

Appraising Surface Water Quantity and Quality in the Upper Arkansas River Basin in Chaffee County, Colorado

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Abstract. The Arkansas River, one of four major rivers that begin in Colorado, has the largest drainage basin in the state and serves as a vital source of water. At peak flows, the Arkansas River swells by 70% through Chaffee County, in the heart of the Rockies, and only increases by 20% before exiting the mountains onto the high plains near Pueblo. The production of this discharge depends on a complex natural system of snowmelt and groundwater-stream interactions, as well as on numerous human interventions. The Arkansas valley in Chaffee County, from Granite to Salida, is characterized as an intermountain, high altitude, agricultural, small-municipal, and recreational region. Increasing demands on the stream-aquifer system have necessitated more up-to-date, integrated, and technology-driven data to assist water users, managers, and decision makers in moving toward optimal overall water use. Monthly synoptic measurements and triannual water sampling over July 2009 – January 2011 at 19 river and tributary sites provide data on discharge; dissolved oxygen; pH; specific conductance; oxidation reduction potential; temperature; and major dissolved ions, uranium, selenium, and other select minerals. Data analysis for the range of hydrologic conditions during the study period reveals flow conditions similar to long-term averages. Relationships of specific conductance and total dissolved solids derived from field samples yields equations useful for estimation of mass loading in the river system. Spatial and temporal analysis of tributary to river discharge and dissolved solids loading helps quantify and qualify water sources as well as potential aquifer interactions. Overall water quality is good, with some constituents worthy of continued active monitoring.

1. Introduction

Water is a critical resource for the arid Western United States, including Colorado, and the challenge of ensuring the viability of that resource into the future is escalating. Demand is increasing for the combination of municipal, industrial, and agricultural uses; new water supplies are becoming more difficult and expensive to develop; climate change and highly variable snowpack conditions seem apparent; there is a growing group of stakeholders interested in in-stream flows for recreational and ecological purposes; and population is increasing.

In 2004, the Colorado Water Conservation Board (CWCB) began releasing the results of an ongoing study regarding the state's water resources supply and demands. That study, called the Statewide Water Supply Initiative (SWSI), projected population growth of 25% to 99% in Colorado river basins over the period from 2000 to 2030. Water demands for the same period are projected to surge between 20% and 84% (CWCB 2004). The SWSI

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report called to action stakeholders and researchers to prepare to meet those projected needs.

In the Arkansas River Basin, the largest drainage basin in the state (Figure 1), projections show a 55% population increase from 2000 to 2030, producing a 38% increase in gross water demand (CWCB 2004). In the portion of the basin above Pueblo Reservoir, known as the Upper Arkansas River Basin (UARB), the population is projected to increase by 72% within that same time period, resulting in a 60% increase in gross water demand (CWCB 2004).



Figure 1. River Basins of Colorado showing the study area in central Colorado in the upper headwaters of the Arkansas River Basin.

1.1 Objectives

Better management of the water resources in the Arkansas River Basin will be required to meet increased future demands, and improved management will require more data collection and analysis of this complex water system. To that end, this report aims to describe the basic water quantity and quality characteristics of the Arkansas River Basin in the critical headwaters area of Chaffee County based upon data gathered over a recent 18-month period. Specifically, this report aims to analyze hydrologic conditions of river and tributary flows, explore seasonal variations of tributary-supplied flow and mass load contributions to the system, and evaluate basic surface water quality, all with a view towards determining priority hydrologic characteristics for a future decision support system. The outline of the analyses in this study is as follows. First, the conditions during the study period will be compared to long-term hydrologic conditions to provide context

for the results of the study. Second, a water quantity analysis will be made to evaluate the contribution of tributaries and other sources to the flow in the Arkansas River. Third, an examination will be made of dissolved mass load contributions from these sources. Finally, an analysis of water quality will be made to assess broad indicator characteristics such as temperature and dissolved oxygen, various tested metals, and other dissolved compounds.

