation and accounting modeling in the lower Crystal River provide critical hydrological information necessary for the informed development and evaluation of water conservation measures by the Town of Carbondale and other conservation groups, individuals and entities engaged in water resource use and management in the Crystal River watershed.

2. METHODS

2.1 Model Selection and Network Development

While a water rights allocation and accounting model for the Upper Colorado River Basin (including the Roaring Fork and Crystal River watersheds) created by CDWR and the Colorado Water Conservation Board (CWCB) already exists, the node-spacing scheme and resolution used in this model render it too coarse to be useful for effective evaluation of proposed water conservation measures on the lower Crystal River. Thus, stakeholders required a model built specifically for the Crystal River watershed. MODSIM-DSS, a Decision Support System developed at Colorado State University, simulates stream diversions, in-stream demands, well pumping and recharge, reservoir operations, and river flows, while accounting for water rights administration and enables comparative analyses of various historic and future water management scenarios in a river basin (Labadie, 2010). MODSIM-DSS was used to simulate baseline streamflow conditions (in the absence of active management of surface water and groundwater resources) and modified streamflows on the lower Crystal River as affected by surface water rights allocations across a range of hydrological conditions.

Network nodes in MODSIM-DSS corresponded to the locations of physical diversion structures and tributary inflows on the Crystal River from above its confluence with Avalanche Creek to the confluence with the Roaring Fork River (Figure 1). The network model did not include well structures due to their limited pumping rates and presumed negligible effect on in-channel flows. The model network did not include all tributary streams to the Crystal River. Rather, the network included only significant perennial streams that consistently contribute flow to the Crystal River, or otherwise would in the absence of consumptive and non-consumptive water use. Due to a dearth of historical streamflow data from most tributaries, identification of tributary streams critical for inclusion in the model network relied on anecdotal evidence provided by local water users and the expert knowledge of the watershed provided by the local water commissioner.

The model required several data inputs for executing streamflow simulation and routing simulations: hydrology inflow data for the Crystal River and contributing tributaries, hydrogeological parameters governing the timing of groundwater return flows, consumptive and non-consumptive water demands, and legal and administrative conditions associated with a particular hydrological conditions. Data was aggregated from various sources, including Colorado's Decision Support System (CDSS), local irrigators and water users, the district water commissioner, and published hydrogeologic studies.

2.2 Hydrological Data

Hydrological data for the lower Crystal River watershed was derived from historical stream gage data and through regression analyses using the USGS StreamStats application. Table 1 below lists the gages on the Crystal River within the study area and corresponding operational time periods.

Figure 1. Lower Crystal River MODSIM Model Network

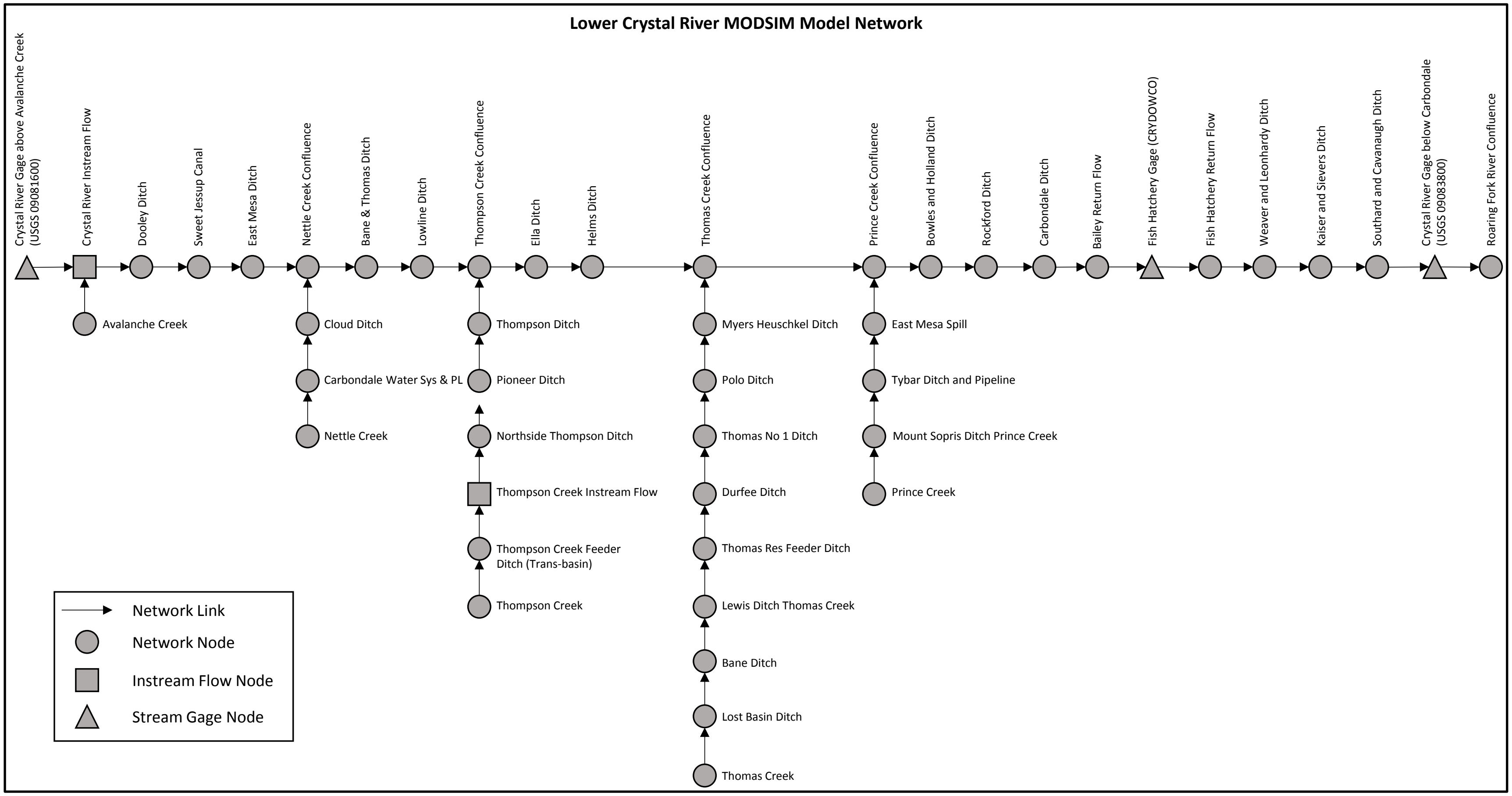


Table 1. Stream gages on the lower Crystal River, Colorado.

Agency	Gage ID	Gage Name	Operational Period
USGS	09081600	CRYSTAL RIVER ABOVE AVALANCHE CREEK, NEAR REDSTONE, CO	1955-Present
CDWR	CRYDOWCO	CRYSTAL RIVER AT DOW FISH HATCHERY ABOVE CARBONDALE	2007-Present
USGS	09083800	CRYSTAL RIVER BELOW CARBONDALE, CO	2000-2010

The five major ungaged tributaries in the lower Crystal River watershed built into the model network included Avalanche Creek, Nettle Creek, Thompson Creek, Thomas Creek, and Prince Creek. The USGS web application StreamStats generated average monthly streamflows for each of these tributaries (http://water.usgs.gov/osw/streamstats). StreamStats uses regional regression equations to estimate mean monthly flows at ungaged sites based on watershed characteristics and historical data collected in similar locations across Colorado (Capesius and Stephens 2009). Table 2 presents monthly streamflows for each of the tributaries in the study area, calculated using the area-averaged method in StreamStats. Mean monthly discharge statistics were also estimated for the Crystal River using historical data (e.g. 1956-2006 to parallel the data sets utilized by StreamStats) generated at the USGS station above Avalanche Creek. Linear models were constructed to describe the relationship between average flows calculated for the Crystal River and each of the five tributaries included in the model. These linear models were then used to predict daily streamflow on each tributary stream as a function of observed streamflow in the Crystal River above Avalanche Creek. Appendix A includes plots of the linear models relating streamflows in the Crystal River to each tributary.

Table 2. StreamStats estimated monthly mean discharge[1] (cubic feet per second, cfs)

Month	Crystal River[2]	Avalanche Creek	Nettle Creek	Thompson Creek	Thomas Creek	Prince Creek
JAN	43.30	13.30	0.75	17.50	0.99	1.33
FEB	43.60	12.10	0.68	16.30	0.91	1.25
MAR	51.80	13.70	0.71	19.00	0.99	1.41
APR	187.00	34.90	1.52	48.60	2.26	3.18
MAY	774.00	176.00	12.40	225.00	15.90	20.10
JUN	1280.00	303.00	26.40	348.00	28.70	32.50
JUL	620.00	137.00	10.00	137.00	10.50	11.30
AUG	199.00	51.40	3.98	55.80	4.55	5.36
SEP	121.00	32.60	2.19	37.80	2.70	3.46
OCT	83.50	28.90	1.64	33.40	1.98	2.46
NOV	62.90	20.30	1.16	24.70	1.43	1.82
DEC	48.30	14.60	0.85	19.00	1.10	1.46

[1] Monthly mean discharge was estimated using USGS StreamStats statistics (area-averaged).

[2] StreamStats mean monthly discharge estimates for the Crystal River are based on data collected between 1956 and 2006.

