APPENDIX A:

An EcoDSS for Balancing Consumptive and Non-Consumptive Water Uses on the Crystal River, Colorado

Technical Report

An Ecological Decision Support System for Balancing Consumptive and Non-Consumptive Water Uses on the Crystal River, Colorado

lōtic hydrological

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DEFINITION OF TERMS

AF: Acre Feet

CFS: Cubic Foot per Second

CDSS: Colorado Decision Support System

CDWR: Colorado Division of Water Resources

CRD: Colorado River District

CRMP: Crystal River Management Plan

CWCB: Colorado Water Conservation Board

GIS: Geographic Information System

HSC: Habitat Suitability criteria

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

IHA: Indicators of Hydrologic Alteration

ISF: Instream Flow

USGS: United States Geological Survey

WUA: Weighted Usable Area

1. Introduction

The nexus of growing populations, recurring droughts, and limited water supply in basins across the state leaves many streams and rivers with substantially depleted flows. Where these conditions occur frequently, some corresponding loss in functionality of the riverine ecosystem likely results. Reduced ecological functionality impacts the ability of rivers and streams to provide important ecosystem services critical for protecting native species, supporting vibrant recreation-tourism economies, and improving or maintaining local residents' high quality of life. Diverse stakeholders representing multiple water use types increasingly recognize the importance of non-consumptive water uses during water resource planning processes. Unfortunately, the relative dearth of comprehensive and widespread non-consumptive use evaluation tools (e.g. quantitative frameworks designed to elucidate the environmental or social costs/benefits associated with a proposed action), policies, and planning documents confound efforts to explicitly recognize and include non-consumptive use protection in long range water resource planning efforts currently underway in Colorado.

Local and regional governments, watershed groups, and water users continue to search for creative solutions for improving in-stream conditions within existing legal and administrative frameworks (e.g. water banking projects; water leasing, loan or acquisitions programs; infrastructure efficiency improvements; channel modification; etc.). However, these efforts largely occur in the absence of regional planning and/or project prioritization. Without such planning in place to help anticipate the ecological benefits realized from implementation of proposed projects or management strategies, non-consumptive use protection or enhancement project implementation occurs on an opportunistic basis that may misdirect focus to low priority issues and may constitute inefficient expenditures of limited funding. Furthermore, where only a limited or qualitative understanding of the actual non-consumptive use needs for a given river exist, water resource development projects may produce unintended consequences that damage local economies, degrade habitat, or otherwise impair water quality. Comprehensive *stream management planning* provides stakeholders with needed guidance and decision frameworks for prioritizing and evaluating the costs/benefits associated with a variety of proposed actions.

The development of the Crystal River Management Plan (CRMP) utilized existing and newly collected data and analysis to prioritize the allocation of water resources between multiple competing environmental, municipal, and agricultural uses to ensure both the protection of those existing uses, and the long-term viability and resilience of riverine ecosystems. Ultimately, stream management planning on the Crystal River helped stakeholders and resource managers better understand the interplay between hydrology, hydraulics, channel form, alternative water use/management strategies, and the physical and biological processes the support and ecological function.

Stakeholder interest in these complex relationships stemmed from work conducted on the Crystal River during drought conditions, which highlighted the spatial nature of water depletions and their correlation to temperature increases predicted to undermine fishery health. Questions raised during conversations between local water users, water managers, conservation groups and water leasing entities underscored the need for a flexible decision-making framework to support rapid quantification of the ecological impact associated with a range of alternative water management scenarios or channel modification projects. An Ecological Decision Support System (EcoDSS) developed in support of the CRMP provides this much-needed support for water management decision-making processes.

The EcoDSS utilizes a hierarchical framework to examine the spatial and temporal effects of management on the Crystal River. The assessment of first-order effects includes the management-induced changes on the magnitude, frequency, and duration of various measures of hydrological regime behavior. The investigation of second-order effects considers the interplay between hydrology and channel structure and the way that changes to the flow regime impacts hydraulics. Third-order effects exist at the intersection between channel hydraulics and the processes and conditions most relevant to aquatic and riparian biota. Implementation of this hierarchical framework results in a collection of loosely coupled hydrologic, hydraulic and statistical models to 1) predict and simulate rainfall-runoff processes contributing streamflow to the lower Crystal River watershed, 2) allocate and account for 'paper' and 'real' water along the lower Crystal River according to Colorado Water Law, 3) estimate spatially distributed water surface elevations, stream depths, and velocity profiles corresponding to a range of hydrological conditions, water conservation scenarios, or physical channel modifications, and 4) quantify the morphological and ecological effects of alteration of streambed topography or incremental increases/decreases in streamflow on adjoining reaches of the river (Figure 1). This structure allows stakeholders and resource managers to quantitatively evaluate the current functional condition of the riverine ecosystem, and investigate the ecological benefits realized by any proposed action to adjust the magnitude and duration of water diversion and/or modify the structure of the stream channel.

The complex interplay between the human, physical, chemical, and biological components of the Crystal River, and of riverine systems in general, complicates the task of identifying appropriate management strategies that respond to local concerns about one or more of the attributes most commonly associated with the delivery of ecosystem goods and services. The EcoDSS implements the hierarchical framework described above to evaluate ecosystem metrics that reflect fundamental behaviors and characteristics of channel dynamics, riparian resiliency, and aquatic habitat (Figure 2).

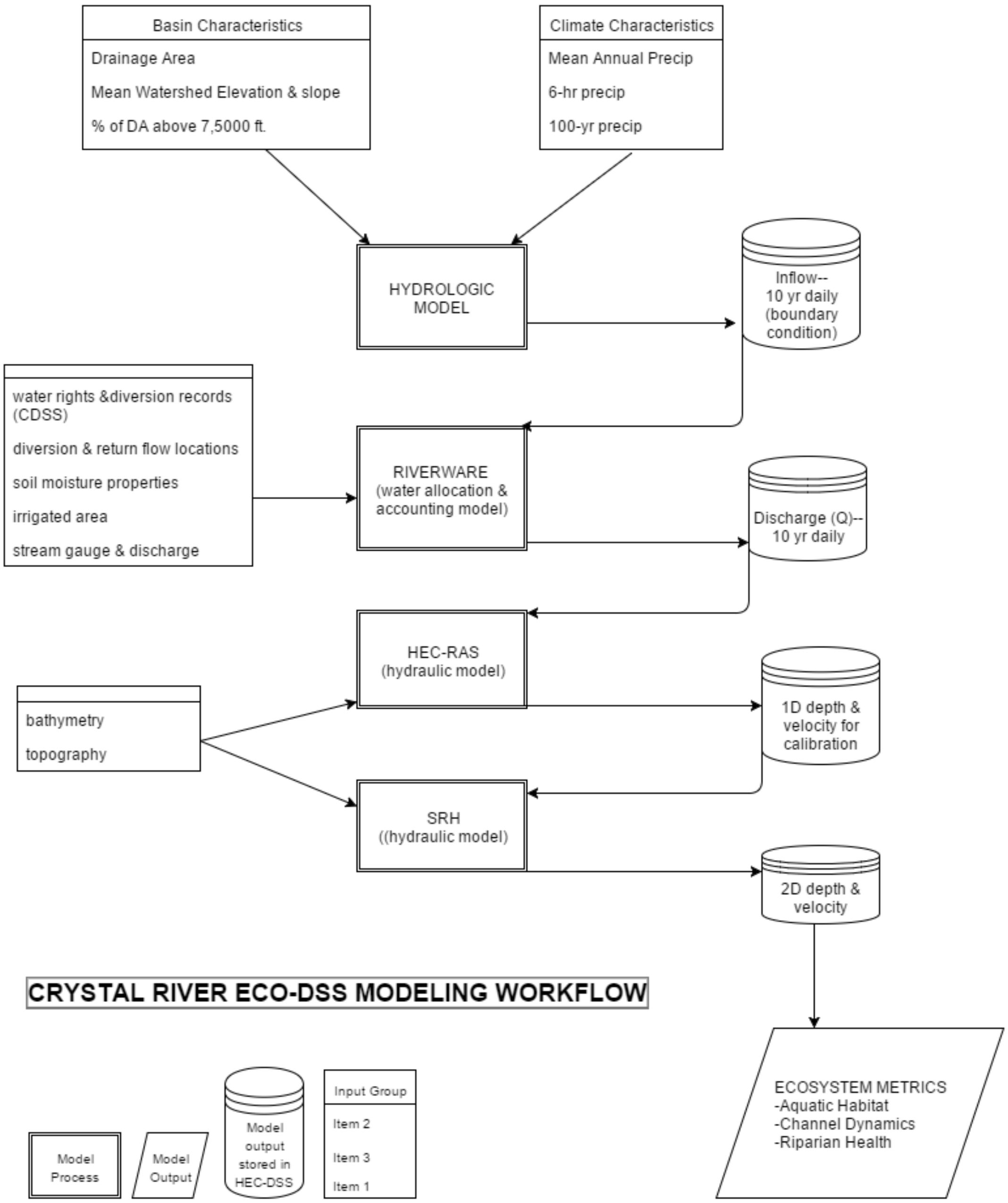

Figure 1. EcoDSS modeling workflow

Channel Dynamics

Channel dynamics encompass the fluvial and geomorphological processes that interact to control channel form and evolution across a range of spatial and temporal scales. Channel dynamics respond to interactions between patterns of rainfall and runoff, catchment-scale physical attributes (e.g. surficial geology, topography), riparian community structure, and local use practices (e.g. transportation corridor alignment, grazing practices). As a result, human management activities that modify the hydrological regime, alter patterns of erosion, adjust the structure of the channel bed, or modify riparian vegetation may yield fundamental shifts in the geometry and behavior of the stream at the channel (tens of yards) or reach (hundreds of yards) scale.

Alteration of sediment supply, channel forming flows, or streambank vegetation may lead to complex interactive effects that result in reduced resiliency of local channel forms. For example, in unconfined alluvial streams, degradation of riparian forests frequently results in diminished bank cohesion, an increased rate of channel avulsion, and a progressive widening and filling of the stream channel itself. These high-dynamic channel states generally provide poor aquatic habitat and present a risk to streamside property and infrastructure.

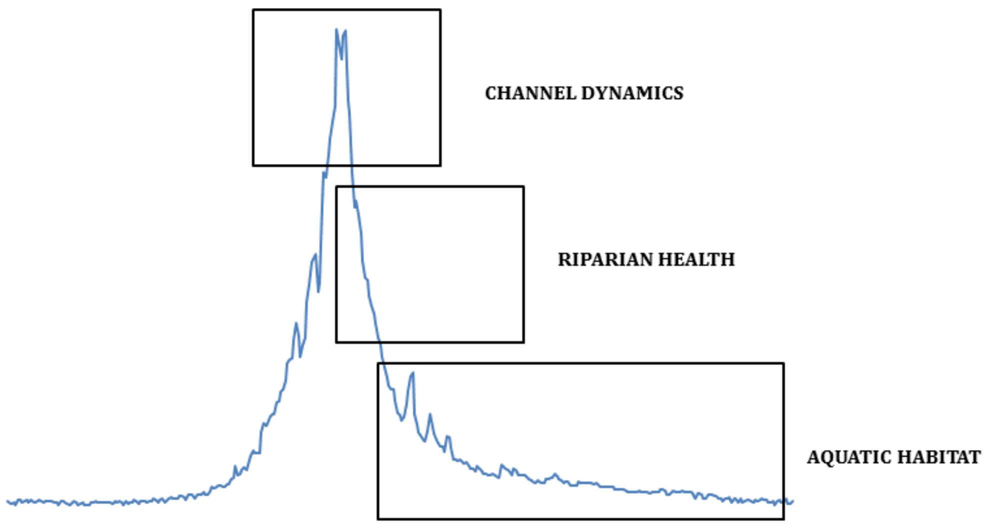

Figure 2. The EcoDSS considered three primary ecosystem attributes: channel dynamics, riparian health and aquatic habitat. An extensive modeling framework supported investigation into the first, second, and third order effects of resource management on each attribute.