1.2 Hydrologic Setting

The study area (Figure 1) lies in Chaffee County and extends from the town of Granite in the north to Salida in the south. The valley floor of the Arkansas River is a relatively flat, deposit-filled inter-montane valley (Figure 2). It is the second northernmost structural basin of the Rio Grande Rift (Chapin and Cather, 1994). Tectonic rifting formed a deep structural basin bounded by normal faults, which has filled with alluvial, glacial, and other basin-fill deposits to a depth of about 5,000 ft (Watts 2005). On the west side of this valley is the Sawatch Range, which contains a large number of 14,000-foot mountain peaks and collects considerable snowpack during the winter. The Sawatch Range feeds four major, perennial tributaries to the Arkansas River within Chaffee County. On the east side of the valley is the Mosquito Range, which has 2 peaks over 13,000 feet in Chaffee County (most of the range crests near 10,000 ft) and receives much lower precipitation. The Mosquito Range feeds one small perennial stream north of Buena Vista, called Fourmile Creek. Precipitation is highly variable within the study region, ranging from about 10 in/yr on the valley floor to as much as 40 in/yr in the surrounding mountains, particularly the Sawatch Range (Crouch et al 1984).

Runoff from precipitation, primarily snow in the Sawatch Range, is the sustaining source of tributary flow (Abbott 1985). Correlations between monthly average streamflow and total monthly precipitation are poor, but correlations between the April 1 snowpack water content and annual average streamflow are statistically significant (Burns 1985). Mean annual runoff is more than 30 inches at high elevations in the Sawatch Range, but it is 2 to 5 inches on the Arkansas Valley floor (U.S. Geological Survey 1970, as cited in Abbott 1985). The principal tributaries in the study region going from north to south consist of Clear Creek, Cottonwood Creek, Chalk Creek, and the South Arkansas River, all of which drain from the Sawatch Range (Figure 2). Smaller perennial tributaries include Pine Creek, Fourmile Creek, and Browns Creek. The tributaries flow across the alluvial, glacial, and basin-fill deposits of the valley floor to the Arkansas River, which is on the eastern edge of the valley. Tributaries are typically sources of groundwater recharge near the mountain front, losing flow as they cross the valley floor. However, the tributaries represent groundwater discharge locations in their downstream reaches, closer to their confluence with the Arkansas River (Watts 2005). The Arkansas River and the South Arkansas River are gaining reaches due to discharge from the regional ground-water system (Watts 2005). Surface water diversions in Chaffee County are used primarily for agriculture including alfalfa and hay cultivation as well as irrigated pasture (Abbott 1985). Municipal public water supplies for the largest towns in the UARB (Salida and Buena Vista) also rely in part on surface water diversions (Watts 2005).