Historical gage data from the USGS station above Avalanche Creek on the Crystal River (USGS 09081600) supported the identification of a simulation period representing 'average', 'moderate drought', and 'severe drought' conditions. First, irrigation year (November-October) water yields were calculated for each year of the historical record (1956-2013), followed by a calculation of the exceedance probability of each year's yield. The 50, 90 and 95 percent exceedance probabilities were identified to represent average, moderate drought, and severe drought conditions respectively. A review of the exceedance probabilities associated with each year of record led to the selection of the years 2010, 2013, and 2012 to represent average, moderate-drought and severe-drought conditions respectively. While these years do not correspond exactly to percentile rankings identified above, it was determined that their selection would not violate the intention of the comparative analysis and actually provided significant benefits to model calibration (see Section 3). Table 3 summarizes the yearly yields in acre-feet (AF) and the exceedance probabilities associated with each of the simulated irrigation years. Results from the analysis discussed above and the availability of data from downstream gages (i.e. CDWR CRYDOWCO and USGS 09083800) for model calibration resulted in selection of a study period spanning irrigation years 2007 through 2013.

Table 3. Irrigation year (Nov-Oct) annual yields and exceedances probabilities calculated from data collected at the Crystal River gage above Avalanche Creek between 1956 and 2013.

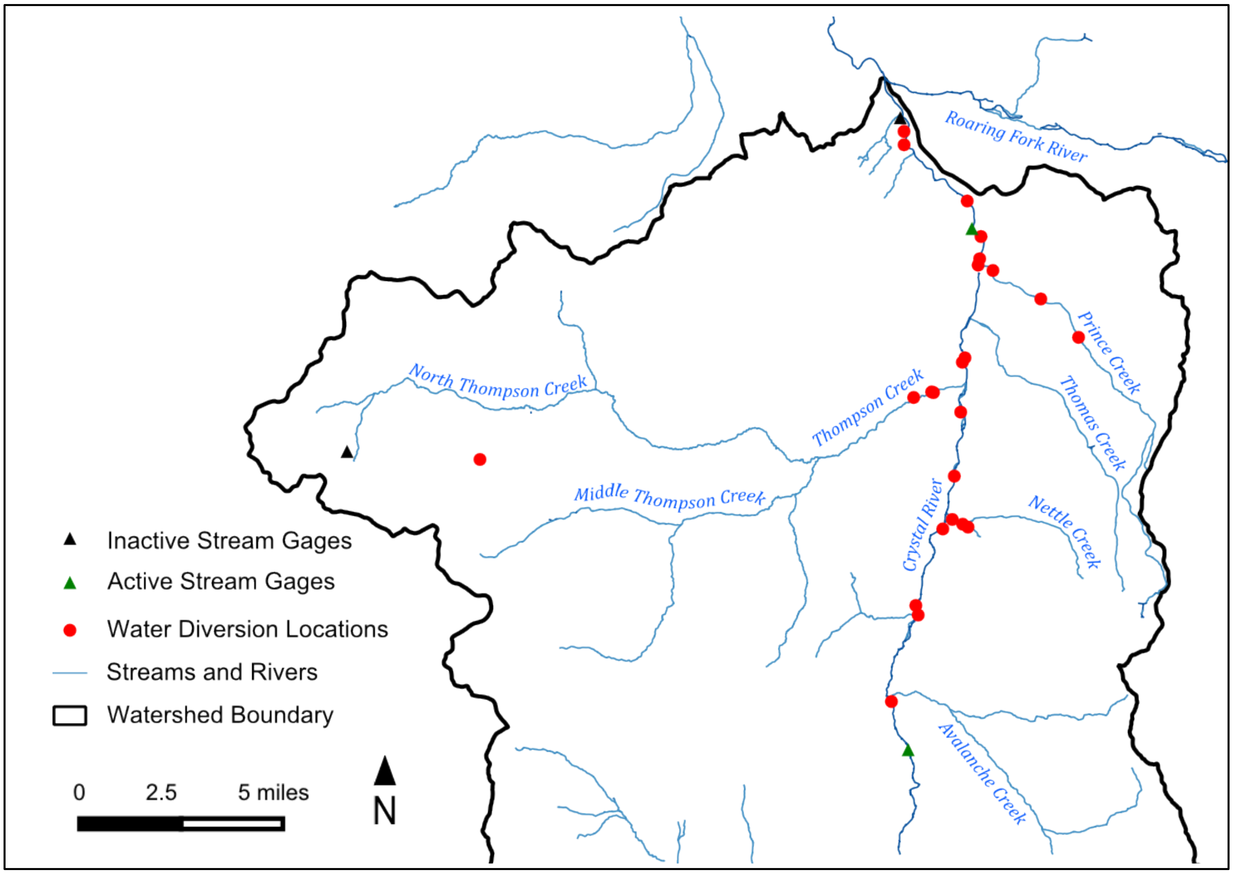
Modeled Condition	Exceedance Probability (%)	Yield (AF)	Irrigation Year
Moderate Drought	88	148,257	2013
Severe Drought	95	113,288	2012
--	7	331,204	2011
Average Conditions	47	208,921	2010
--	32	237,830	2009
--	20	274,687	2008
--	56	195,291	2007

2.3 Consumptive and Non-consumptive Use Data

Numerous surface water and groundwater diversions are present in the lower Crystal River watershed. A thorough evaluation of water diversion infrastructure, historical water demands, and legal and administrative conditions associated with particular hydrological conditions was required to identify those diversions with the potential to impact the hydrologic regime or longitudinal patterns in streamflow in the mainstem Crystal River. A water rights evaluation, a hydrologic study, discussions with water users along the Crystal River and its tributaries, and information acquired from the District 38 Water Commissioner contributed to selection of the modeled consumptive and non-consumptive water diversions. Figure 2 displays water diversion locations included in the MODSIM-DSS model network. Table 4 lists the modeled diversion structures along with their associated water rights information.

Irrigation and municipal water use diversions along the Crystal River and the five major contributing tributaries (Avalanche Creek, Nettle Creek, Thompson Creek, Thomas Creek and Prince Creek) in use during the study period under investigation (irrigation years 2007-2013) were included in the MODSIM-DSS model network. Diversion information, including structure names, locations, decreed amounts, and priority information, was downloaded from the Colorado Decision Support System (CDSS) water rights database, HydroBase. Domestic use wells were not included in the network due to their minimal withdrawal rates (e.g. roughly 0.3 AF per year). Some smaller diversions were not included due to incomplete diversion and/or water rights data records.

Figure 2. Map of lower Crystal River watershed stream network showing diversion structure and gage locations.



The CDSS HydroBase provided daily diversion records for most modeled diversion locations. If HydroBase did not include time series diversion records for a given diversion structure, but did indicate current and ongoing water use, then the modeled diversion time series utilized the full amount of water decreed for that structure for the entire irrigation season (May-November). Use of actual diversion records in model construction eliminated the need to include downstream senior water rights (e.g. Cameo) in the model network. The diversion records reflect the impact of any downstream 'calls' on the river occurring over the simulation period.

Water users in the lower Crystal River do not operate entirely within the administrative framework established by Colorado water law. Colorado dictates that senior water users' rights are satisfied entirely before junior water users receive water. Due to a water rights and property ownership situation that pits many water rights holders against themselves when faced with making a 'call' on the river, and a tradition of local water administration, water users in the lower Crystal River tend to operate outside of the prior appropriations system. This presents some inherit difficulties when constructing water rights allocation and accounting models that expect water routing rules to operate according to a water rights seniority system. In order to avoid construction of an unrealistic model, historical diversion records rather than decreed water rights governed the routing of water in the constructed MODSIM-DSS model network.