Riparian Health

Riparian areas support a wide variety of physical, biological, and ecological processes. Riparian zones generate important organic inputs for stream ecosystems, support streambank cohesion, perform vital nutrient cycling roles, and lend to the quality of aquatic habitat by providing shade and buffering against temperature extremes. The hydrological regime, sediment and channel dynamics, invasive vegetation, and near-stream land uses frequently impact the functionality of riparian areas.

Riparian areas exist in a complex equilibrium state governed by the local geometry of the channel/floodplain system and the inter-annual pattern of flood flows and baseflows. Occasional scouring of overbank areas provides the necessary habitat for germination of many riparian plant species. Following germination, seedlings require a relatively slow reduction in water table height over the progression of the growing year. Rapid water table reduction or late season water table heights that drop below the rooting depth of cottonwoods and other riparian plants stresses vegetation and can lead to mortality. Management activities that alter the magnitude, timing, or frequency of peak flows and baseflows, therefore, may limit riparian recruitment leading to decadent stands with little or no regeneration.

Aquatic Habitat

Interactions between streambed structure, channel hydraulics, water chemistry, vegetative shading, and organic matter inputs dictate the quality of habitat available for fish, macroinvertebrates, and macrophytes. In alluvial stream systems, high quality habitat typically supports vibrant and productive aquatic ecosystems—the kind of ecosystems that sustain robust trout fisheries. Habitat quality shares a directly proportional relationship to food chain length in many systems. Ecosystems supporting long food chains tend to display greater resilience to changing external forcing variables like climate. Land and water management activities that affect sediment transport dynamics, streambed complexity, riparian shading, and local hydraulics comprise important primary controls on aquatic habitat quality.

Many aquatic species rely on specific and relatively narrow ranges of water depth, velocity and substrate types to perform various feeding/resting behaviors or complete different life stages. Fragmentation or degradation of habitat for aquatic species may, therefore, arise from modification of the hydrological regime, which alters local channel hydraulics and the spatial distribution of water depths and velocities. In a similar fashion, activities that physically alter the structure of the streambed may impact habitat quality by transforming the local hydraulic channel response to a given streamflow. The critical interaction between local structure and hydraulics gives credence to restoration approaches that aim to improve ecosystem function by reconfiguring channel cross-sectional geometry or planform patterns.

1.1 Planning Context

When executed properly, stream management plans can address a multitude of water-related issues, including: sedimentation and erosion, flooding risk and mitigation, drinking water quality and supply, agricultural and industrial water supply, water storage, urban runoff, and habitat for aquatic life. Such planning exercises are well suited to decision-making and project identification in situations where competing water use needs produce potential for conflict. Once completed, these plans are meant to assist water users in planning for a sustainable future with the underlying assumption that a healthy watershed will support vibrant local economies and the high quality of life enjoyed by local residents. Meeting these lofty goals requires collaborative, integrated watershed planning and management rooted in robust understanding of local physical processes. Utilization of the EcoDSS in the development of the CRMP enabled a comprehensive review of stream processes affected by management activities.

Colorado's Western Slope is especially disadvantaged by the lack of non-consumptive use planning due to the geographic density of streams with high environmental or recreational value, widespread economic dependence on recreation and tourism, and the value local residents place on a healthy ecosystem. As a result, the Colorado River Basin Roundtable recently identified establishment of a basin-wide stream management planning effort as a high-priority action (Colorado Basin Roundtable 2015). The EcoDSS was developed in consideration of this planning goal. The framework described here represents a modular and scalable approach for evaluating current ecosystem conditions and enabling a robust cost-benefit analysis of alternative management approaches or projects.

2. Study Area

A wide base of ecological research by Poff (2009) and others elevates the hydrological regime to the position of "master variable." This ecological theory presumes that changes to the hydrological regime and subsequent feedbacks between the physical structure of the stream channel and the biota that live there represent primary controls on the functioning of riverine ecosystems. In recognition of this work, development of the EcoDSS focused on the portion of the Crystal River subjected to the greatest amount of surface water diversion activity (Figure 3). More than 30 surface water diversions exist on the Crystal River and its tributaries between Avalanche Creek and the Roaring Fork River. Accounting for the first-order effects of management decisions, therefore, required modeling surface water hydrology for Avalanche Creek, Nettle Creek, Thompson Creek, Thomas Creek, Prince Creek, and the Crystal River mainstem below the stream gauge (USGS 09081600) near Redstone.

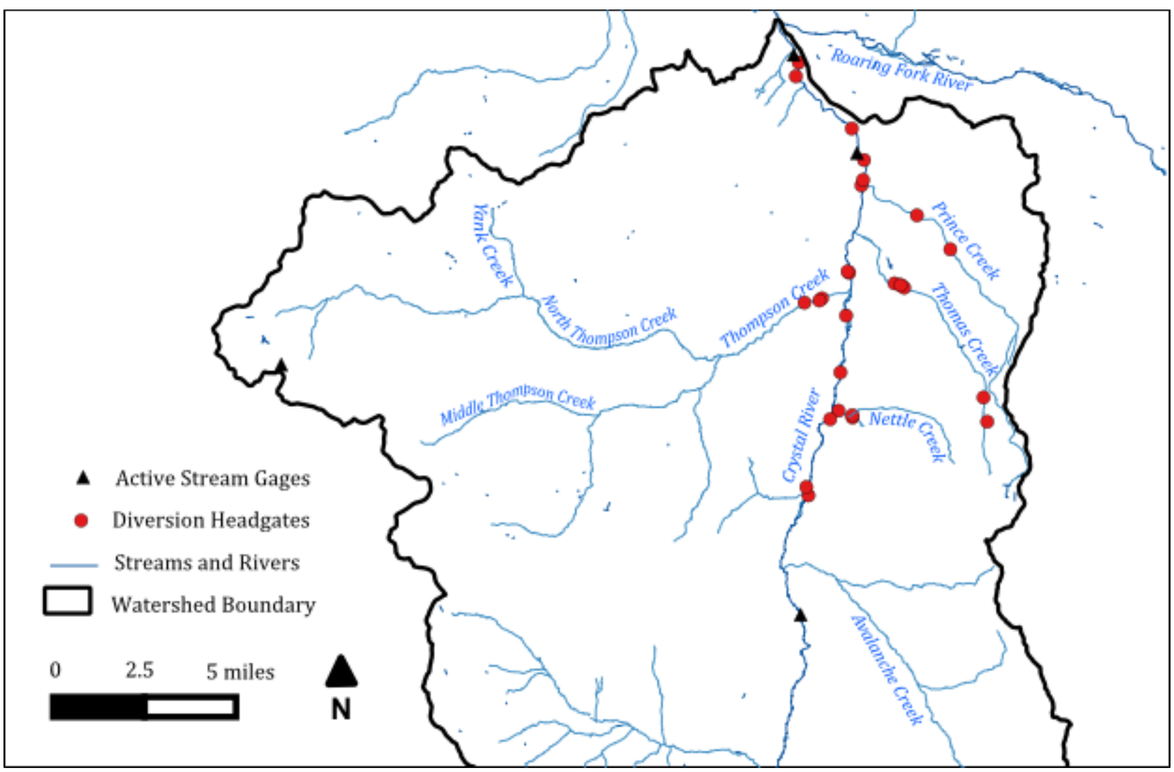

Figure 3. The hydrological modeling components of the EcoDSS included segments of the Crystal River between Avalanche Creek and the Roaring Fork River.

Evaluation of second and third-order management effects in the Crystal River watershed did not include tributaries or reaches of the Crystal River mainstem above the confluence with Bill Creek. The seven miles of the Crystal considered were delineated into ten management reaches whose boundaries were defined by surface water diversion points and/or changes in dominant channel type (Figure 4).

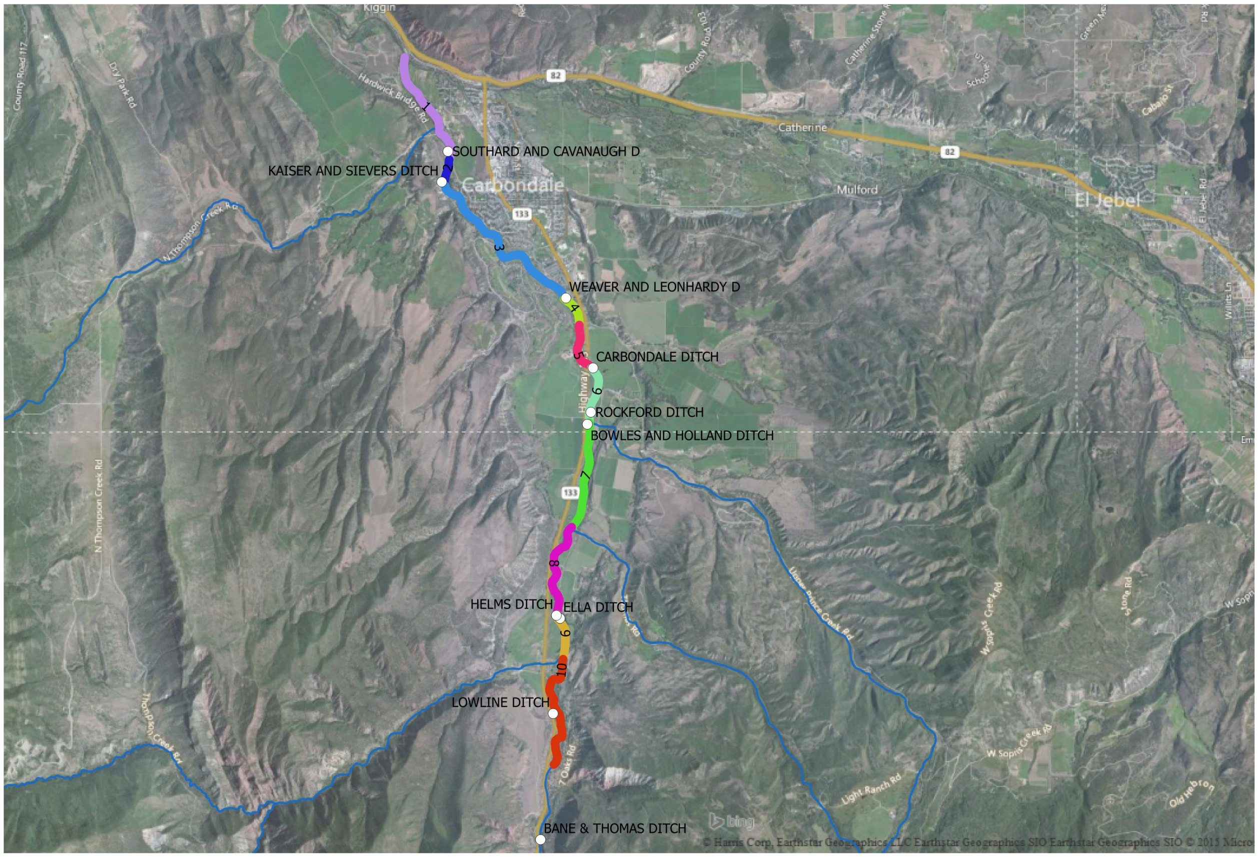

Figure 4. The hydraulic and ecological modeling components of the EcoDSS included ten segments of the Crystal River between Bill Creek and the Roaring Fork River.