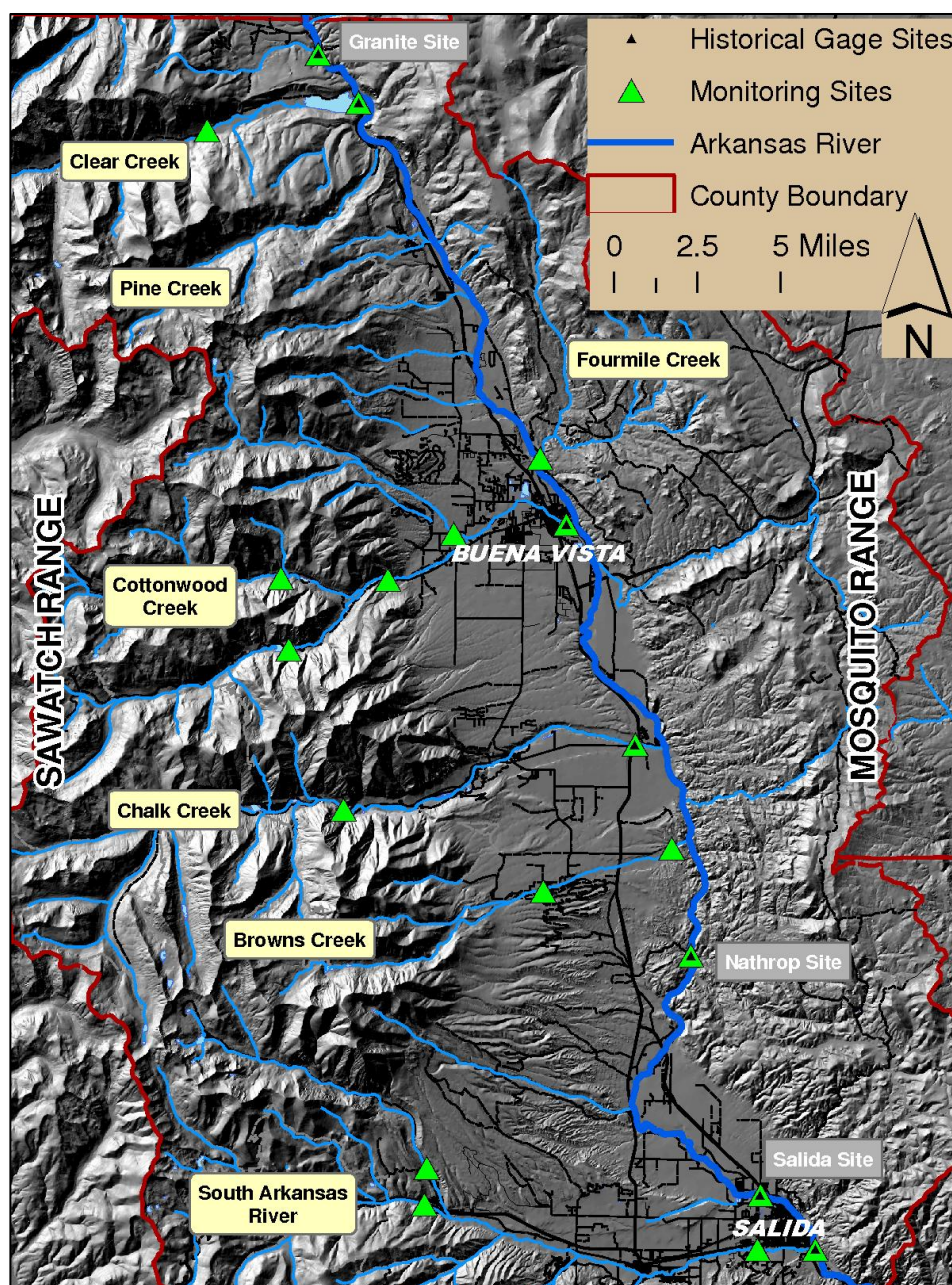


Figure 2. Study area and water monitoring network.

2. Methodology

This section describes the data collection efforts that were undertaken to characterize the basic water quantity and quality characteristics of the study region. Data collection included in-situ measurements of discharge and other water characteristics, as well as laboratory analysis of water quality samples. Discharge data were collected to examine flow accumulation in the system and to calculate mass loading rates. In-situ measurements of basic water characteristics like temperature and dissolved oxygen were made to broadly

evaluate water quality of different locations in the system. Finally, laboratory analyses of water samples were performed to measure the concentration of particular dissolved compounds and metals.

2.1 Selection of Sites for Data Collection

Data collection sites were selected to observe both the main stem of the Arkansas River and its largest tributaries in Chaffee County (Figure 2). Routinely monitored tributaries include Clear Creek, Fourmile Creek, Cottonwood Creek, Chalk Creek, Browns Creek, and the South Arkansas River. In most cases, upstream and downstream sites were identified. To the extent possible, the upstream sites are located upstream of the points where the tributaries enter the Arkansas River valley and upstream of any diversions. If the tributary forks into several branches within the valley, multiple upstream sites were monitored. In the end, the data at the upstream sites are intended to characterize the flows before they are modified by interactions with the groundwater or interventions by humans. The downstream points are located very close to each tributary's junction with the Arkansas River, so these observations characterize the flows as they enter the main stem. Three sites were used to monitor the main stem of the Arkansas River. One point is located where the river enters the study region, one point is located at an intermediate point, and one point is located near where the river leaves the study region.