2.4 Return Flow Estimates

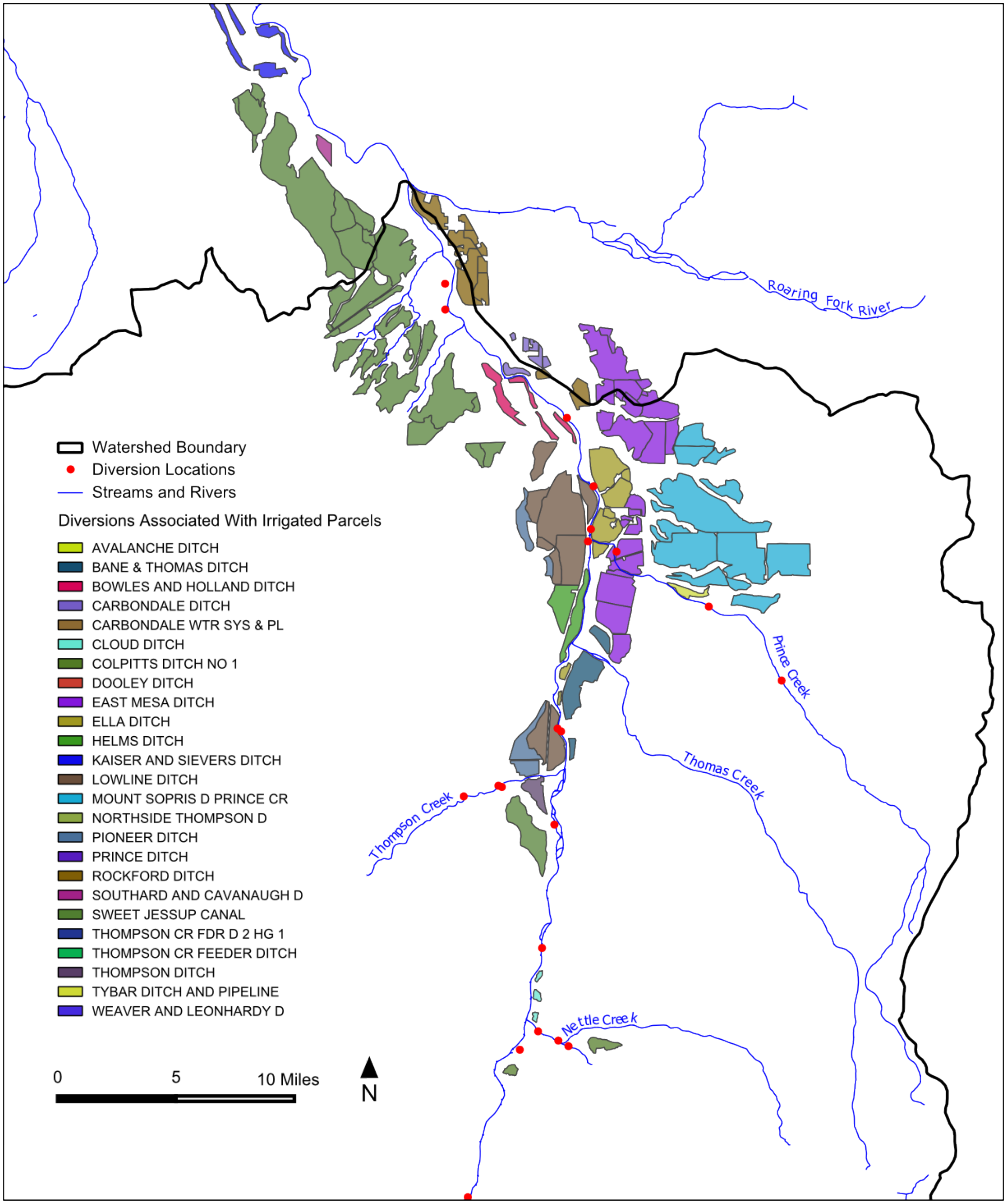
Irrigation return flows were included in the MODSIM-DSS model for the lower Crystal River to improve simulation results and provide opportunity for more varied water conservation scenario testing. Calculation of lag response coefficients for groundwater returns from irrigated acreages required estimates of water application efficiency, aquifer transmissivity, specific yield, and average distance to return nodes.

Identification of groundwater return flowpath lengths required mapping the irrigated parcels associated with the modeled water diversions. Irrigated parcel locations and orientations were initially procured from the CDSS. However, discussions with the local water commissioner and several water users identified the need for revision and refinement. Several individuals were subsequently consulted to improve the accuracy and resolution of ditch-irrigated acreage associations (Figure 3). Using the revised map, researchers at the University of Michigan calculated groundwater return flowpath lengths in a geographic information system (GIS). Researchers used a least-cost path analysis to compute the downhill distance from each parcel's centroid to the nearest stream or river. This downhill distance was assumed to approximate the mean groundwater flowpath length associated with each group of irrigated parcels associated with a given water right.