3. First-Order Effects - Assessing Hydrological Modification

The first-order effects examined on the Crystal River included the changes in streamflow duration, frequency and magnitude induced by surface water diversion activity or hydrological condition (i.e. drought vs. flood). Assessment of drought or flood responses required statistical prediction of hydrological boundary conditions on the Crystal River and its tributaries. Understanding the complex interplay between inflow hydrology and the exercise of surface water diversion water rights under Colorado Water Law necessitated development of a water rights allocation and accounting model. Integration of the two efforts produced a modeling framework for predicting the impacts of resource management decisions and climatic conditions on streamflow on a daily timestep at 33 locations across the watershed.

3.1 Hydrological Boundary Conditions

The historical data record for tributary streamflows in the Crystal River watershed is extremely sparse. Daily streamflow datasets available for Thompson Creek and Prince Creek are either from too high in the tributary watershed or do not cover a long enough period to be useful. Fortunately, a robust data set exists for the Crystal River mainstem. The historical record at this location (USGS 09081600) provided a critical data set for predicting flows in Avalanche Creek, Nettle Creek, Thompson Creek, Thomas Creek, and Prince Creek. A statistical approach was use to model daily streamflows at each of these locations across a range of flood and drought conditions.

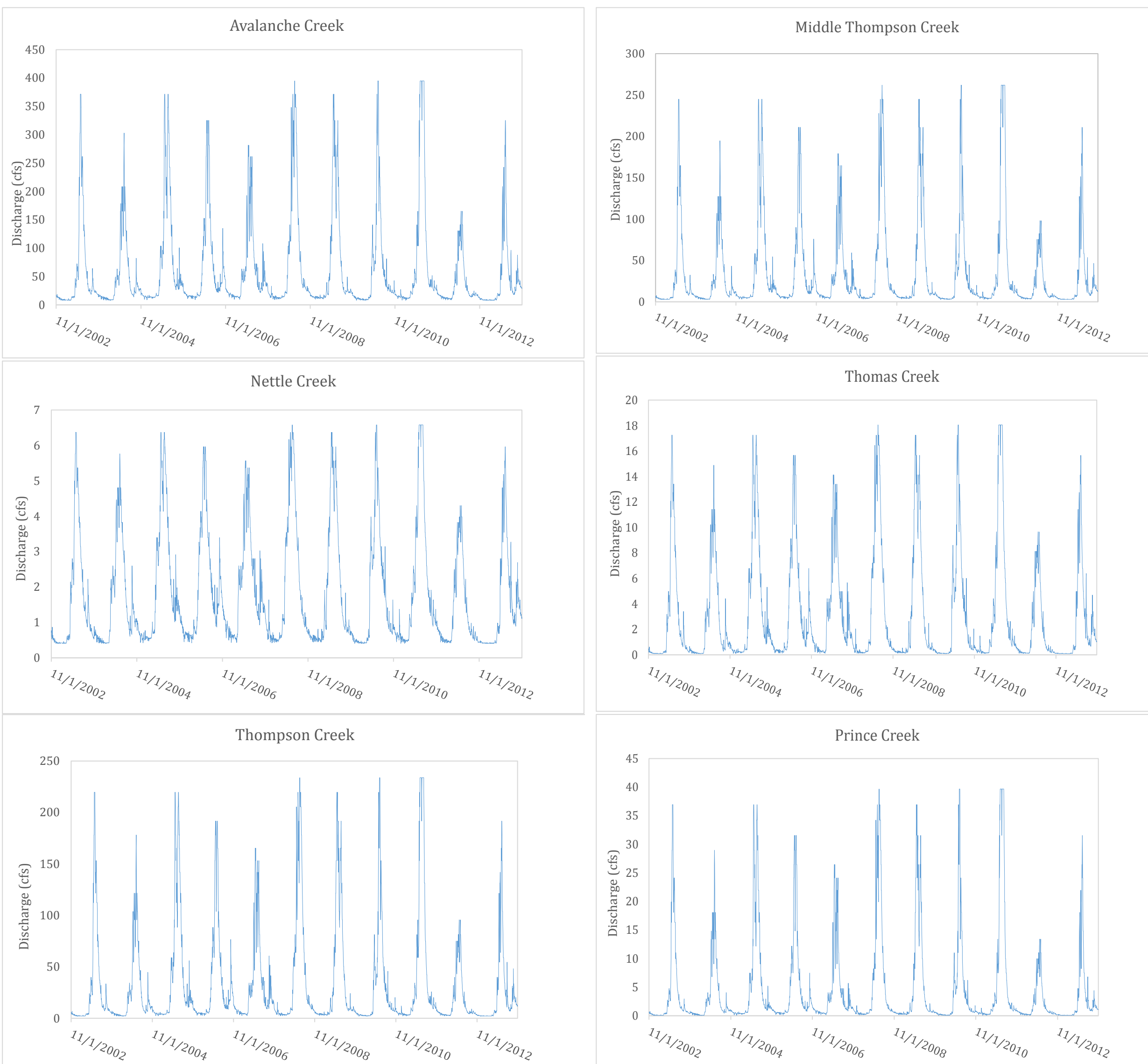

Figure 5: Predicted hydrological inflows from major tributaries in the lower Crystal River watershed.

Typically, investigators use process-based models or statistical regression models generate streamflow estimates for ungaged basins. Use of statistical regression models like USGS StreamStats program presents some limitations and difficulties when conducting long simulations covering a range of meteorological and hydrological conditions. An alternative method for estimating streamflow statistics for ungaged systems is the spatial interpolation of point data from characteristic streams with unaltered flow regimes. In the Crystal River watershed, flow-duration curves were predicted using a three dimensional canonical kriging approach (3DCK) or physiographical-space-based interpolation. 3DCK allowed for the spatial interpolation of streamflow statistics using a two-dimensional spatial representation of the physiographical qualifiers (the physiographic space) of each tributary watershed (Archfield et al. 2013; Castiglioni, Castellarin, and Montanari 2009).

Implementation of the 3DCK approach initially required identification of a set of reference gauges. The USGS Hydro-Climatic Data Network (HCDN) provided a list of gauges from unaltered watersheds across the Colorado Rocky Mountain region (Table 1) to serve this purpose. The selected reference gauges were minimally altered by regulation, diversion, mining and other anthropogenic activities. Canonical correlation analysis (CCA) was used to generate a pair of canonical correlation coefficients for each reference and prediction basin based on the degree of similarity to the set of reference gauges for eight physiographic qualifiers (e.g. mean slope, average precipitation) (Table 2). A flow duration curve (FDC) for each reference gauge was developed using the gauged period of record. The FDCs and the canonical correlation coefficients became the basic set of data used to implement 3DCK as described by Castellarin (2014). The USGS stream gauge on the Crystal River near Redstone was used as the donor gauge to calculate daily streamflow time series from the FDCs for each tributary in the watershed.

Table 1: Reference gauges used in calculation of hydrological boundary conditions on tributary streams in the Crystal River Watershed.

USGS ID	Station Name
9081600	CRYSTAL RIVER AB AVALANCHE C, NEAR REDSTONE, CO.
9110000	TAYLOR RIVER AT ALMONT, CO.
9112500	EAST RIVER AT ALMONT CO.
9115500	TOMICHI CREEK AT SARGENTS, CO.
9119000	TOMICHI CREEK AT GUNNISON, CO.
9124500	LAKE FORK AT GATEVIEW, CO.
9125000	CURECANTI CREEK NEAR SAPINERO, CO.
9128500	SMITH FORK NEAR CRAWFORD, CO.
9132500	NORTH FORK GUNNISON RIVER NEAR SOMERSET, CO.
9134500	LEROUX CREEK NEAR CEDAREDGE, CO.
9165000	DOLORES RIVER BELOW RICO, CO.
9168100	DISAPPOINTMENT CREEK NEAR DOVE CREEK, CO.
9239500	YAMPA RIVER AT STEAMBOAT SPRINGS, CO.
9241000	ELK RIVER AT CLARK, CO.
9245000	ELKHEAD CREEK NEAR ELKHEAD, CO.
9250000	MILK CREEK NEAR THORNBURGH, CO.
9256000	SAVERY CREEK NEAR SAVERY, WY
9304500	WHITE RIVER NEAR MEEKER, CO.
9352900	VALLECITO CREEK NEAR BAYFIELD, CO.
9361500	ANIMAS RIVER AT DURANGO, CO.

Various hydrological or climatic conditions were modeled using the period of record for the USGS gauge near Redstone. Initially, hydrological boundary conditions for tributaries were calculated using 30 years of mean daily streamflows measured at the USGS gauge near Redstone (Figure 5). Subsequently, daily streamflows corresponding to exceedance probabilities for a range of hypothetical drought and flood (P05, P10, P20, P25, P50, P75, P80, P90, P95) were derived from the historical data set. Streamflow time series were then simulated for each tributary using the FDC mapping approach described above. The above approaches yielded two primary data sets to support hydrological simulation modeling: 1) a 30-year historical data set for the period from 1983-2013, and 2) a synthetic, nine-year data set simulating a range of flood and drought conditions (Figure 6). The former data set was used primarily for model calibration and for characterizing the effects of current management practices. The latter was used for investigating the impact of various water management scenarios or projects under different hydrological or climatic conditions.

Table 2. Basin characteristics and CCA coefficients calculated for reference and prediction basins.

Station	Latitude	Longitude	Drainage Area (mi2)	Mean Slope (%)	Averate Precip. (in)	Average Elev. (ft)	Elev. Above 7500 (ft)	100-year 6-hr Precip. (in)	First CCA Coefficient	Second CCA Coefficient
Reference Locations										
9081600	39.2322	-107.2273	167.3	48.4	39.5	10166	97.7	2.3	170.87	128.45
9110000	38.6644	-106.8453	477.1	30.9	23.9	10647	100	2.2	171.14	129.25
9112500	38.6644	-106.8481	289.3	34.2	31.7	10272	100	2.3	170.4	127.91
9115500	38.4117	-106.4228	148.3	31.2	21.4	10237	100	2.2	169.45	129.07
9119000	38.5217	-106.9409	1059.9	24.2	18.6	9733	100	2.1	169.64	128.66
9124500	38.2989	-107.2301	339.2	42.7	28.2	10884	100	2.4	171.5	129.75
9125000	38.4878	-107.4151	35	38.5	22.7	9674	100	2.3	169.35	130.05
9128500	38.7278	-107.5067	43.4	43.6	25.6	9165	97.3	2.3	168.74	129.86
9132500	38.9258	-107.4342	525.6	33	28.5	8886	87.1	2.3	169.6	127.77
9134500	38.9264	-107.7937	34.7	17.1	33.5	9723	99.5	2.5	171.3	126.97
9165000	37.6389	-108.0604	105.6	38.2	36.1	10631	100	2.7	171.75	127.75
9168100	37.8767	-108.5831	147	27.6	21.5	7932	65.4	2.3	169.55	126.8
9239500	40.4836	-106.8323	567.4	21.7	31.5	8782	86.3	2.2	170.5	127.51
9241000	40.7175	-106.9159	216.5	27.3	38.1	9106	99.4	2.4	170.44	128.16
9245000	40.6697	-107.2851	67.7	20.4	30.7	8414	94.5	2.2	169.69	128.32
9250000	40.1936	-107.7323	63.3	21.3	24.3	7906	62.9	2.2	170.92	127.95
9256000	41.0978	-107.3819	332.4	15.3	26.6	7837	74.8	2.1	170.6	128.01
9304500	40.0336	-107.8623	760.3	24.9	30.9	8938	84	2.4	171.89	128.29
9352900	37.4775	-107.5437	72.5	57.9	39.5	11350	100	3.5	172.57	130.3
9361500	37.2792	-107.8803	709.6	46.6	35.9	10146	93.5	2.9	170.91	127.61
Prediction Locations										
Avalanche	39.2473	-107.2339	42.9	56	39.83	10500	98	2.4	171.34	129.6
Nettle	39.298	-107.2136	3.59	47	32.07	9220	89	2.2	169.5	129
Thompson	39.3334	-107.2087	77.3	31	32.34	9120	93	2.3	169.63	127.63
Thomas	39.3523	-107.2055	6.1	27	28.07	8650	74	2.2	170.03	127.03
Prince	39.3672	-107.2013	10.9	27	24.13	8210	66	2.1	169.65	127.21