Where possible, the sites were selected to coincide with locations planned for new gage installations by the Upper Arkansas Water Conservancy District (UAWCD) and with any existing gages operated by the Colorado Division of Water Resources (CDWR) or the United States Geological Survey (USGS). There were 9 active gaging stations along the main stem and tributaries operated by the USGS and the CDWR at the time of site selection. Neglecting a site measuring inflow to Clear Creek Reservoir and a seasonally-operated site near another gage at Granite, 7 were selected for monitoring. Three are on the main stem, and 4 are on tributaries near their respective river confluence points. The CDWR gage on the South Arkansas River was taken out of service during the study period, and replaced with a new gage just upstream; both gages are shown in Figure 2. In addition, the UAWCD recently has established new permanent gaging stations at several locations that correspond to upstream tributary locations in the present study.

2.2 Data Collection

Each data collection site was visited approximately monthly from July 2009 to January 2011. During these site visits, measurements were made of discharge (if the site was not gaged) and common in-situ water properties. In addition, triannually during the same period (five times), water quality samples were collected for laboratory analysis.

Flow measurements were made using a *Sontek Flowtracker Handheld Acoustic Doppler Velocimeter* (ADV)TM which uses the Doppler shift of sound pulses in a sample volume of flowing water to determine its relative velocity. Flow measurements were not gathered when winter weather, ice, or dangerously high flow levels prevented access. Use of the ADV for discharge measurements has been found to compare with a 95% confidence level with standard USGS current meter measurements (Rehmel 2007). Typical discharge measurements at a cross-section involved recording 30 to 60

measurements of a 30-second averaged downstream velocity. Measurement points were determined by segmenting the cross-section width in a manner that strives to capture no more than 5% of the relative flow in any segment, typically resulting in 25 to 30 subsections. At each location on the cross-section, velocity was measured at a point 0.6 times the depth for flow depths less than 1 foot and at 0.2, 0.6, and 0.8 times the depth for flow depths deeper than 1 foot, all measured from the water surface. This approach is similar to methods used by the USGS (Buchanan 1969) and the USDA (Harrelson et al. 1994). At locations with existing gages, the discharge was obtained from published or provisional postings by the agency that operates the gage.

Water properties including specific conductance [electrical conductivity (EC) at 25°C standard temperature], pH, dissolved oxygen (DO), oxidation reduction potential (ORP), and temperature were measured using a *YSI 6-Series Multiparameter Sampling System*TM. The probe was operated according to manufacturer recommendations and care was taken to measure water away from the banks, any particularly turbulent or stagnant locations, or other anomalies. Instrument sensors for measuring pH, EC, and DO were calibrated daily during data collection events and ORP was calibrated every 4 to 6 months. The pH calibration involved a 3-point method using solutions of pH 4.0, 7.0, and 10.0 with corrections made for temperature. Calibration for DO considered current barometric pressure and sensor membrane replacement as needed or at a minimum of every 60 days. EC and ORP were calibrated using separate reference solutions.

Water quality samples were taken for laboratory analysis in July 2009, November 2009, May 2010, August 2010, and November 2010. Samples were collected following methods approved by the Colorado Water Quality Control Division in previous project discussions. A peristaltic pump with pre-cleaned sampling tubes and a 0.45 µm capsule filter was used to extract samples from the streams. The sampling tubes were decontaminated using a dilute hydrochloric acid solution, followed by a phosphate-free detergent solution, and two rinses of deionized water. The laboratory analysis of the water samples included estimation of total dissolved solids (TDS), specific salt ions, dissolved selenium, and dissolved uranium. Uranium and selenium water samples were treated with a nitric acid preservative as stipulated by the laboratory to prohibit precipitation of the metals in transit. For two sampling events (May 2010 and November 2010) dissolved zinc, copper, iron, manganese, cadmium, aluminum, fluoride, and lead also were measured. These samples also were treated with a nitric acid preservative. During each sampling event, sample blanks of distilled water and at least one duplicate set of samples were collected for comparative and quality-control purposes. Custodial responsibility and quality control of the samples included labeling protocol, temperature control from the time of sampling to the time of shipping, and chain of custody forms. Samples requiring temperature control were shipped overnight on ice to the pertinent laboratory.