Table 4. List of diversions included in the MODSIM-DSS model network

Water Right Name	ID	Water Source	Adjudication Date	Previous Adjudication Date	Appropriation Date	Admin No	Priority # / Case #	Rate Absolute (CFS)	Rate Conditional (CFS)	Rate Apex (ACFT)
BANE & THOMAS DITCH	522	CRYSTAL RIVER	1889-05-11		1886-10-10	13432.00000	165	4.00	0.00	0.00
BANE & THOMAS DITCH	522	CRYSTAL RIVER	1936-08-25	1934-09-18	1935-05-13	31178.00000	440	0.36	0.00	0.00
BANE & THOMAS DITCH	522	CRYSTAL RIVER	1949-08-25	1940-02-05	1937-08-01	32907.31989	466	0.64	0.00	0.00
BANE & THOMAS DITCH	522	CRYSTAL RIVER	1949-08-25	1940-02-05	1943-06-01	34119.00000	471	1.00	0.00	0.00
BOWLES AND HOLLAND DITCH	547	CRYSTAL RIVER	1889-05-11		1884-04-09	12518.00000	81	2.80	0.00	0.00
BOWLES AND HOLLAND DITCH	547	CRYSTAL RIVER	1920-02-21	1919-10-20	1887-06-15	25494.13680	180B	3.20	0.00	0.00
BOWLES AND HOLLAND DITCH	547	CRYSTAL RIVER	1936-08-25	1934-09-18	1890-06-15	30941.14776	311	14.00	0.00	0.00
BOWLES AND HOLLAND DITCH	547	CRYSTAL RIVER	1995-12-31	1994-12-31	1995-11-15	53279.00000	03CW0146	3.80	1.20	0.00
CARBONDALE DITCH	574	CRYSTAL RIVER	1889-05-11		1887-04-01	13605.00000	169	5.00	0.00	0.00
CARBONDALE DITCH	574	CRYSTAL RIVER	1936-08-25	1934-09-18	1920-04-01	30941.25658	408	36.24	0.00	0.00
CGFP WELL NO 3 CRYSTAL	6636	CRYSTAL RIVER	1972-12-31	1971-12-31	1971-09-01	44559.44438	90CW0350	0.00	0.00	1.00
CGFP WELL NO 3 CRYSTAL	6636	CRYSTAL RIVER	1990-12-31	1989-12-31	1971-09-01	51134.44438	90CW0350	0.00	0.00	1.67
CRYSTAL RIVER REAR PL D	1858	CRYSTAL RIVER	1990-12-31	1989-12-31	1962-01-12	51134.40919	90CW0349	1.50	0.00	0.00
DOOLEY DITCH	640	CRYSTAL RIVER	1958-06-20	1952-10-24	1899-08-01	37552.18110	644	1.00	0.00	0.00
EAST MESA DITCH	651	CRYSTAL RIVER	1902-12-12	1902-11-17	1894-08-10	19313.16293	210A	31.80	0.00	0.00
EAST MESA DITCH	651	CRYSTAL RIVER	1952-10-24	1949-08-25	1942-05-01	36396.33723	549	10.00	0.00	0.00
EAST MESA DITCH	651	CRYSTAL RIVER	1998-12-31	1997-12-31	1998-11-16	54376.00000	549	0.00	1.00	0.00
ELLA DITCH	663	CRYSTAL RIVER	1902-12-12	1902-11-17	1885-06-22	19313.12957	127A	9.10	0.00	0.00
ELLA DITCH	663	CRYSTAL RIVER	1936-08-25	1934-09-18	1926-06-22	30941.27931	423	3.45	0.00	0.00
ELLA DITCH	663	CRYSTAL RIVER	1952-10-24	1949-08-25	1949-04-28	36396.36277	584	2.00	0.00	0.00
ELLA DITCH	663	CRYSTAL RIVER	1971-12-31	1970-12-31	1971-12-29	44557.00000	W2683	0.25	0.00	0.00
ELLA DITCH	663	CRYSTAL RIVER	1994-12-31	1993-12-31	1993-11-02	52595.52536	94CW0161	0.30	0.00	0.00
HELMS DITCH	747	CRYSTAL RIVER	1903-02-02	1902-12-15	1899-11-17	19341.18218	213A	2.93	0.00	0.00
HELMS DITCH	747	CRYSTAL RIVER	1936-08-25	1934-09-18	1924-05-01	30941.27149	420	3.07	0.00	0.00
KAISER AND SIEVERS DITCH	1147	CRYSTAL RIVER	1889-05-11		1885-11-02	13090.00000	136	3.68	0.00	0.00
KAISER AND SIEVERS DITCH	1147	CRYSTAL RIVER	1889-05-11		1886-10-12	13434.00000	166	3.19	0.00	0.00
KAISER AND SIEVERS DITCH	1147	CRYSTAL RIVER	1910-08-26	1910-07-28	1902-04-15	22123.19097	217AA	1.77	0.00	0.00
KAISER AND SIEVERS DITCH	1147	CRYSTAL RIVER	1952-10-24	1949-08-25	1948-04-01	36396.35885	577	12.80	0.00	0.00
KAISER AND SIEVERS DITCH	1147	CRYSTAL RIVER	1998-12-31	1997-12-31	1998-11-20	54380.00000	06CW0073	5.68	4.32	0.00
LOWLINE DITCH	840	CRYSTAL RIVER	1902-12-12	1902-11-17	1890-09-25	19313.14878	208C	19.00	0.00	0.00
LOWLINE DITCH	840	CRYSTAL RIVER	1936-08-25	1934-09-18	1923-10-10	30941.26945	417	21.50	0.00	0.00
MIN FLOW CRYSTAL R LOWER	2114	CRYSTAL RIVER	1975-12-31	1974-12-31	1975-05-01	45776.00000	W2720	100.00	0.00	0.00
ROCKFORD DITCH	970	CRYSTAL RIVER	1889-05-11		1883-01-11	12064.00000	51	10.00	0.00	0.00
ROCKFORD DITCH	970	CRYSTAL RIVER	1936-08-25	1934-09-18	1915-06-04	30941.23895	399	25.00	0.00	0.00
ROCKFORD DITCH	970	CRYSTAL RIVER	1952-10-24	1949-08-25	1951-07-26	37096.00000	627	0.20	0.00	0.00
SOUTHARD AND CAVANAUGH D	1018	CRYSTAL RIVER	1889-05-11		1885-03-23	12866.00000	106	1.50	0.00	0.00
SOUTHARD AND CAVANAUGH D	1018	CRYSTAL RIVER	1889-05-11		1885-04-20	12894.00000	117	1.96	0.00	0.00
SOUTHARD AND CAVANAUGH D	1018	CRYSTAL RIVER	1889-05-11		1887-04-04	13608.00000	170	1.20	0.00	0.00
SOUTHARD AND CAVANAUGH D	1018	CRYSTAL RIVER	1892-02-09	1892-02-08	1889-04-01	15379.14336	206	1.00	0.00	0.00
SOUTHARD AND CAVANAUGH D	1018	CRYSTAL RIVER	1936-08-25	1934-09-18	1890-04-15	30941.14715	298	3.70	0.00	0.00
SOUTHARD AND CAVANAUGH D	1018	CRYSTAL RIVER	1936-08-25	1934-09-18	1915-06-04	30941.23895	399	3.04	0.00	0.00
SOUTHARD AND CAVANAUGH D	1018	CRYSTAL RIVER	1998-12-31	1997-12-31	1998-11-20	54380.00000	06CW0073	5.68	4.32	0.00
SWEET JESSUP CANAL	1038	CRYSTAL RIVER	1905-06-01	1905-05-31	1902-01-14	20239.19006	216AA	50.00	0.00	0.00
SWEET JESSUP CANAL	1038	CRYSTAL RIVER	1936-08-25	1934-09-18	1923-10-10	30941.26945	418	14.08	0.00	0.00
SWEET JESSUP CANAL	1038	CRYSTAL RIVER	1949-08-25	1940-02-05	1943-06-01	34119.00000	472	10.92	0.00	0.00
WEAVER AND LEONHARDY D	1082	CRYSTAL RIVER	1889-05-11		1885-04-20	12894.00000	117	2.84	0.00	0.00
WEAVER AND LEONHARDY D	1082	CRYSTAL RIVER	1924-05-01	1924-02-08	1923-05-01	27066.26783	238	1.52	0.00	0.00
WEAVER AND LEONHARDY D	1082	CRYSTAL RIVER	1936-08-25	1934-09-18	1924-05-01	30941.27149	419	8.00	0.00	0.00
CARBONDALE WTR SYS & PL	1052	NETTLE CREEK	1922-11-03	1922-06-19	1910-08-29	26467.22155	6AA	5.75	0.00	0.00
CLOUD DITCH	600	NETTLE CREEK	1923-06-30	1922-11-27	1886-04-15	26628.13254	141A	0.70	0.00	0.00
CLOUD DITCH	600	NETTLE CREEK	1952-10-24	1949-08-25	1948-05-01	36396.35915	578	2.50	0.00	0.00
MOUNT SOPRIS D PRINCE CR	1633	PRINCE CREEK	1889-05-11		1881-04-01	11414.00000	6, 87	2.60	0.00	0.00
MOUNT SOPRIS D PRINCE CR	1633	PRINCE CREEK	1889-05-11		1883-05-01	12174.00000	63	2.20	0.00	0.00
MOUNT SOPRIS D PRINCE CR	1633	PRINCE CREEK	1889-05-11		1885-07-15	12980.00000	130	0.00	0.00	5.00
MOUNT SOPRIS D PRINCE CR	1633	PRINCE CREEK	1889-05-11		1887-10-01	13788.00000	183	0.00	0.00	1.50
PRINCE DITCH	948	PRINCE CREEK	1991-12-31	1990-12-31	1982-05-15	51499.48347	91CW0115	13.40	0.00	0.00
TYBAR DITCH AND PIPELINE	1511	PRINCE CREEK	1985-12-31	1984-12-31	1984-11-02	49308.49249	89CW0171	3.00	0.00	0.00
TYBAR DITCH AND PIPELINE	1511	PRINCE CREEK	2002-12-31	2001-12-31	1999-11-03	55517.54728	02CW0023	0.00	3.00	0.00
BANE DITCH	521	THOMAS CREEK	1889-05-11		1886-07-23	13353.00000	161	1.40	0.00	0.00
BANE DITCH	521	THOMAS CREEK	1991-12-31	1990-12-31	1966-05-01	51499.42489	91CW0002	0.60	0.00	0.00
DURFEE DITCH	644	THOMAS CREEK	1919-06-09	1918-09-27	1907-05-15	25106.20953	226AAB-1	1.85	0.00	0.00
LEWIS DITCH THOMAS CR	816	THOMAS CREEK	1936-08-25	1934-09-18	1928-05-01	30941.28610	425	2.50	0.00	0.00
LEWIS DITCH THOMAS CR	816	THOMAS CREEK	1990-12-31	1989-12-31	1990-05-01	51255.00000	98CW0222	1.50	0.00	0.00
LOST BASIN DITCH	835	THOMAS CREEK	1892-02-09	1892-02-08	1889-06-27	15379.14423	208	5.20	0.00	0.00
MYERS & HEUSCHKEL DITCH	1344	THOMAS CREEK	1997-12-31	1996-12-31	1973-07-12	53691.45118	97CW0187	3.00	0.00	0.00
POLO DITCH	1903	THOMAS CREEK	1990-12-31	1989-12-31	1990-05-01	51255.00000	98CW0222	1.00	0.00	0.00
THOMAS NO 1 DITCH	1044	THOMAS CREEK	1889-05-11		1882-04-25	11803.00000	24	1.00	0.00	0.00
THOMAS NO 1 DITCH	1044	THOMAS CREEK	1889-05-11		1884-04-01	12510.00000	80	1.20	0.00	0.00
THOMAS NO 2 DITCH	1045	THOMAS CREEK	1889-05-11		1884-04-10	12519.00000	82	2.00	0.00	0.00
THOMAS RES FEEDER DITCH	1480	THOMAS CREEK	1889-05-11		1887-07-05	13700.00000	RES3	2.00	0.00	0.00
THOMAS RES FEEDER DITCH	1480	THOMAS CREEK	1990-12-31	1989-12-31	1990-05-01	51255.00000	98CW0222	2.00	0.00	0.00
MIN FLOW THOMPSON CRK LWR	2032	THOMPSON CREEK	2003-12-31	2002-12-31	2003-01-22	55904.00000	03CW0275	12.40	0.00	0.00
NORTHSIDE THOMPSON D	909	THOMPSON CREEK	1936-08-25	1934-09-18	1905-05-01	30941.20209	362	1.07	0.00	0.00
NORTHSIDE THOMPSON D	909	THOMPSON CREEK	1952-10-24	1949-08-25	1950-08-20	36756.00000	610	8.23	0.00	0.00
PIONEER DITCH	939	THOMPSON CREEK	1889-05-11		1881-05-01	11444.00000	7	5.60	0.00	0.00
PIONEER DITCH	939	THOMPSON CREEK	1889-05-11		1882-05-20	11828.00000	32	4.70	0.00	0.00
PIONEER DITCH	939	THOMPSON CREEK	1936-08-25	1934-09-18	1900-09-05	30941.18510	334	2.21	0.00	0.00
THOMPSON CR FDR D 2 HG 1	1771	THOMPSON CREEK	1952-10-24	1949-08-25	1951-08-23	37124.00000	628	8.00	12.00	0.00
THOMPSON CR FEEDER DITCH	4680	THOMPSON CREEK	1949-08-25	1940-02-05	1937-08-01	32907.31989	467	24.00	0.00	0.00
THOMPSON DITCH	1131	THOMPSON CREEK	1889-05-11		1881-05-01	11444.00000	7	0.10	0.00	0.00
THOMPSON DITCH	1131	THOMPSON CREEK	1889-05-11		1881-10-15	11611.00000	18A	1.30	0.00	0.00
THOMPSON DITCH	1131	THOMPSON CREEK	1936-08-25	1934-09-18	1905-09-10	30941.20341	365	2.27	0.00	0.00

Figure 3. Map of irrigated parcels and associated diversion structures on the lower Crystal River.



Transmissivity estimates were generated using the range of values for hydraulic conductivity and aquifer thickness presented by Kolm et al. (2008). Their report estimated hydraulic conductivities for the unconsolidated materials in the alluvial aquifer between 10 to 100 feet per day (ft/d), and aquifer thicknesses between 1 to 100 feet (ft) (Kolm et al., 2008). Estimation of specific yield relied on comparison of the empirical relationships published by Johnson (1967) against Kolm et al.'s (2008) description of the unconsolidated materials comprising the alluvial aquifer. The Integrated Decision Support Group's Alluvial Water Accounting System (IDS AWAS) calculated lag response coefficients for each irrigated acreage (http://www.ids.colostate.edu/). The IDS AWAS model used the Glover (Glover, 1977) method and the *alluvial aquifer* boundary condition to calculate daily lag response coefficients for groundwater return flows using estimates of return flowpath length, transmissivity, and specific yield. Lag response coefficients were subsequently incorporated into the MODSIM-DSS model at each consumptive water use node.

Estimating return flow fractions for each water demand required investigation into the water application method used on each irrigated parcel. For each water right, return flow fractions and locations were modeled according to the distributed ownership amounts and spatial orientation of associated irrigated parcels. Conversations with the District 38 Water Commissioner indicated that overland return flow from irrigated parcels contribute to the Crystal River at many locations. Overland return flow estimates were therefore included in the MODSIM-DSS model for parcels associated with the following diversions: Ella Ditch, Bane & Thomas Ditch, East Mesa Ditch, Helms Ditch, Lowline Ditch, Bowles and Holland Ditch and Pioneer Ditch. The irrigated parcels associated with these diversions are generally located in close proximity to the Crystal River.