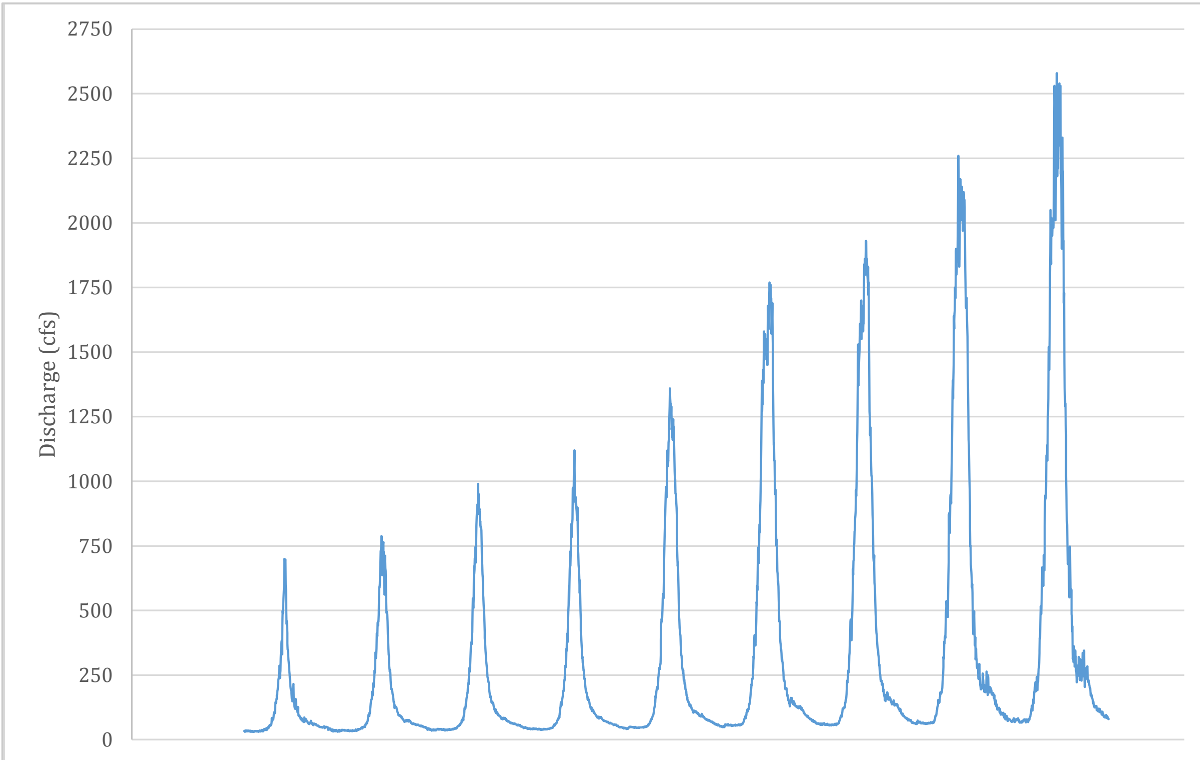

Figure 6. Synthetic hydrographs simulating change from very dry conditions to very wet conditions (P95, P90, P80, P75, P50, P25, P20, P10, P05) for the Crystal River.

3.2 Hydrological Simulation Modeling

Water resource planning questions regarding water availability, patterns of local use, and discrepancies between use needs and water supply rely heavily on hydrological simulation models. Linear network flow modeling allows investigators to simulate longitudinal streamflow conditions as they are affected by surface water rights administration under Colorado water law across a range of hydrological conditions. While a regional water supply planning model for the Upper Colorado River Basin (including the Crystal River watershed) already exists, the node-spacing scheme and temporal resolution used in this model render it too coarse to be useful for evaluation of water uses and effective development of a stream management plan for the Crystal River. The EcoDSS relied instead on a standalone object-oriented and data-centered hydrological simulation model for the Crystal River. The model, developed using the RiverWare platform, simulated tributary inflows, allocated surface water to diversions according to the Prior Appropriation System, and routed groundwater and surface water return flows from irrigated acreages back to the river on a daily timestep across a range of drought and flood conditions.

3.2.1 Water Rights Allocation and Accounting

The RiverWare simulation model required several data inputs for executing streamflow and routing simulations: hydrological boundary conditions 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 condition. Data aggregated from various sources, including Colorado's Decision Support System (CDSS), local irrigators and water users, the District 38 Water Commissioner, and published hydrogeological studies provided the necessary input information. The simulated river network included the five major contributing tributaries (Avalanche Creek, Nettle Creek, Thompson Creek, Thomas Creek and Prince Creek) and all significant agricultural and municipal water diversions (Figure 7). Domestic wells were not included in the network due to their minimal withdrawal rates (e.g. roughly 0.3 AF per year). Some smaller diversions on tributaries were similarly not included due to incomplete diversion and/or water rights data records. The model derived diversion information, including structure names, locations, decreed amounts, priority date, application type, and irrigated acres, from the Colorado Division of Water Resources water rights database, HydroBase (Table 3). Where necessary, information communicated by the Water Commissioner and several water users helped refine this data.

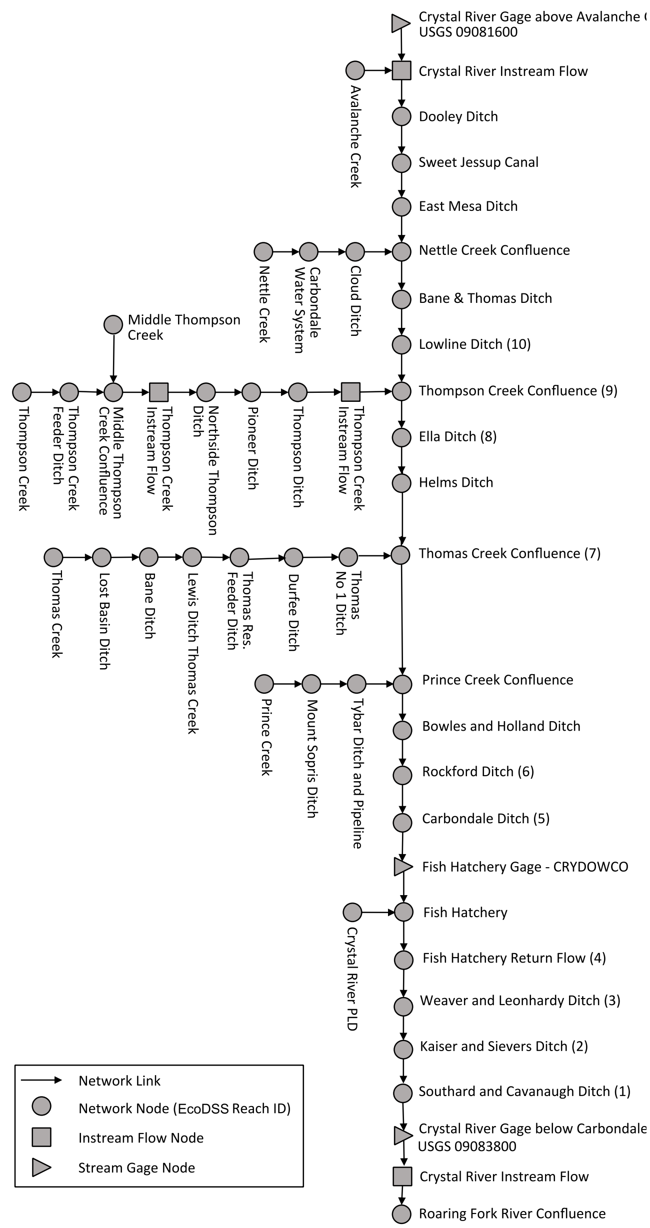

Figure 7. Water rights allocation and accounting model network for the lower Crystal River.

Table 1. List of diversions included in the water rights allocation and accounting 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
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
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
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
CRYSTAL RIVER PL D	1858	CRYSTAL RIVER	1990-12-31	1989-12-31	1962-01-12	51134.40919	90CW0349	1.5000	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
DURFEE DITCH	644	THOMAS CREEK	1919-06-09	1918-09-27	1907-05-15	25106.20953	226AAB-1	1.85	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
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
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	1.20	0.00	0.00
LEWIS DITCH THOMAS CR	816	THOMAS CREEK	1889-05-11		1882-04-25	11803.00000	24	0.00	0.00	1.00
LOST BASIN DITCH	835	THOMAS CREEK	1892-02-09	1892-02-08	1889-06-27	15379.14423	208	5.20	0.00	0.00
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
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
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
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
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 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
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
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
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

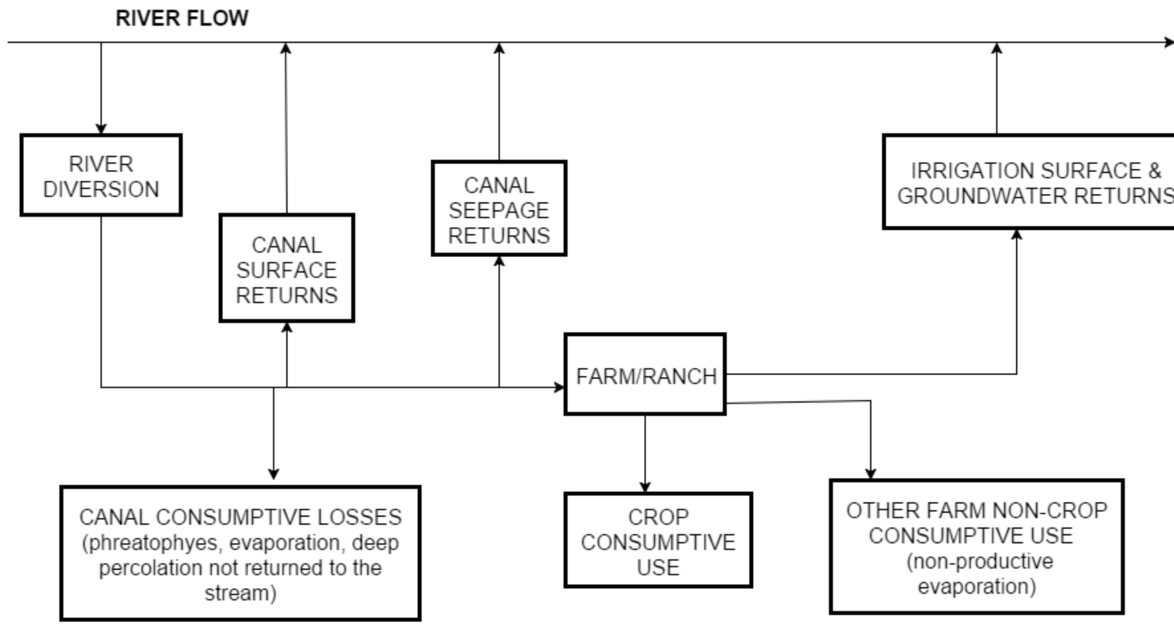

Figure 8. Irrigation system schematic demonstrating the paths water flows along before being consumed by crops or returning to the river. Adapted from Colorado Agricultural Water Alliance (2008).