3. Results

3.1 Water Quantity

Figure 3 shows the daily average flow rate at the three gaging stations along the Arkansas River during the study period (June 2009 – February 2011) normalized by the

long-term average flow rates on the same date. The long-term average was calculated using the preceding 20 to 25 years, depending on the available gage records. The plot shows a noteworthy consistency across all three sites for the flow patterns during the study period. The averages of the normalized flow rates during the study period for the Granite, Nathrop, and Salida sites are 1.01, 0.88, and 0.94, respectively. These values suggest that, during the study period as a whole, the flows at these sites were close to or slightly below the long-term average conditions.

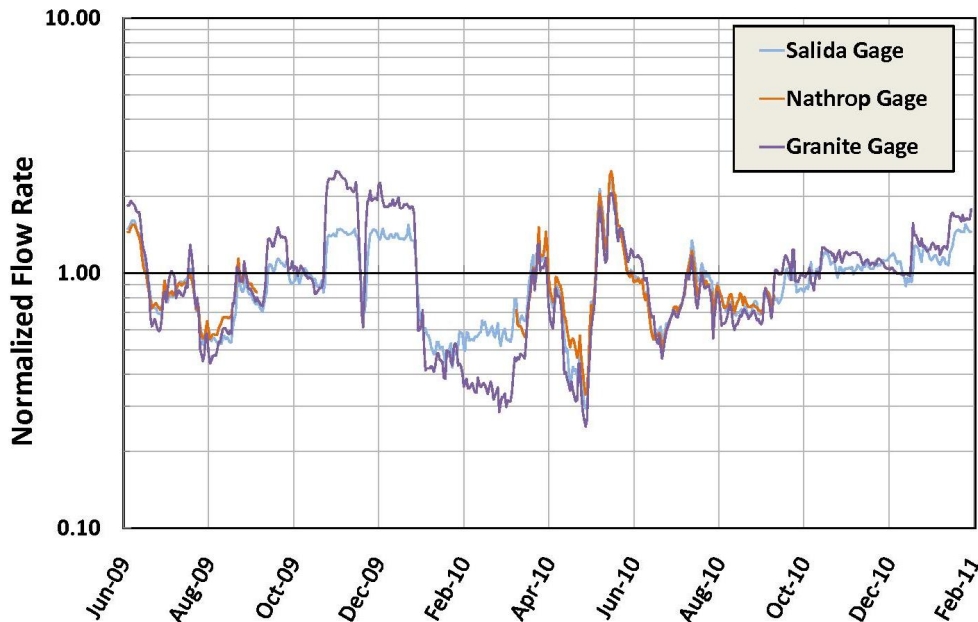


Figure 3. Daily mean flow rate at three Arkansas River gages during the study period normalized by the long-term average of the daily mean flow rate for the same day.

Figure 4 shows a similar plot for three tributary gages near their confluences with the Arkansas River. The site at the South Arkansas River confluence was taken out of service during the period of monitoring due to long-term impairment and thus was not utilized for long-term data analysis. The Clear Creek gage is just downstream of Clear Creek Reservoir and measures controlled releases based upon reservoir operational rules. Abrupt jumps on November 15 and April 15 in the Clear Creek plot suggest recurring adjustments in the reservoir releases on those dates. The averages of the normalized flow rates during the study period for Clear Creek, Cottonwood Creek, and Chalk Creek are 0.55, 0.87, and 1.07, respectively. The low value for Clear Creek suggests that Clear Creek Reservoir was generally in a period of net storage gain during the study period rather than more typical flow releases. Cottonwood Creek and Chalk Creek appear to have near normal flows with the exception of a notable spike during the 2010 snowpack runoff. Greater relative variability in the Cottonwood Creek plot could be a reflection of anthropogenic influences. Cottonwood Creek runs through the town of Buena Vista, has multiple upstream reservoirs, and, according to the records of Water District 11 found at the Chaffee County Courthouse, is subjected to 63 adjudicated water rights totaling over 213 cfs. For comparison, Chalk Creek has only 29 adjudicated rights totaling 150 cfs.