For any given water demand, the application efficiency dictated the amount of water available for return to the Crystal River or its tributaries. Table 5 indicates the application efficiency estimates incorporated into the model. The application types associated with each irrigated parcel were initially procured from HydroBase and were subsequently verified/modified with expert knowledge provided by several local water users. Where water users implement mixed water application systems, efficiency numbers for the least efficient method were applied. Of the available return flow water for parcels located near the river, the model generally moved 85 percent as groundwater and 15 percent as overland flow. Exceptions to this routing approach occurred when/where large overland return flows consistently contribute flow to the Crystal. For parcels where overland flows were determined insignificant or non-existent, the model moved 100 percent of the available return flow as groundwater.

Table 5. Application efficiencies associated with various irrigation systems.

Irrigation System		Application Efficiency
Surface Irrigation	Wild Flood	15-40%
	Graded Furrow	50-80%
	Level Furrow	65-95%
Sprinkler	Mini gun	55-75%
	Side Roll	60-85%
	Center Pivot	75-95%
Microirrigation		70-95%

Source: Barta et al., 2004, Byelich et al., 2013

Table 6. Lower Crystal River, Colorado Return Flow Parameters

Diversion Node	CDSS Diversion ID	Consumptive Use Node(s)	Return Flow Node	Average Distance to Return Nodes (ft)	Irrigation Efficiency
Cloud Ditch	3800600	Cloud Ditch IRR1 - IRR2	Bane & Thomas Ditch	543	40%
Bane & Thomas Ditch	3800522	Bane & Thomas Ditch IRR1 - IRR4	Thomas Creek Confluence	1488	40%
Bowles and Holland Ditch	3800547	Bowles & Holland Ditch IRR1 - IRR4	Kaiser and Sievers Ditch	933	40%
Carbondale Ditch[1]	3800574	Carbondale Ditch IRR1 - IRR2	Roaring Fork River Confluence	525	85%
Dooley Ditch	3800640	Dooley Ditch IRR	East Mesa Ditch	855	85%
East Mesa Ditch	3800651	East Mesa Ditch IRR1- IRR2	Weaver and Leonhardy Ditch	3338	85%
Ella Ditch[2]	3800663	Ella Ditch IRR1	Carbondale Ditch	1398	40%
Ella Ditch[2]	3800663	Ella Ditch IRR2 - IRR5	Carbondale Ditch	689	40%
Helms Ditch	3800747	Helms Ditch IRR1 - IRR2	Bowles and Holland Ditch	907	40%
Lowline Ditch[3]	3800840	Lowline Ditch IRR1	Bailey Return Flow	2139	85%
Lowline Ditch[3]	3800840	Lowline Ditch IRR2	Bailey Return Flow	2481	85%
Pioneer Ditch[3]	3800939	Pioneer Ditch IRR1	Helms Ditch	2969	40%
Pioneer Ditch[3]	3800939	Pioneer Ditch IRR2	Bowles and Holland Ditch	3800	40%
Pioneer Ditch[3]	3800939	Pioneer Ditch IRR3	Bowles and Holland Ditch	3450	40%
Rockford Ditch	3800970	Rockford Ditch IRR1 - IRR3	Roaring Fork River Confluence	2053	40%
Sweet Jessup Canal	3801038	Sweet Jessup Canal IRR1 - IRR3	Roaring Fork River Confluence	4216	40%
Thompson Ditch	3801131	Thompson Ditch IRR1 - IRR3	Thompson Creek Confluence	1764	40%
Tybar Ditch and Pipeline	3801511	Tybar Ditch IRR1	Prince Creek Confluence	888	40%
Weaver and Leonhardy Ditch[1]	3801082	Weaver and Leonhardy IRR1 - IRR3	Roaring Fork River Confluence	525	85%

[1] Return flow locations for the Carbondale Ditch and the Weaver and Leonhardy Ditch were provided by the Town of Carbondale. However, return flow amounts have not been measured to date.

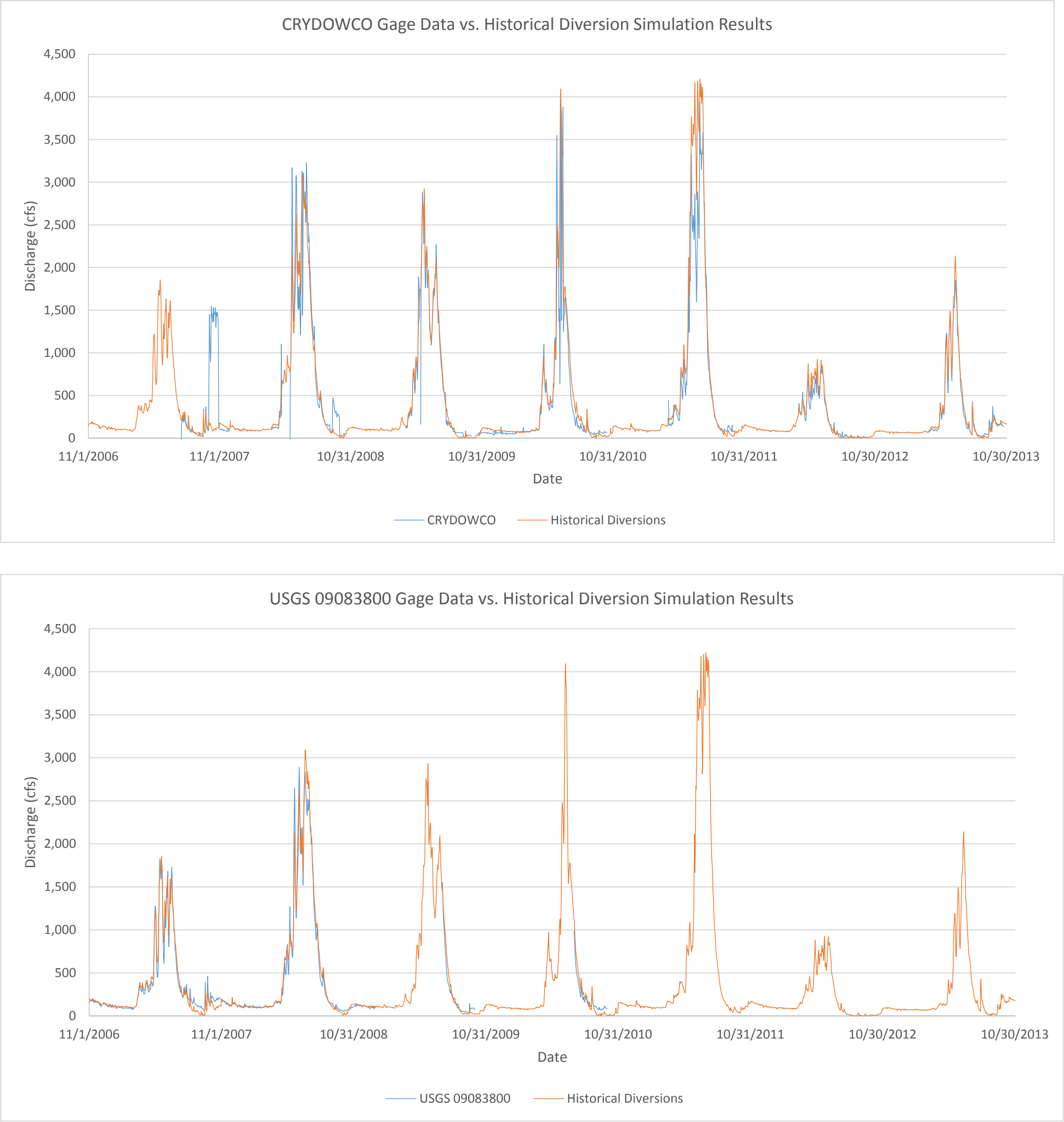
[2] Irrigation return flow fractions for the Ella Ditch were distributed based on water rights and associated irrigation parcels.

[3] Irrigation return flow fractions for the Lowline and Pioneer Ditches were estimated from water right ownership percentages and associated irrigation parcels.

3. MODEL CALIBRATION AND VALIDATION

Model performance was evaluated by comparing simulation results against observed data collected at two streamflow gauging stations: a CDWR gage (CRYDOWCO) located south of Carbondale and a USGS gage (09083800) located above the confluence with the Roaring Fork River (Figure 4). Three years of the total simulation period (2008, 2009, and 2011) were reserved for model calibration and optimization. The mean absolute difference objective function quantified model error during optimization runs (Tables 7 and 8). Calibration of the MODSIM-DSS model required manual adjustment of the parameters governing the quantity and timing of groundwater and overland return flows from consumptive use nodes. Changes to estimates of transmissivity and aquifer thicknesses occurred over the ranges of expected values for those parameters presented by Kolm et al. (2008) and eventually settled on a universal aquifer transmissivity of 5,000 feet squared per day (ft^2/d) and a specific yield of 0.23. Calibration sought to minimize mean absolute error observed during optimization runs. Comparison of simulation results over the years of interest (2010, 2012, and 2013) allowed for quantitative validation of model performance (Table 9).

Figure 4. Hydrographs comparing observed vs. simulated discharge data at two gage locations


CRYDOWCO Gage Data vs. Historical Diversion Simulation Results

USGS 09083800 Gage Data vs. Historical Diversion Simulation Results

Table 7. Model performance evaluated using the mean absolute difference objective function. Simulation results compared to observed data at CDWR gage CRYDOWCO, south of Carbondale.