3.2.2 Flow Routing

The RiverWare model routed water along stream reaches and through water diversion networks on a daily timestep. Streamflows accrued or depleted in a downstream direction in response to tributary inflows and surface water diversions. The vast majority of surface water diversions in the Crystal River watershed support agricultural production. Therefore, surface water demands were modeled based on the interplay between water availability, crop consumptive use and the seniority of a given water right. Crop consumptive use was calculated for each irrigated parcel based on the total irrigated acreage and mean monthly evapotranspiration rates for a given crop type. In the model, water diverted for irrigation satisfied crop needs only after compensating for inefficiencies in the system (e.g. evaporative losses, surface runoff, deep percolation, ponding, and hydraulic push water) (Figure 8). Total system efficiencies were estimated based on primary conveyance system characteristics, primary conveyance system length, on-farm conveyance system characteristics, and irrigation application type (Table 4). The application types associated with each irrigated parcel were initially procured from HydroBase and were subsequently verified/modified with expert knowledge provided by local water users. Where water users implemented mixed water application systems, efficiencies were estimated with a weighted average based on the relative proportions of total irrigated acreages utilizing each application type.

Table 4. Efficiency estimates for components of the irrigation water budget. (Colorado Water Conservation Board and Colorado Division of Water Resources, 2008; Lee and Plant, 2013; Barta et al., 2004)

Conveyance Efficiency	
Lined	95%
Unlined, Medium (200-2000m)	75%
Unlined, Long (>2000m)	60%
Application Efficiency	
Flood	45%
Sprinkler	75%
On-farm Conveyance Efficiency	
Fields larger than 50 acres	
Unlined	80%
Lined or Piped	90%
Fields up to 50 acres	
Unlined	70%
Lined or Piped	80%

Total diversion demands were calculated by first estimating a depletion request that reflected crop consumptive uses (1). The surface water diversion request was then calculated based on the consumptive use requirements and the total efficiency of the conveyance and application system (2).

(1) $$Consumptive\ Use = Irrigated\ Area \times Evapotranspiration\ Rate$$

(2) $$Diversion\ Request = \frac{Consumptive\ Use}{Total\ Efficiency}$$

Actual diversions were allocated among uses based on available water at the headgate and the priority of the given water right. Irrigation shortages were calculated by comparing the actual diversion to the diversion request for each timestep in the simulation period (Figure 9).

Surface water and groundwater irrigation return flows were included in the RiverWare 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. Physical properties associated with estimating soil moisture demand, including irrigated acreage, evapotranspiration, and soil properties were incorporated into return flow estimates. Irrigated parcel locations and orientations were initially procured from the CDSS. However, discussions with the District 38 water commissioner and several water users identified the need for revision and refinement. Several individuals were subsequently consulted to improve the accuracy of the mappings between diversion structures and irrigated acreages (Figure 10). Groundwater flowpath lengths were calculated in a geographic information system (GIS) using 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 for a given water right.

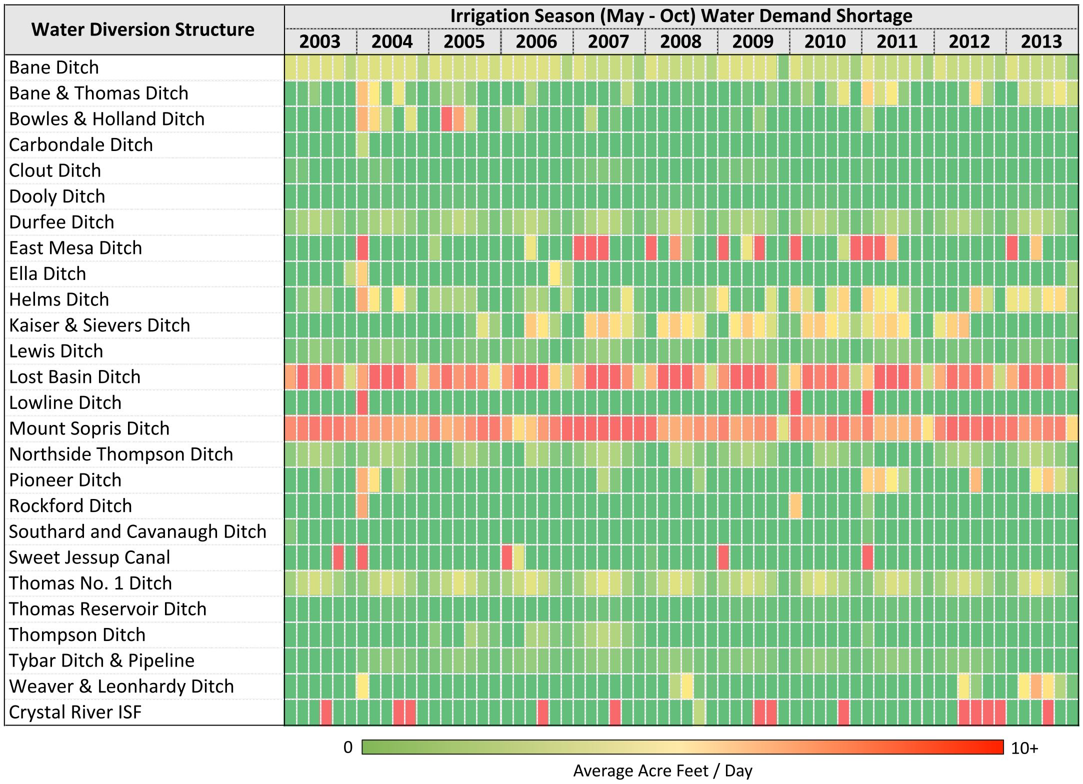

Figure 9. Diversion shortages under existing conditions predicted by the EcoDSS.

Transmissivity estimates were generated using the range of values for hydraulic conductivity and aquifer thickness presented by Kolm, Heijde, and Dechesne (2008). This 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). Estimation of specific yield relied on comparison of the empirical relationships published by (A. I. 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 method (Glover 1977) 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 RiverWare model at each irrigation water use node.

Conversations with the District 38 Water Commissioner indicated that overland return flow from irrigated parcels contribute to the Crystal River at many locations. Estimating surface water return flow fractions for each water demand required researching the water application method used on each irrigated parcel. For each water right, surface water return flow fractions and locations were modeled according to the distributed ownership amounts and spatial orientation of associated irrigated parcels. Overland return flow estimates were included for irrigated parcels located in close proximity to the Crystal River. Surface water return flows were not lagged and accrued to the river on the same time step they were generated on the irrigated parcel.

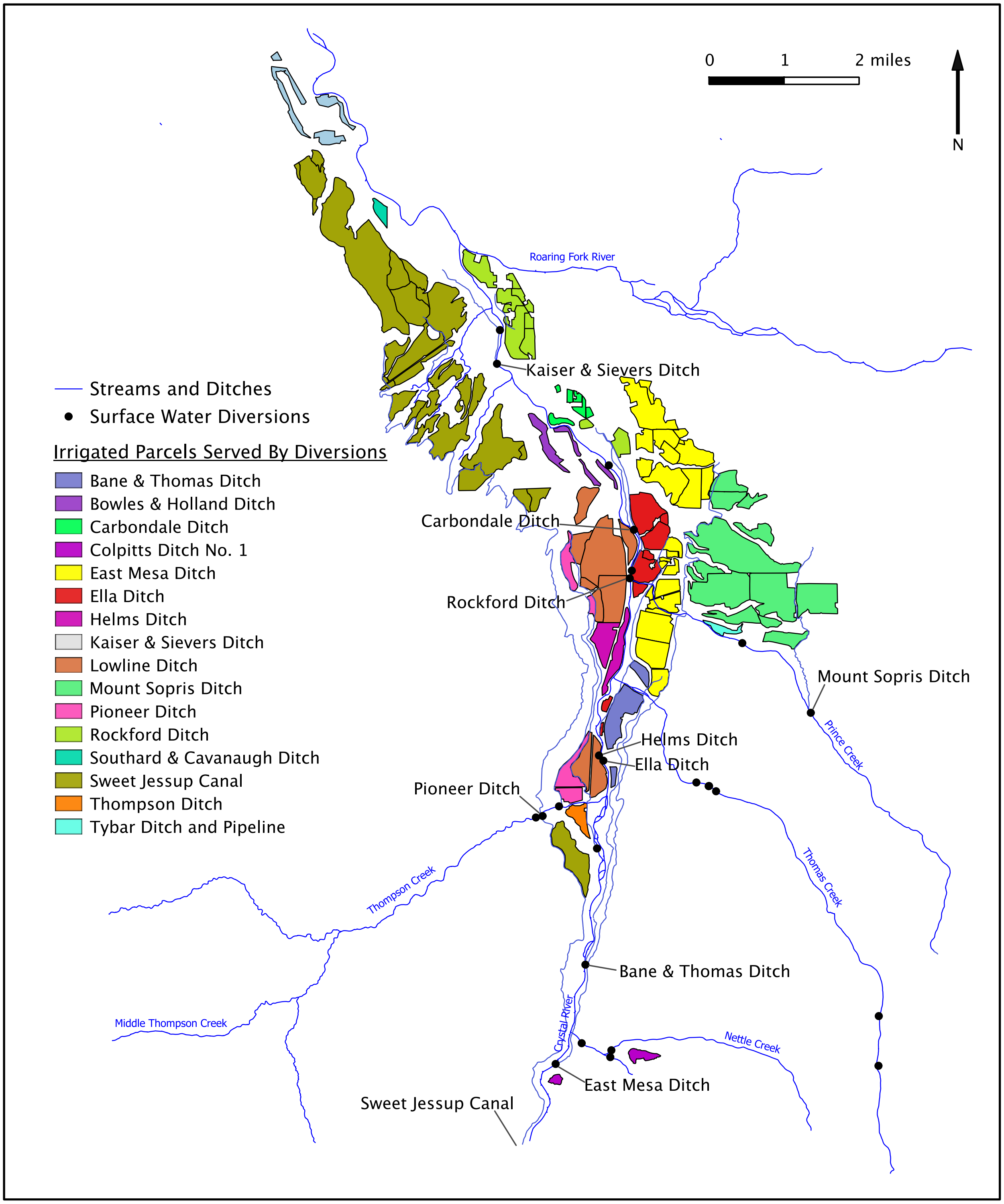

Figure 10. Map of irrigated parcels and associated diversion structures on the lower Crystal River

3.2.3 Model Calibration and Validation

Hydrological simulations were performed on a daily timestep using the historical streamflow dataset. A review of the historical diversion records available in HydroBase for the Crystal River watershed and subsequent conversations with the District 38 Water Commissioner suggested that records kept before 2003 were largely unreliable. Recognition of the difficulty this would pose for successful model calibration prompted elimination of all but the most recent eleven years of simulation results (2003-2013) during optimization. Model performance was evaluated by comparing simulation results against observed streamflows measured at two downstream gaging stations: a CDWR gage (CRYDOWCO) located south of Carbondale near the Colorado Parks and Wildlife (CPW) fish hatchery and a USGS gage (09083800) located above the confluence with the Roaring Fork River (Figure 11). Several model parameters were manually adjusted until a visual and statistical 'best-fit' in the observed vs. simulated conditions was identified. Calibration sought to minimize mean absolute error over the entire calibration period.