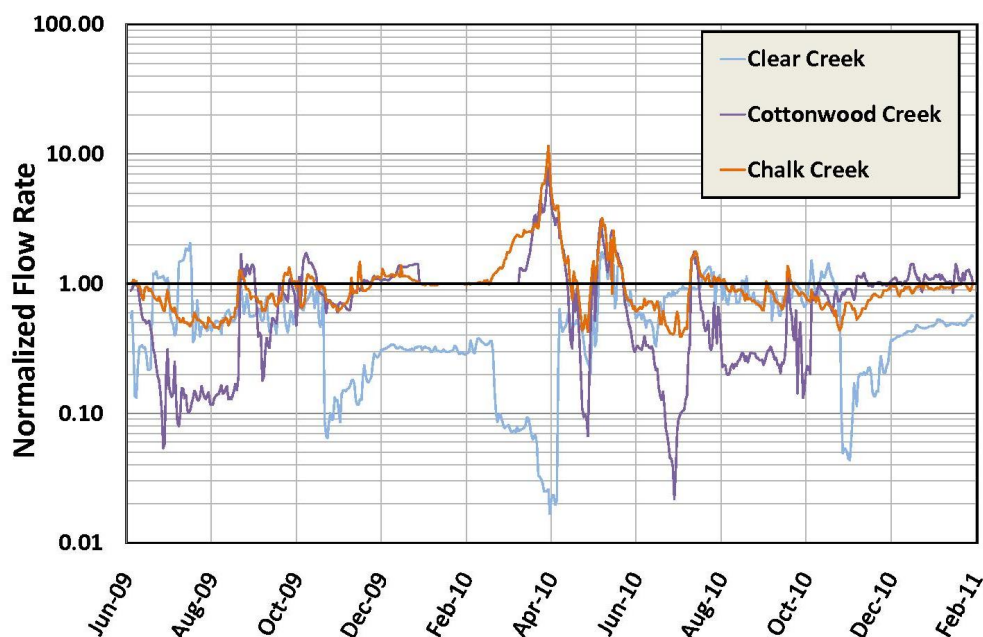


Figure 4. Daily mean flow rate at three tributary gages during the study period normalized by the long-term average of the daily mean flow rate for the same day.

Figure 5 examines whether longer-term trends are observed in the discharge at the gage locations. To create this plot, the average value of the normalized flow rate is calculated for each water year (October 1 – September 30) from 1983 to 2008. In this plot, a year for which every daily value matches the long-term average daily value would have a value of 1 for that year. The Nathrop and Clear Creek gages are not shown because of seasonal-only operation and highly controlled reservoir release flows, respectively. The four gages plotted show consistency over the time period analyzed. Cottonwood Creek's variation from average is larger than the other gages, with higher peaks and lower valleys in the plot (note that data are unavailable for this gage from 1988 to 1992). However, the relatively short time period and high overall variability prohibit any definitive conclusions. Further analysis over a longer time period with particular attention to Cottonwood Creek is warranted before any conclusion is reached.