Irrigation Year	Mean Absolute Error (cfs)
2008	162.8
2009	66.8
2010	102.1
2011	266.2
2012	38.2
2013	44.7

Table 8. Model performance evaluated using the mean absolute difference objective function. Simulation results compared to observed data at USGS gage 09083800, near the confluence with the Roaring Fork River.

Irrigation Year	Mean Absolute Error (cfs)
2007	49.5
2008	56.9
2009	36.4
2010	67.0

Table 9. Summary of model performance during simulation and validation runs.

Stream Gage ID	Model Optimization		Model Validation	
	Irrigation Years	Mean Absolute Error (cfs)	Irrigation Years	Mean Absolute Error (cfs)
CRYDOWCO	2008, 2009, 2011	165.3	2010, 2012, 2013	61.7
USGS 09083800	2007, 2008, 2009	47.6	2010	67.0

The calibrated model generally performed better during the validation period than it did over the optimization period. The higher than average streamflows observed during the optimization years (2008, 2009, and 2011) may explain these results. Wet hydrologic conditions likely trigger flows in otherwise ephemeral or intermittent tributary streams not included in the model network. Additionally, the linear models used to describe relationships between tributary streamflows and flows observed in the Crystal River above Avalanche Creek may break down at higher flows. Another possible explanation for the poorer model performance during the optimization period may come from the timing of the CDWR gage (CRYDOWCO) installation. CDWR began publishing data from this gage in October 2007. A review of the available data suggests that CDWR may not have established reliable rating curve for the site until after 2008. Thus, erroneous values recorded at the CDWR gage potentially impacted model performance evaluation during the optimization runs.

During both optimization and validation runs, the model frequently under-predicted streamflows at both the CDWR gage (CRYDOWCO) and the downstream USGS gage (09083800). The model performed best during dry years and winter months, suggesting shallow groundwater flows (not accounted for by irrigation return flows) and interactions between the river and alluvial aquifer may play an important role in governing streamflows in the lower Crystal River. Unfortunately, a lack of data describing groundwater behavior in the basin makes inclusion of such interactions in the model difficult.

4. SIMULATIONS AND SCENARIO TESTING

Five daily streamflow simulations were conducted to provide water resource managers and conservation groups with valuable information regarding the effects of alternative water use scenarios on in-channel flows in the lower Crystal River. The first simulation modeled spatial and temporal patterns in streamflows in the complete absence of consumptive and non-consumptive water use (i.e. baseline conditions). The second simulation modeled streamflows as affected by historical patterns of water use. The final three simulations modeled the effects of potential conservation strategies by the Town of Carbondale (TOC). Each simulation produced daily estimates of streamflow over the entire model simulation period (2007-2013) at each link in the model network.

Implementation of potential conservation strategies in the MODSIM-DSS model required reducing diversion rates at the Town of Carbondale Ditch, the Weaver and Leonhardy Ditch, and the Nettle Creek Pipeline by the percentages indicated in Table 10. Indoor use reductions were applied to the Carbondale Water Sys & PL diversion node and outdoor use reductions were applied to Town of Carbondale Ditch and the Weaver and Leonhardy Ditch diversion nodes (see Figure 1). The 'best-case scenario' implementation strategy used in the model assumed that TOC transits any water savings realized at diversion locations all the way to the Roaring Fork River (e.g. via unofficial agreements with other local water users or through use of new water conservation policy instruments currently under consideration by the Colorado legislature).

Table 10. Alternative water conservation scenarios tested during simulation runs[1].

Conservation Strategy	Indoor Use Reduction (%)	Outdoor Use Reduction (%)
Low Savings	11	8
Medium Savings	15	12
High Savings	19	16

Review of simulation results produced for the years of interest (2010, 2012, and 2013) at key locations in the model network provides a mechanism for assessing the impacts of consumptive/non-consumptive water use and potential municipal conservation strategies on streamflows across a range of hydrologic conditions (i.e. average conditions in 2010, moderate drought in 2013, and severe drought in 2012).

---

[1] Colorado Basin 2030 forecast savings as a percent of baseline (Colorado Water Conservation Board 2011)

5. RESULTS AND DISCUSSION

Results from each model simulation were compared to identify the timing and magnitude of changes in baseline streamflow conditions as affected by active water use without conservation and active water use with implementation of three alternative water conservation strategies by TOC. Model simulation results were assessed at model links on the mainstem Crystal River, immediately downstream from each diversion location where conservation was applied. These locations occurred below the Nettle Creek Confluence node, below the Carbondale Ditch node, and below the Weaver and Leonhardy node (see Figure 1). Due to the 'best-case-scenario' implementation of water conservation strategies in the model, the absolute quantity of conserved water realized at these locations propagated along all downstream segments. Simulation results were assessed on a monthly time step during the receding limb of the hydrograph (July-October) for each tested hydrologic condition (Tables 11-13).

Table 11. Simulation results produced below Nettle Creek Confluence node.

Simulation Scenario	Mean Monthly Discharge (cfs)											
	Average Conditions				Moderate Drought[1]				Severe Drought			
	JUL	AUG	SEPT	OCT	JUL	AUG	SEPT	OCT	JUL	AUG	SEPT	OCT
Baseline Conditions	505.29	256.55	119.37	99.71	297.00	149.03	187.23	155.92	161.11	94.40	79.57	66.28
Historical Diversions	423.51	162.28	74.30	83.87	199.35	60.50	117.15	138.57	74.06	39.28	32.79	33.99
Low Conservation Strategy	423.67	162.38	74.28	83.88	199.45	60.57	117.27	138.68	74.10	39.04	32.51	33.99
Medium Conservation Strategy	423.73	162.42	74.27	83.88	199.48	60.59	117.31	138.72	74.12	38.96	32.45	34.00
High Conservation Strategy	423.79	162.46	74.27	83.88	199.51	60.62	117.35	138.76	74.13	38.93	32.40	34.00
Average[2] (cfs)	**423.67**	**162.38**	**74.28**	**83.88**	**199.45**	**60.57**	**117.27**	**138.69**	**74.10**	**39.05**	**32.54**	**33.99**
Average Deviation[2] (cfs)	**0.01**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.01**	**0.01**	**0.00**	**0.02**	**0.02**	**0.00**

[1] Moderate drought monthly averages for September and October elevated due to several large precipitation events observed during the late summer and early fall of 2013.

[2] Calculations do not include simulation data produced in the absence of water diversions.

Table 12. Simulation results produced below Carbondale Ditch node.

Simulation Scenario	Mean Monthly Discharge (cfs)											
	Average Conditions				Moderate Drought[1]				Severe Drought			
	JUL	AUG	SEPT	OCT	JUL	AUG	SEPT	OCT	JUL	AUG	SEPT	OCT
Baseline Conditions	694.98	332.45	159.11	127.95	399.07	202.12	229.63	205.56	213.78	123.60	103.60	87.96
Historical Diversions	510.56	141.77	27.76	36.18	220.57	41.88	98.15	171.22	46.06	10.12	6.98	23.22
Low Conservation Strategy	512.10	143.36	28.80	36.77	221.67	42.97	99.30	171.85	46.97	10.61	7.41	23.31
Medium Conservation Strategy	512.84	144.13	29.31	37.07	222.20	43.50	99.86	172.15	47.42	10.91	7.71	23.36
High Conservation Strategy	513.59	144.91	29.83	37.36	222.73	44.04	100.42	172.46	47.88	11.26	8.04	23.40
Average[2] (cfs)	**512.27**	**143.54**	**28.93**	**36.85**	**221.79**	**43.10**	**99.43**	**171.92**	**47.08**	**10.72**	**7.53**	**23.32**
Average Deviation[2] (cfs)	**1.25**	**1.35**	**0.59**	**0.19**	**0.64**	**0.64**	**0.70**	**0.21**	**0.45**	**0.17**	**0.15**	**0.00**

[1] Moderate drought monthly averages for September and October elevated due to several large precipitation events observed during the late summer and early fall of 2013.

[2] Calculations do not include simulation data produced in the absence of water diversions.

Table 13. Simulation results produced below Weaver and Leonhardy Ditch node.

Simulation Scenario	Mean Monthly Discharge (cfs)											
	Average Conditions				Moderate Drought[1]				Severe Drought			
	JUL	AUG	SEPT	OCT	JUL	AUG	SEPT	OCT	JUL	AUG	SEPT	OCT
Baseline Conditions	716.15	354.89	179.03	147.07	408.48	210.59	238.73	214.25	224.61	133.77	112.32	95.55
Historical Diversions	526.06	157.48	41.35	49.17	229.41	49.96	106.98	180.99	55.58	18.30	13.37	31.13
Low Conservation Strategy	528.11	159.68	42.99	50.37	230.63	51.17	108.26	181.67	56.67	19.04	14.11	31.33
Medium Conservation Strategy	529.12	160.77	43.82	50.98	231.23	51.76	108.89	181.99	57.21	19.46	14.56	31.43
High Conservation Strategy	530.12	161.85	44.64	51.59	231.83	52.36	109.51	182.32	57.75	19.94	15.04	31.53
Average[2] (cfs)	**528.35**	**159.95**	**43.20**	**50.53**	**230.77**	**51.32**	**108.41**	**181.74**	**56.81**	**19.19**	**14.27**	**31.36**
Variance[2] (cfs)	**2.26**	**2.61**	**1.48**	**0.80**	**0.80**	**0.79**	**0.88**	**0.24**	**0.64**	**0.36**	**0.38**	**0.02**

[1] Moderate drought monthly averages for September and October elevated due to several large precipitation events observed during the late summer and early fall of 2013.