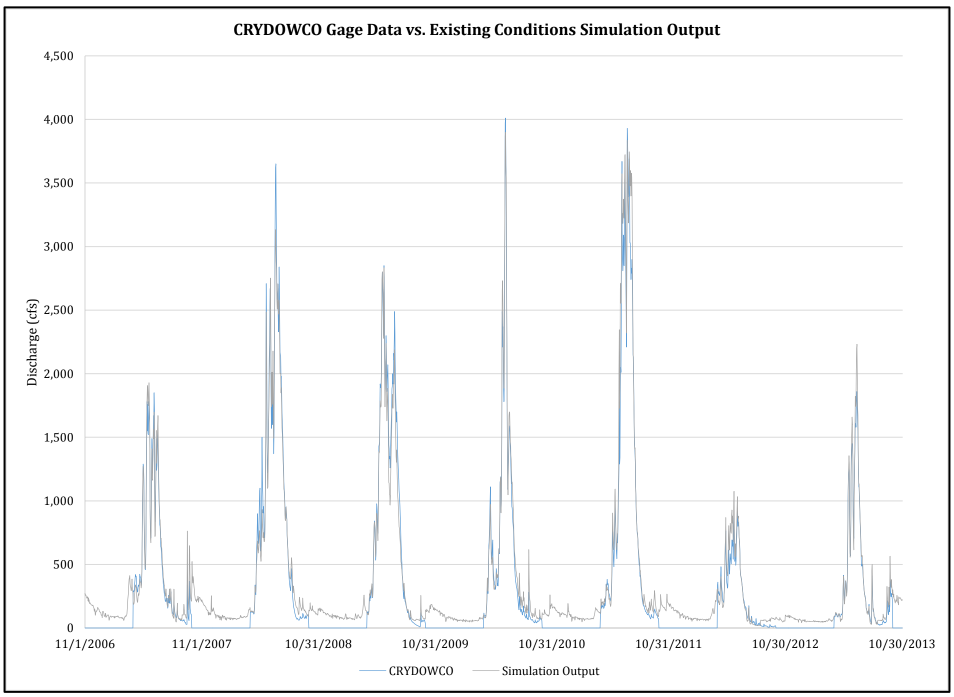

Figure 11. Hydrographs comparing observed vs. simulated discharge data at CRYDOWCO

The calibrated model performed similarly at the two gage locations. Simulation results more closely matched observed conditions in relatively dry years. Wet hydrologic conditions likely trigger flows in otherwise ephemeral or intermittent tributary streams not included in the model network. Additionally, the statistical and linear models used to describe relationships between tributary streamflows and flows observed in the Crystal River above Avalanche Creek might break down at higher flows. The model performed poorly at both calibration locations during late summer monsoon conditions. This is likely due to the fact that hydrological boundary conditions were calculated based on flows in the Crystal River near Redstone and, thus, did not account for localized effects of strong monsoon rain events in the lower watershed. Overall, calibration results indicated adequate model performance for 1) characterizing general hydrological conditions throughout the watershed, and 2) supporting water management scenario testing across a range of drought and flood conditions.

3.3 Hydrological Alteration

Broad patterns of precipitation and topography largely determine a river's flow regime. In turn, fluvial ecologists generally treat flow regime as the "master variable" exerting the largest influence on riverine ecosystem form and function (Poff et al. 2009). 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 stream habitat. Alterations to natural patterns of flow variability, including 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).

IHA Metric	Location Along the Crystal River													
	Avalanche Creek Confluence	Sweet Jessup Canal	Nettle Creek Confluence	Lowline Ditch	Ella Ditch	Thompson Creek Confluence	Prince Creek Confluence	Rockford Ditch	Carbondale Ditch	Fish Hatchery	Weaver & Leonhardy Ditch	Kaiser & Sievers Ditch	Southard & Cavanaugh Ditch	Roaring Fork Confluence
Median Annual Flow (cfs)	0%	5%	9%	6%	10%	11%	11%	11%	14%	12%	10%	9%	10%	3%
Median August Flow (cfs)	0%	23%	41%	24%	48%	52%	51%	44%	59%	49%	37%	25%	27%	5%
Median September Flow (cfs)	0%	22%	41%	14%	42%	44%	44%	40%	52%	41%	33%	20%	22%	3%
Median 3-day Maximum Flow (cfs)	0%	0%	0%	0%	2%	3%	3%	3%	4%	4%	4%	3%	3%	3%
Julian Date of Maximum Flow	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Median January Flow (cfs)	0%	0%	0%	0%	0%	0%	0%	3%	3%	5%	7%	7%	7%	10%
Base Flow Index (cfs)	0%	6%	28%	15%	85%	81%	80%	60%	95%	528%	2%	1%	2%	9%
Julian Date of Minimum Flow	0.00	10.00	243.00	237.00	236.00	244.00	244.00	251.00	234.00	249.00	239.00	33.00	36.00	33.00
Median Positive Rate Change (cfs)	0%	0%	2%	9%	12%	13%	13%	13%	8%	3%	8%	6%	3%	2%
Median Negative Rate of Change (cfs)	0%	2%	1%	7%	10%	5%	2%	0%	5%	3%	2%	5%	2%	3%

Figure 12: A subset of IHA assessment results indicating the degree of departure from natural conditions on various reaches of the Crystal River. All flow-based metrics represented as absolute percent changes. Metrics based on Julian date represented as a total difference in days.

The Indicators of Hydrologic Alteration (IHA) methodology (Richter et al. 1996) was used to quantitatively assess first-order effects of resource management activities on ten focus reaches in the RiverWare model network. IHA analysis considered 32 measures of hydrological change. Hydrological simulation modeling results representing existing conditions, natural conditions (i.e. no surface water diversion activity), and several alternative management scenarios provided the basis for comparison and computation of changes to the hydrological regime (Figure 12).

4. Second-Order Effects – Assessing Channel Hydraulics

Given particular channel morphology, changes in streamflow alter water surface elevations and velocity profiles along a reach, supporting or degrading various ecosystem functions. For a given streamflow, changes in channel morphology also produce changes in water surface elevations and velocity profiles. Thus, efforts to understand ecological costs/benefits associated with either implementation of water conservation strategies or modifications of streambed topography required a physically based model capable of simulating a range of hydraulic conditions. The 1-dimensional HEC-River Analysis System (RAS) and the 2-dimensional Sedimentation and River Hydraulics - 2D River Flow Model (SRH-2D) met these requirements and were selected for use in the EcoDSS.

4.1 Topographic and Bathymetric Mapping

Development of 1-dimensional and 2-dimensional hydraulic models for the Crystal River required surveys of the physical structure of the stream channel and floodplain. Channel bathymetry and floodplain elevations were collected between South Bill Creek Road and the confluence with the Roaring Fork River. Field personnel conducted bathymetric surveying during spring runoff conditions using military-grade real time kinematic (RTK) global positioning system (GPS) surveying equipment and an integrated sonic depth sensor. Data collection from a floating platform using a multi-pass approach ensured adequate characterization of major channel forms and orientations. This survey yielded over 20,000 bathymetric and surface water elevation points over seven miles of stream channel. A subsequent survey using optical surveying equipment tied channel bed elevations to selected control points to verify vertical and horizontal accuracy of the bathymetric survey.

Ordinary kriging using a spherical model was used to create a regular 5-foot grid of channel elevations from irregularly spaced survey data. Topographic modeling of the floodplain extended approximately 500 ft from either side of the river channel. NEXTMap™ 5m digital terrain models provided floodplain elevation data. This data was resampled to produce a 25-foot regular grid of elevation points. Staff utilized a GIS and AutoCAD 2014 to convert point data to a triangular irregular network (TIN) of channel bathymetry and floodplain elevations (Figure 13). Modification of the TIN enabled simulation of various structural modification projects that altered channel geometry.

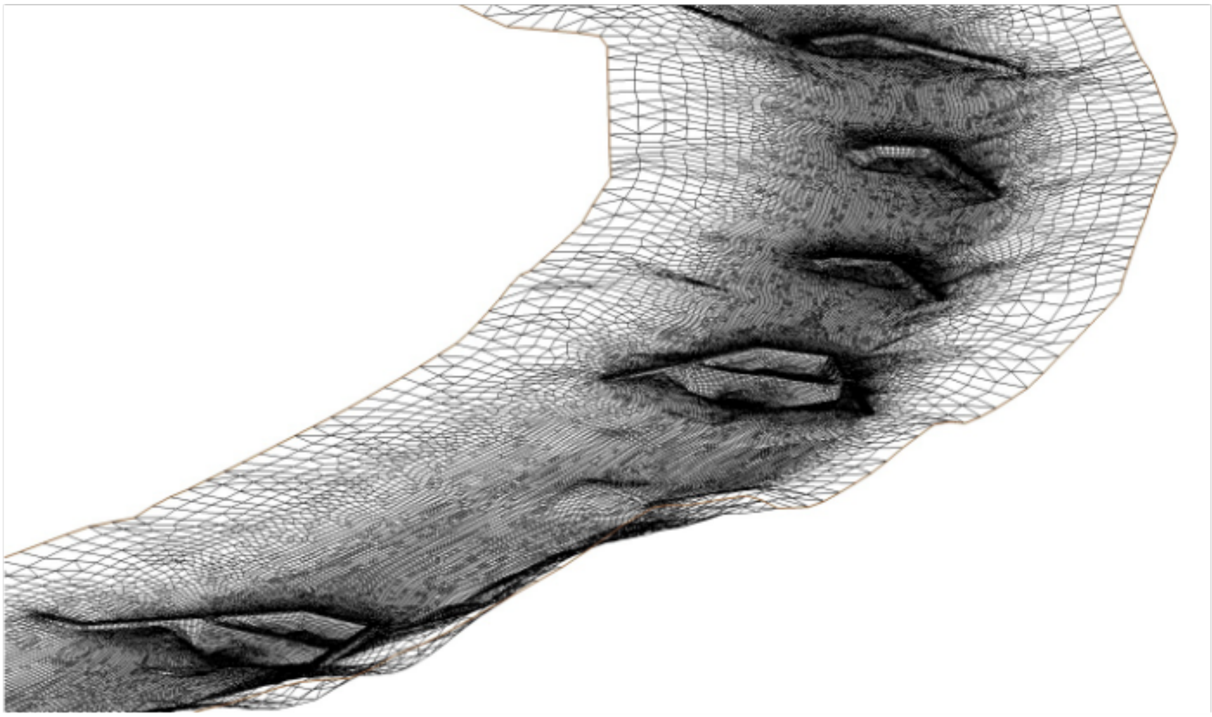

Figure 13. Example of the hydraulic modeling mesh utilized to test the second-order impacts of management and structural alteration on the Crystal River.

4.2 Hydraulic Modeling

Topographic and bathymetric elevation data provided the basis for construction of a pair of hydraulic models: a 1-dimensional HEC-RAS model, and a 2-dimensional SRH-2D model. HEC-RAS was developed by the U.S. Army Corps of Engineers and performs 1-dimentional hydraulic calculations for open-channel flow (US Army Corps of Engineers, 2016). The SRH-2D model was developed by the U.S. Bureau of Reclamation and implicitly solves the two-dimensional Navier-Stokes equations of fluid motion on regular or irregular meshes (Reclamation, 2008). The HEC-RAS model solved for channel hydraulics across varying stream discharges at 384 cross sections. The SRH-2D model simulated fluid motion at 273,578 simulation nodes.