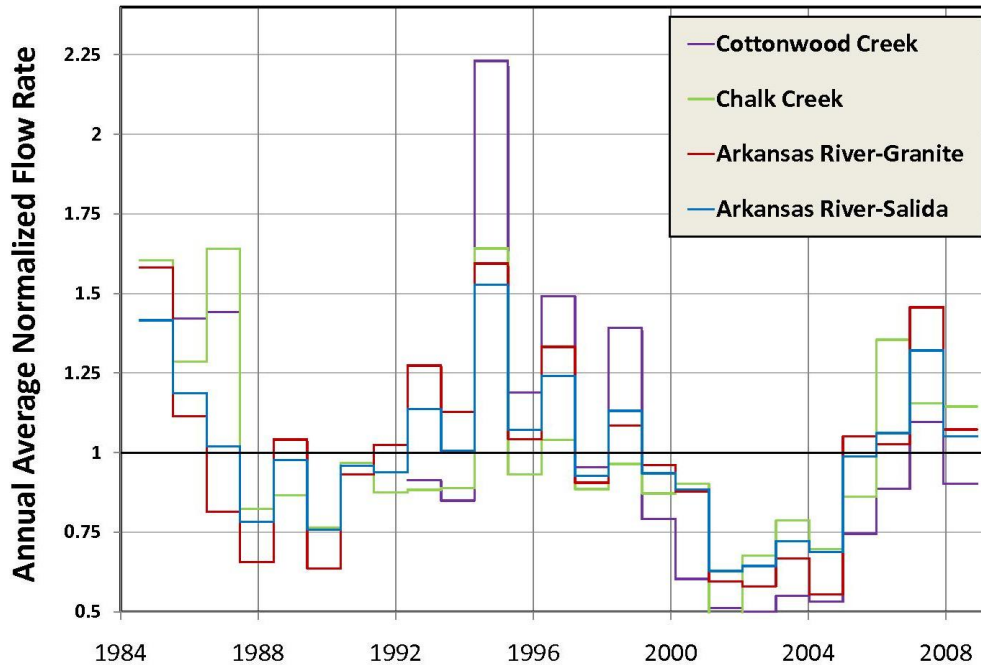


Figure 5. Water year (Oct 1 – Sept 30) average of normalized daily mean flow rates at selected gages over the period 1984 through 2009.

Seasonal flow rates also were analyzed to understand the contributions from tributaries to the main stem of the Arkansas River, as well as potential gains and losses in the streams due to interactions with the groundwater. Each year of the long-term gage records was divided into the irrigation season (April 15th - October 15th) and the winter season (October 16th – April 14th). During the irrigation season, the discharge in the main stem of the Arkansas River increases 63% along the reach between Granite and Nathrop. The gaged tributaries of Clear Creek, Cottonwood Creek, and Chalk Creek account for 67% of this increase. Based on the 8 discharge measurements taken during the irrigation seasons for 2009 and 2010, Fourmile Creek and Browns Creek contribute 1% and 2%, respectively, to the flow increase. In the reach from Nathrop to Salida, the flow in the Arkansas decreases 3% or an average of 23 cfs. The decrease in discharge in the lower reach is attributable to the lack of any perennial streams to contribute flow and due to large irrigation diversions that calculate to as much as a 13% relative decrease (102 cfs based on adjudicated diversion water rights in this reach). Overall, the flow in the Arkansas River increases 62% from Granite to Salida. During the winter season, the Nathrop gage is non-operational, so only the discharge records at Granite and Salida are available on the main stem. The average increase in discharge through this reach is 86%, and the three long-term gaged tributaries account for only 34% of this increase. Using monthly measurements during 2009 and 2010, Fourmile Creek and Browns Creek contribute only 1% and 3%, respectively, to this flow increase.

Putting these numbers in terms of volumetric discharges, the flow rate increase from Granite to Salida is 298 cfs and 147 cfs during the irrigation and winter seasons, respectively. Removing the calculated contributions from the tributaries, we can approximate the magnitude of other sources, which might include groundwater discharge, irrigation return flows, other unmeasured tributaries, and precipitation. We find that the

other sources provide 89 and 91 cfs in the irrigation and winter seasons, respectively. These figures suggest that the other sources are relatively constant between the seasons but are proportionally much more significant during the winter season when the total flow is lower.