[2] Calculations do not include simulation data produced in the absence of water diversions.

Results comparison indicated that the most effective conservation measures proposed by TOC exist at the Carbondale Ditch and Weaver and Leonhardy Ditch. All three conservation scenarios failed to yield meaningful gains on the Crystal River downstream of the TOC municipal water supply on Nettle Creek. This is largely due to the small amount of water diverted by the pipeline in any given year. Larger conservation gains occurred below the Carbondale Ditch and Weaver and Leonhardy Ditch. The Carbondale Ditch and Weaver and Leonhardy Ditch divert the largest amounts of water for TOC residents.

Currently, CWCB holds a summer instream flow (ISF) right of 100 cfs and a winter ISF right of 60 cfs on the Crystal River from the confluence with Avalanche Creek to the confluence with the Roaring Fork River. These ISF rights are frequently not met during moderate drought and severe drought conditions. This conclusion led to the investigation of alternative low-flow discharge requirements for habitat maintenance for the lower Crystal River. S.K.Mason Environmental, LLC (now Lotic Hydrological Consulting Services) conducted that analysis in 2012 using the CWCB's R2CROSS methodology (Espegren, 1996) and the Wetted Perimiter methodology (Gippel, and Stewardson, 1998). The R2CROSS methodology produced a preliminary summer stream flow recommendation of 195 cfs at a study site located downstream from the CDWR stream gage on the lower Crystal River. The 95 cfs discrepancy between this recommendation and the CWCB ISF right may be explained by differences in cross-section morphology between the original CWCB survey point and the study location discussed here; water availability considerations by CWCB staff; or the incorporation of expert biological opinion into the original CWCB recommendation. The R2CROSS results identified a preliminary winter stream flow recommendation of 40 cfs, which is similar in magnitude to the existing CWCB ISF right. The Wetted-Perimeter methodology produced a range of preliminary summer stream flow recommendations. Discharges between 50 cfs and 60 cfs approximated the breakpoint in the relationship between wetted perimeter and discharge. This recommendation is intermediate to the summer and winter recommendations produced by R2CROSS, but more closely approximates the R2CROSS winter flow recommendation.

None of the conservation scenarios tested using the MODSIM-DSS for the lower Crystal River generated streamflows below the Carbondale Ditch sufficient to meet either the existing ISF right or the alternative flows discussed above throughout late summer or early fall (Note: several large precipitation events observed during September and October of 2013 elevated the calculated monthly average streamflow for these months during the moderate drought simulation run. Evaluations of simulated streamflow against recommended environmental flows are more easily resolved using model output on a daily timestep). Due to significant inflows to the Crystal River below the CPW Fish Hatchery, simulations indicated more pronounced effects of conservation—measured as a fractional increase in streamflow—below the Carbondale Ditch. Therefore, a conservation strategy whereby TOC aggregates all of its conservation to a single location, rather than equally among all locations, may prove more meaningful to stream ecological processes or habitat quality. By targeting flow improvements in the more flow depleted segment below the Carbondale Ditch, TOC can realize fractionally greater increases in streamflow. A short stream distance separates the Carbondale Ditch headgate from relatively large return flows at the CPW Fish Hatchery. Therefore, while water savings by TOC is likely an important part of watershed wide efforts to address streamflow depletion on the lower Crystal River, efforts focused on enhancing ecological conditions and/or function should continue to consider options for either increasing flows in the Crystal River above the Carbondale Ditch, or making the available flows more supportive of those ecosystem services most highly valued by stakeholders.

REFERENCES

Barta,R., Broner, I., & Schneekloth, J. (2004). Colorado High Plains Irrigation Practices Guide. Colorado Water Resources Research Institute Special Report No. 14.

Byelich, B., Cook, J., Rowley, C. (2013). Small Acreage Irrigation Guide. NRCS Water Rights Irrigation and Management Report. 25 p.

Capesius, J.P., and Stephens, V.C. (2009). Regional regression equations for estimation of natural streamflow statistics in Colorado: U.S. Geological Survey Scientific Investigations Report 2009–5136, 46 p.

Colorado Water Conservation Board [CWCB], Colorado Department of Natural Resources. (2011). SWSI 2010 Municipal and Industrial Water Conservation Strategies. Prepared by Aquacraft Inc. and Headwaters Corporation.

Espergen, G.D. (1996). Development of instream flow recommendations in Colorado using R2CROSS: Denver, CO. Water Conservation Board, 34 p.

Glover, R. (1977). Transient Groundwater Hydraulics, Water Resources Publications, LLC., Highland Ranch, CO.

Gippel, and Stewardson. (1998). Use of wetted-perimeter in defining minimum environmental flows: Regulated Rivers Research and Management. v. 14, pp 53-67.

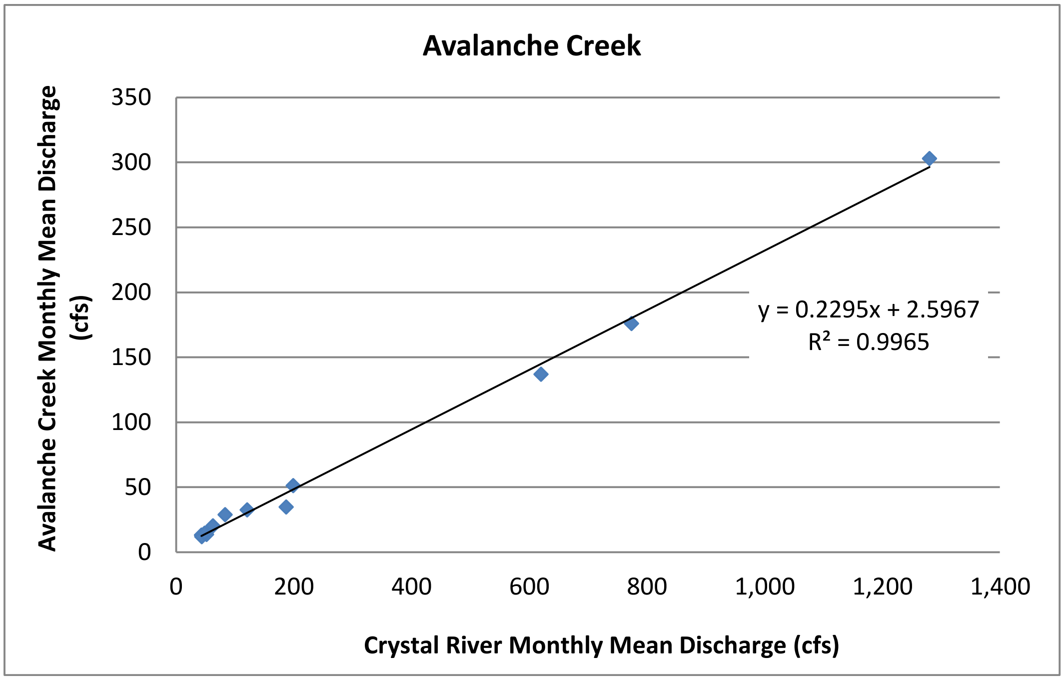
Kolm, K.E., van der Heijde, P.K.M., and Dechesne, M. (2008). GIS-Based Ground Water Resources Evaluation of the Crystal River and West Sopris Creek (CRWS) Study

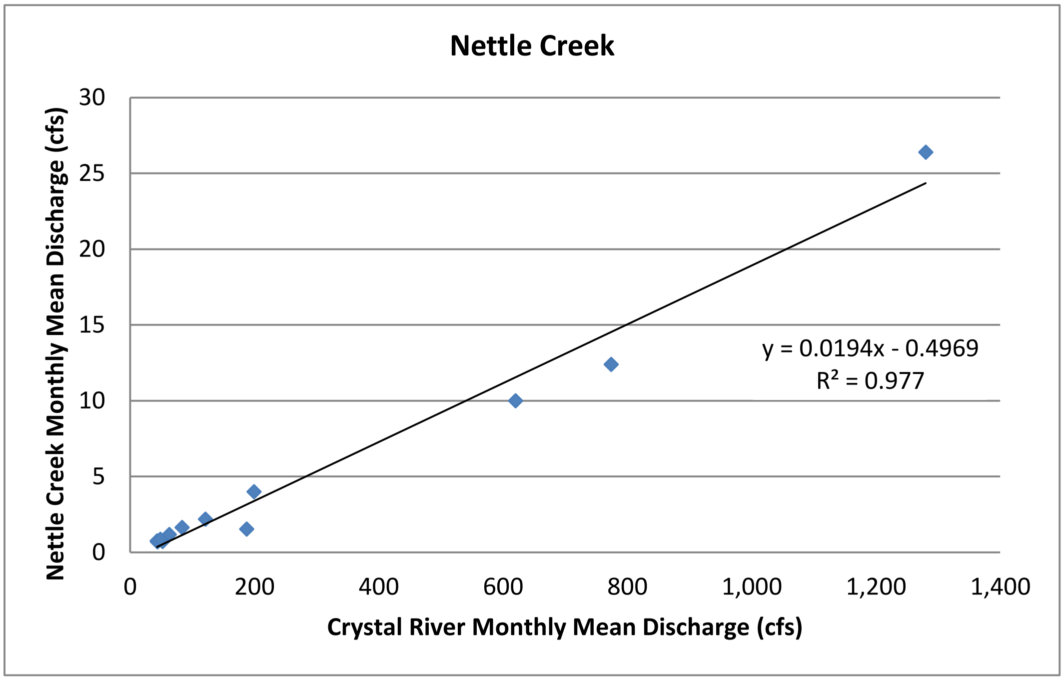
Area, Pitkin County, Colorado. Report for Pitkin County Board of County Commissioners Colorado. Contract No. 132-2007.