Field surveys of water surface elevations, stream discharge, and sediment size distributions collected at several locations across different hydrological conditions supported model calibration. Continuous water surface elevations generated by the HEC-RAS model were additionally used to calibrate the SRH-2D model. Once fully calibrated, simulated hydraulic conditions corresponding to stream discharge events between 5 - 6,000 cfs to compute water surface elevations, velocities, and shear stress along the entire study reach from Bill Creek to the confluence with the Roaring Fork River. Specifically, output for the hydraulic simulations included flow depths, water-surface elevations, Froude number, velocity direction and magnitude, boundary shear stress, turbulent dissipation rate, and turbulent kinetic energy (Figure 14). Output was imported to a GIS to allow for analysis of continuous data surfaces for stream depth and longitudinal velocity profiles.

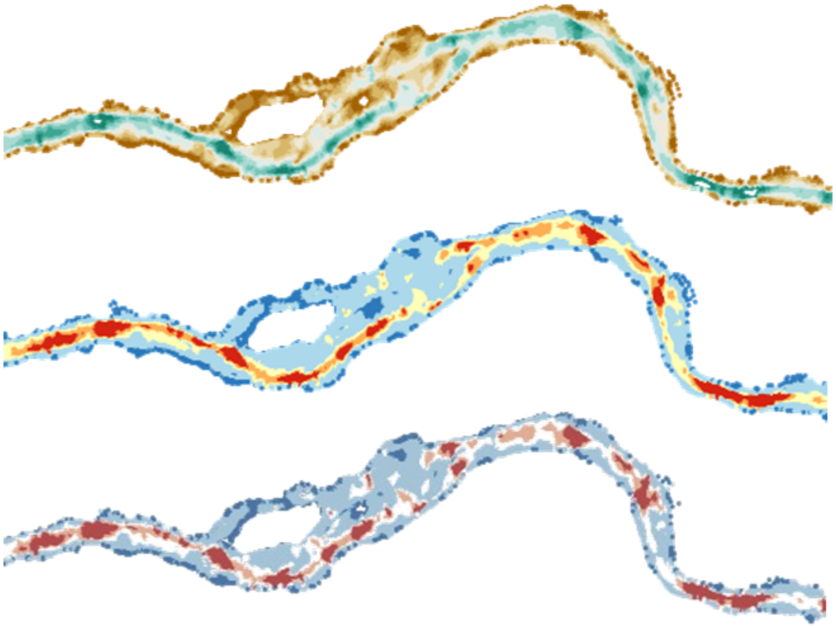

Figure 14. Simulation outputs from 2-dimensional modeling for hydraulic parameters including water depth, water velocity and shear stress.

4.3 Channel Stability

Channel stability reflects the river's ability to balance sediment supply and transport in dynamic equilibrium. High channel stability typically equates to resiliency and the ability of the stream to recover after large disturbances. Morphological impairment on alluvial streams often emerges in the form of local channel instability. Stressors at the channel scale (e.g. bank hardening at a bridge crossing), reach-scale (e.g. bank failure due to riparian vegetation removal), or watershed-scale (e.g. sediment supply disruption due to dam construction) may, in turn, cause this instability.

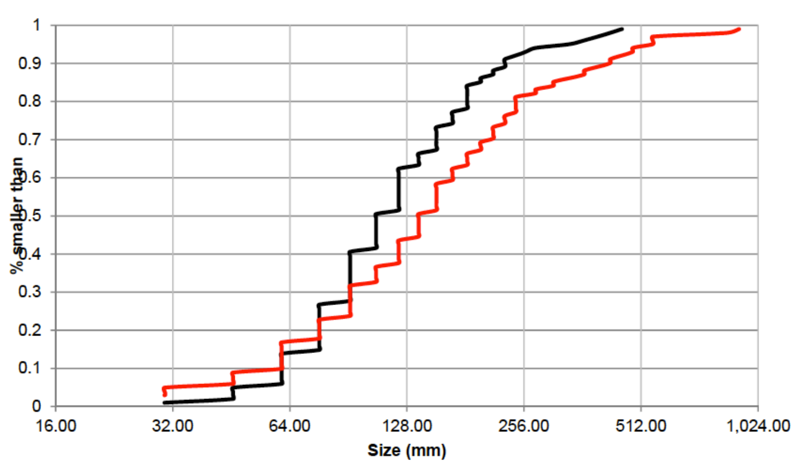

Figure 15: Wolman pebble count results from the Crystal River from pool (red) and riffle (riffle) channel units near the CPW fish hatchery.

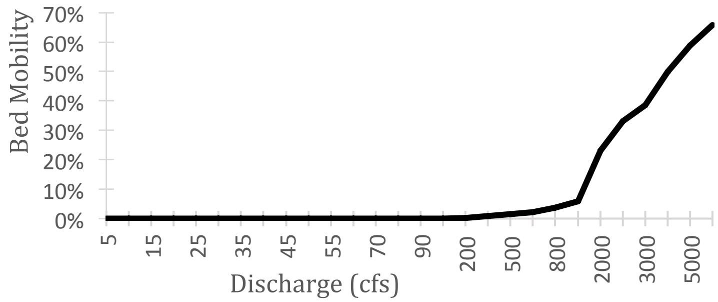

Figure 16: Fractional bed area mobilized under increasing streamflows, as predicted by the EcoDSS for a single focus reach on the Crystal River.

The EcoDSS utilized 2-dimensional hydraulic modeling results for shear stress to evaluate local sediment transport dynamics and the impacts of water management on channel maintenance flows. This approach assessed changes in the fractional area of mobilized bed material for each reach under existing conditions, natural conditions (i.e. no surface water diversions) and a range of alternative management scenarios. Particle mobilization was approximated using the critical shear stress approach. Shear stress values at each simulation node were compared to critical bed shear stress for the average particle size (D50) measured on the Crystal River (Figure 16, Table 5). The representative area for each simulation node was calculated in a GIS using Voronoi polygons. The fractional area of bed mobilization was calculated on a daily timestep by dividing the area where simulated shear stress exceeded critical shear stress by the total bankfull channel area available in each focus reach.

Table 5: Critical shear stress by particle diameter (after Berenbrock and Tranmer 2008)

Particle Class	Particle Diameters (mm)	Critical bed shear stress (τ_c) (N/m2)
Coarse cobble	128 – 256	112 – 223
Fine cobble	64 – 128	53.8 – 112
Very coarse gravel	32 – 64	25.9 – 53.8
Coarse gravel	16 – 32	12.2 – 25.9
Medium gravel	8 – 16	5.7 – 12.2
Fine gravel	4 – 8	2.7 – 5.7
Very fine gravel	2 – 4	1.3 – 2.7
Very coarse sand	1 – 2	0.47 – 1.3
Coarse sand	0.5 – 1	0.27 – 0.47
Medium sand	0.25 – 0.5	0.194 – 0.27
Fine sand	0.125 – 0.25	0.145 – 0.194
Very fine sand	0.0625 – 0.125	0.110 – 0.145
Coarse silt	0.0310 – 0.0625	0.0826 – 0.110
Medium silt	0.0156 – 0.0310	0.0630 – 0.0826
Fine silt	0.0078 – 0.0156	0.0378 – 0.0630

4.4 Floodplain Connectivity

The frequency, lateral extent, and duration of interactions between the channel and floodplain create a characteristic pattern of floodplain connectivity that determines the extent to which the river accesses and hydrates overbank areas. Overbank flows elevate the water table in the alluvial aquifer and produce favorable conditions for riparian vegetation. Typical floodplain connectivity impairments result from watershed-scale impacts to the flow regime or localized geomorphic impacts from artificial levees, ditches, channelization, or channel enlargement (B. Johnson, Beardsley, and Doran 2016).

Evaluations of floodplain connectivity on the Crystal River relied on 2-dimensional hydraulic modeling to simulate the inundation extent associated with various streamflows. The degree of change in lateral connectivity was evaluated by comparing the inundated floodplain area under existing conditions natural conditions, and several alternative management scenarios. The floodplain was delineated by the bankfull discharge water surface elevation and the water surface elevation associated with a 50-year flood event. The active floodplain area at each simulation timestep was calculated by summing the areas of all simulation nodes located within this delineated zone. On each focus reach, the fractional inundation area was converted to a dimensionless index by dividing it by the total reach length.

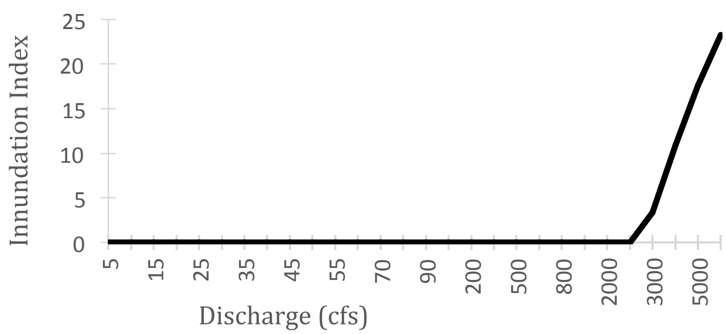

Figure 17: Floodplain innundation under increasing streamflows, as predicted by the EcoDSS for a single focus reach on the Crystal River.

5. Third-Order Effects – Assessing Ecosystem Responses

Third-order impacts describe the ecological response to change in first- and second-order physical parameters (Burke, Jorde, and Buffington 2008). An evaluation of third-order impacts on the Crystal River included consideration of the interplay between stream hydrology, channel hydraulics, riparian recruitment potential, and habitat quality and availability for various life stages of rainbow and brown trout. Linking physical conditions to ecology in the EcoDSS required development of ecosystem response functions. These functions provided a means for propagating changes to the hydrological regime or alterations to channel structure through to the hydraulic characteristics of the stream, and the biotic components of the river ecosystem.

5.1 Riparian Resiliency

Riparian vegetation performs several important functional roles for stream ecosystems. Root systems increase bank stabilization and the vegetative overstory provides detrital input and shading for aquatic species. Riparian forests supply the channel with woody debris, an important determinant in local physical structure. The functional condition of riparian vegetation considers species diversity and the structure of both the woody and herbaceous vegetation communities (B. Johnson, Beardsley, and Doran 2016). Impacts to riparian vegetation include deforestation or habitat degradation resulting from an altered hydrological regime or floodplain disconnections.

The EcoDSS implemented the Recruitment Box methodology (Mahoney and Rood 1998) to provide a quantitative understanding of constraints on cottonwood recruitment success (Figure 18). Simulation of one-dimensional channel hydraulics at representative cross sections throughout the lower Crystal River replicated rates of hydrograph recession and falling water surface elevations. Studies of cottonwood saplings indicate that they require a limited rate of water table decline to ensure that growing roots maintain contact with the free water surface (Mahoney and Rood 1998). The EcoDSS assessed management-induced changes to riparian resiliency by comparing the number of days exhibiting optimal recruitment conditions under natural conditions, existing conditions, and several alternative management scenarios.