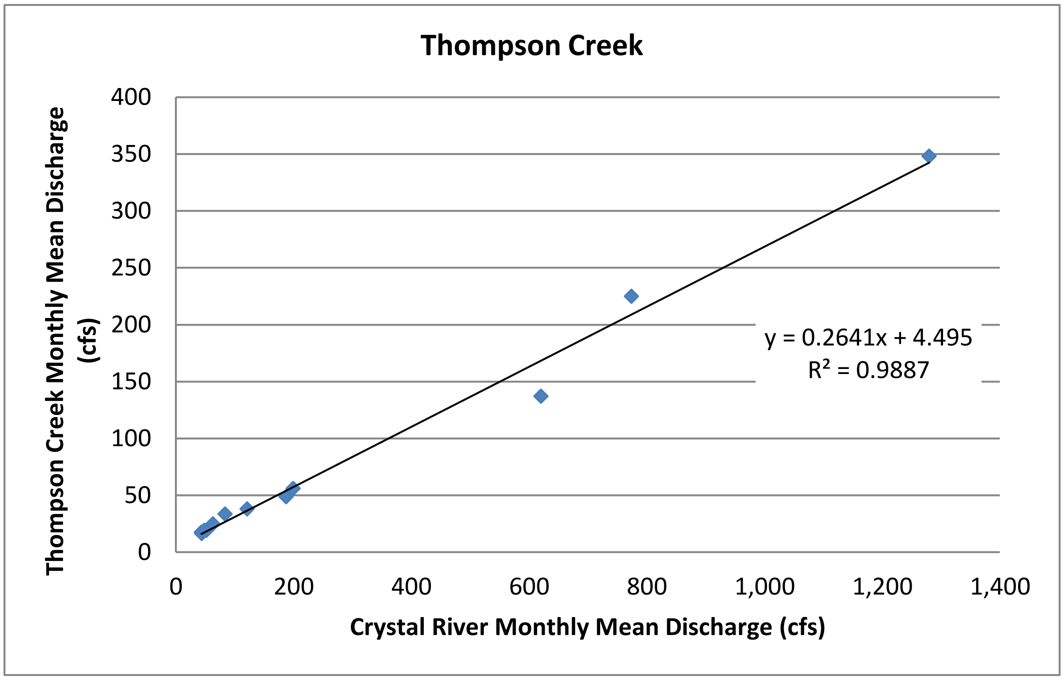
Johnson, A.I. (1967). Specific Yield-Compilation of Specific Yields for Various Materials, U.S. Geological Survey Water Supply Paper 1662-D.

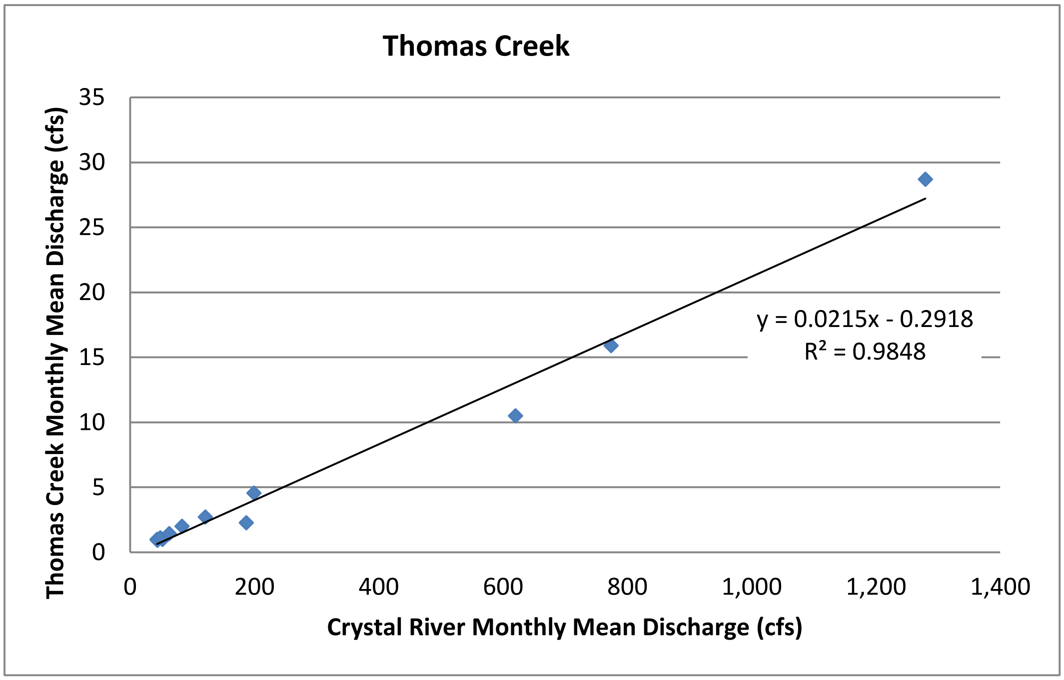
Labadie, J.W. (2010). MODSIM 8.1: River Basin Management Decision Support System User Manual and Documentation, Colorado State University, Ft. Collins, CO.

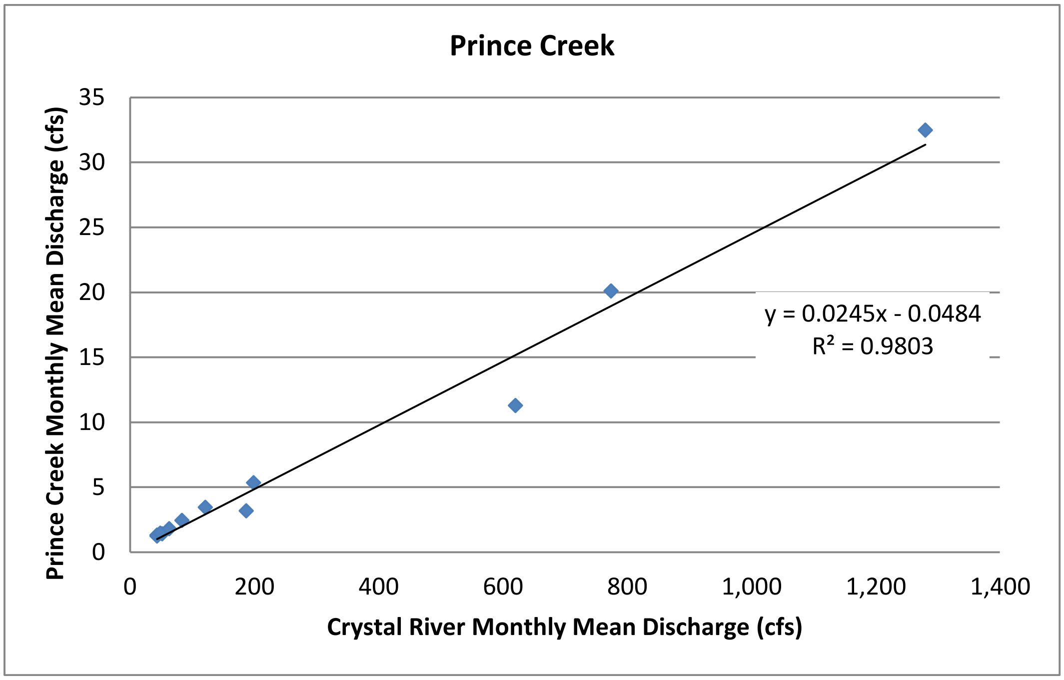
Maasland, M. (1959). Water table fluctuations induced by intermittent recharge. Journal of Geophysical Research, 64(5), 549-559.


Avalanche Creek
Avalanche Creek Monthly Mean Discharge (cfs)
350
300
250
200
150
100
50
0
0
200
400
600
800
1,000
1,200
1,400
Crystal River Monthly Mean Discharge (cfs)
y = 0.2295x + 2.5967
R² = 0.9965


Nettle Creek
Nettle Creek Monthly Mean Discharge (cfs)
30
25
20
15
10
5
0
0
200
400
600
800
1,000
1,200
1,400
Crystal River Monthly Mean Discharge (cfs)
y = 0.0194x - 0.4969
R² = 0.977


Thompson Creek
Thompson Creek Monthly Mean Discharge (cfs)
400
350
300
250
200
150
100
50
0
0
200
400
600
800
1,000
1,200
1,400
Crystal River Monthly Mean Discharge (cfs)
y = 0.2641x + 4.495
R² = 0.9887


Thomas Creek
Thomas Creek Monthly Mean Discharge (cfs)
35
30
25
20
15
10
5
0
0
200
400
600
800
1,000
1,200
1,400
Crystal River Monthly Mean Discharge (cfs)
y = 0.0215x - 0.2918
R² = 0.9848


Prince Creek
Prince Creek Monthly Mean Discharge (cfs)
0
5
10
15
20
25
30
35
Crystal River Monthly Mean Discharge (cfs)
0
200
400
600
800
1,000
1,200
1,400
y = 0.0245x - 0.0484
R² = 0.9803