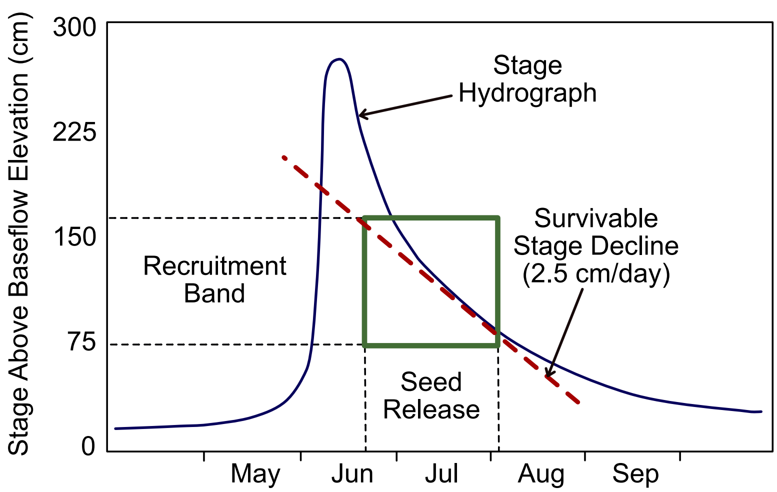

Figure 18: The Recruitment Box methodology compares rates of water table decline to average root growth rates for woody riparian vegetation to identify optimal and sub-optimal conditions for sapling growth

5.2 Aquatic Habitat

Physical heterogeneity in the streambed and water column results from the complex interplay between the patterns of erosion, scour, and deposition that shapes the channel (B. Johnson, Beardsley, and Doran 2016). Activities that physically alter the structure of the streambed, disrupt the sediment regime, or reduce large woody debris supplies frequently impact the physical structure and degree of heterogeneity present. This heterogeneity is a critical determinant of habitat quality for many aquatic organisms including macroinvertebrates and fish.

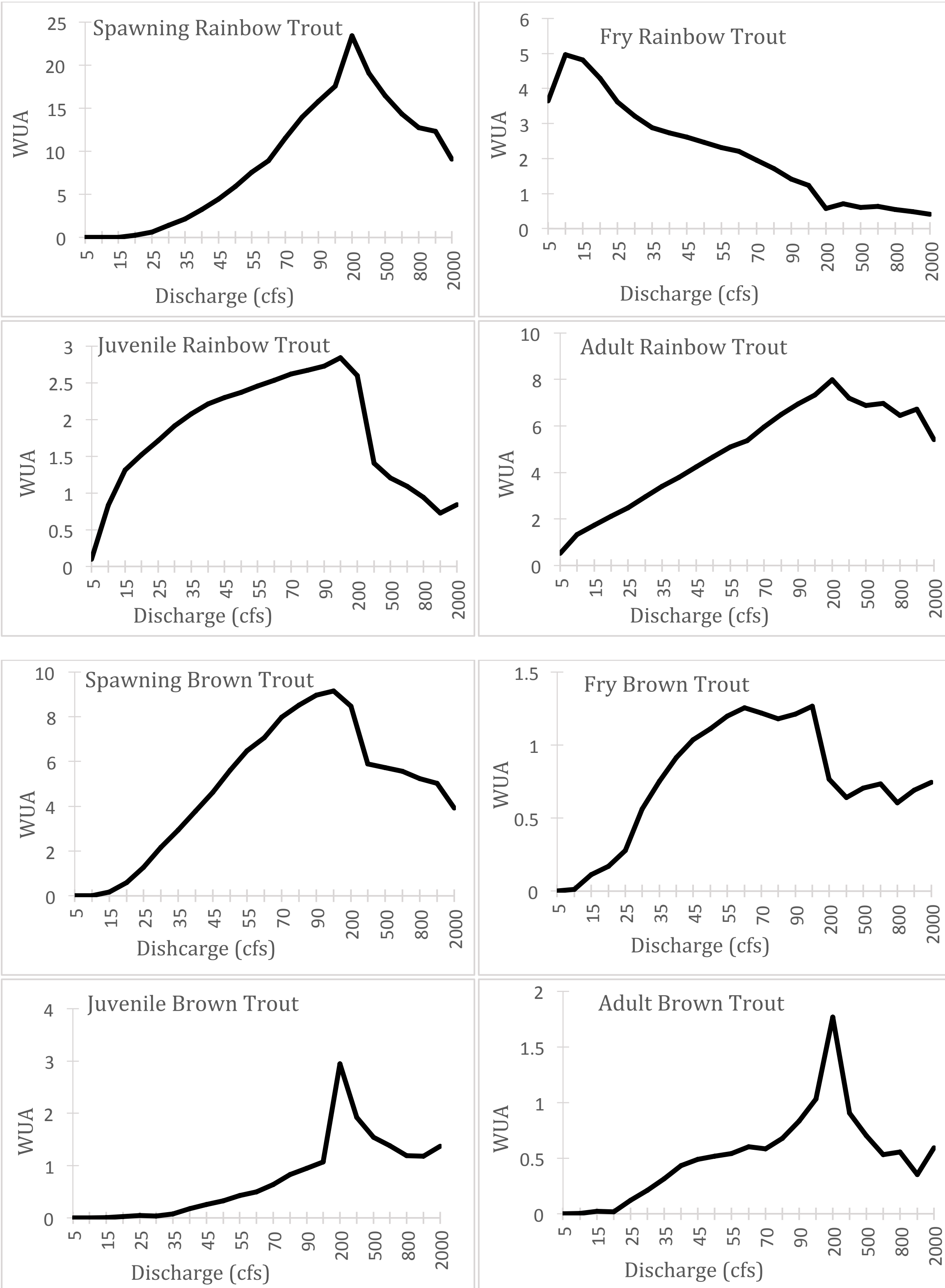

Figure 19. Weighted usable area responses to varying streamflow for several species/life-stage combinations on a single Crystal River focus reach.

Assessments of aquatic habitat in the EcoDSS considered the hydraulic structure (water depth and velocity distributions) of the channel across varying discharges and its relationship to habitat suitability for several species and life stages of trout. Criteria describing habitat quality were derived from published habitat suitability indices for each species/life-stage combination (Raleigh et al. 1984). The assessment employed 2-dimensional modeling results to assess meso-scale (feet to tens of feet) impacts to habitat quality resulting from changing hydrology or alterations to channel geometry. Daily simulation results for water depth and velocity at each model node were assessed against the habitat suitability criteria for each species and life stage. This produced a habitat suitability score that was subsequently multiplied against each simulation node's representative area to produce a fractional area consisting of high quality habitat. These fractional areas were summed across each focus reach and divided by the total reach length to produce a weighted usable area (WUA) for habitat (Figure 19). This methodology is described in detail by Conder and Annear (1987) and others. The EcoDSS simulated changes in WUA for each species and life stage under existing conditions, natural conditions, and several alternative management scenarios (Figure 20).

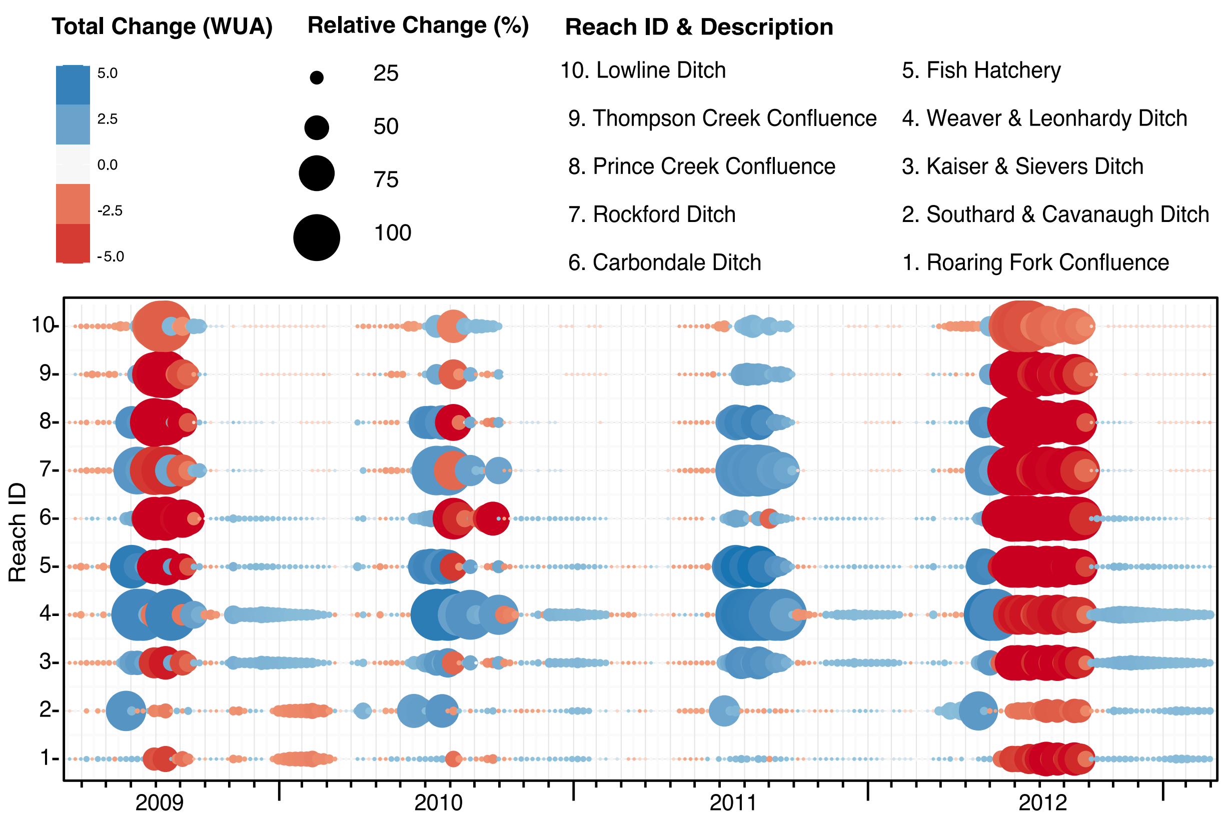

Figure 20. Changes in adult rainbow trout habitat availability due to water management and use on the lower Crystal River across a range of hydrological conditions. Larger, redder circles indicate a significant reduction in habitat quality and availability. Blue circles indicate a relative increase in habitat quality brought about by reductions in water velocity or by late season return flows that accompany agricultural water uses.

6. Scenario Testing with the EcoDSS

Impacts caused by current management practices were determined by simulating both existing and natural hydrological conditions. The degree of departure for the first, second, and third-order metrics of ecosystem function described above was subsequently evaluated. In addition to assessing the impacts of existing management practices on the Crystal River, the EcoDSS was used to consider the relative effectiveness of the following management strategies:

- Market-based incentives for water conservation or bypass flows
- Infrastructure improvements and efficiency upgrades
- Reservoir construction
- Habitat enhancements and channel modification projects

The relative effectiveness of each scenario was evaluated by comparing management outcomes against existing conditions on the Crystal River. Scenarios were constructed to observe management impacts across a range of hydrological conditions (i.e. a very dry year to a very wet year) as described by the following exceedances probabilities: P05, P10, P20, P25, P50, P75, P80, P90, P95. Modeling hydrological boundary conditions using this occurrence frequency approach provides a straightforward method for predicting outcomes associated with an uncertain climate future. In addition to quantifying changes in important ecosystem metrics, the water rights allocation and accounting model in the EcoDSS predicted management impacts on the frequency and severity of agricultural use shortages. The quantitative characterization of ecosystem benefits and water use costs associated with alternative management strategies provided stakeholders in the Crystal River watershed with a data-centered foundation for evaluating the relative effectiveness and feasibility of a given action for meeting local resource management goals and objectives.

8. Conclusions

The EcoDSS utilizes a modular design, state-of-the-art modeling software, and widely available and/or easily procured data. This modular design yields a non-static framework for evaluating future conditions. New information or models may be incorporated into the framework on a continual basis to reflect changes in knowledge regarding important watershed processes, the selection of alternate proxy metrics for ecological function, or the changing needs of the stakeholder group. Furthermore, the flexible, hierarchical, systems-based approach detailed here yields a replicable implementation approach suitable for application in other basins in Colorado and across the Western United States.

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