3.2 Water Quality

The collected dataset also allows an analysis of the TDS and the contributions of the various tributaries to the TDS load. Of the six monitored tributaries, all but the South Arkansas River join the main stem in the reach between Granite and Nathrop. Based upon five sampling events on each of these tributaries, an analysis of TDS loads in tons per day was performed and shows that these tributaries contribute an average of 35% (range is 21% - 45%) of the TDS load increase from Granite to Nathrop. Clear Creek, Fourmile Creek, Cottonwood Creek, Chalk Creek, and Browns Creek are the tributaries in this reach and contribute an average of 12%, 1%, 7%, 14%, and 3% of the load, respectively. From the Nathrop gage to the Salida gage, there are no significant tributaries. In fact, there are significant irrigation diversions along this reach, yet the TDS load increases over the reach. The relative load increases an average of 88% (range is 55% to 120%) from Granite to Nathrop and 17% (range is -7% to 43%) from Nathrop to Salida. Overall, this analysis suggests that well over half of the TDS load increase moving downstream is provided by sources other than the monitored tributaries.

A large number of in-situ water quality measurements and laboratory-analyzed samples were collected. Site visits where in-situ data were collected totaled 57 and 295 for the main stem and tributaries, respectively, while the water quality samples taken for laboratory analysis totaled 23 and 86 for the main stem and tributaries, respectively. Table 1 is a brief summary of the results of those efforts. Results of in-situ measurements of EC, pH, DO, ORP, and temperature are within expected ranges and usually reflect good water quality. Tributary sites generally have a broader range of values in the measurements. DO measurements across all sites are above the 3.0 mg/l required in Colorado surface waters for domestic, agricultural, and recreational purposes, and they are rarely below the more stringent 6.0-7.0 mg/l that is recommended for aquatic life (CDPHE 2010). Seasonal DO behavior varies as expected based on physical relationships with water temperature. January has the highest average DO of 11 mg/L and the lowest average temperature of 1.3 °C, while July has the lowest average DO value of 7.8 mg/l with the highest average water temperature of 14.3 °C. Values of pH between 6.5 and 9.0 are stipulated for aquatic life and recreational contact, while domestic water supply requirements range from 5.0 to 9.0 (CDPHE 2010). Some tributary measurements fall outside this range, but the 15th and 85th percentile values fall within this range at 7.5 and 8.2 respectively.

Table 1. Water quality characteristics at surface water monitoring points over 352 site visits and 109 water quality samples during the period July 2009 through January 2011.

	<i>EC</i>	<i>pH</i>	<i>DO</i>	<i>ORP</i>	<i>Temp.</i>	<i>TDS</i>
Main Stem Sites	$\mu\text{S/cm}$		mg/L	mV	$^{\circ}\text{C}$	mg/L
<i>Minimum</i>	78	7.5	7.0	50	0.0	57
<i>Maximum</i>	231	8.9	15.0	295	18.0	148
<i>Average</i>	164	8.2	9.9	185	7.8	100
Tributary Sites						
<i>Minimum</i>	45	6.2	6.5	17	0.0	37
<i>Maximum</i>	336	9.3	14.6	291	23.5	231
<i>Average</i>	132	7.9	9.6	166	6.9	96

Results of the laboratory analysis for selenium and uranium obtained with every water quality sample showed selenium to be present only at levels at or below the reporting limit of 0.4 $\mu\text{g/l}$. Uranium was detected in all samples at varying levels. Overall, concentrations increased going downstream for all tributaries and the main stem, with the Browns Creek downstream site and the South Arkansas River downstream site yielding the highest average values of 5.3 $\mu\text{g/l}$ and 4.6 $\mu\text{g/l}$, respectively. In the main stem sites, uranium increased from an average 0.29 $\mu\text{g/l}$ at Granite to 2.3 $\mu\text{g/l}$ at Salida. The national primary drinking water regulations for maximum contaminant level of uranium in public water supplies is currently 30 $\mu\text{g/l}$ (EPA 2009), while the human health-based value in Colorado is 16.8 $\mu\text{g/l}$ (CDPHE 2010). Thus, uranium is not currently of concern, but it may be worthy of further study and monitoring. Additional metals were analyzed for two of the five water quality sampling events. These include aluminum, cadmium, lead, copper, zinc, iron, manganese, and fluoride. Results showed only one sample exceeding EPA regulatory drinking water standards. This sample was collected in Fourmile Creek. A manganese concentration of 230 $\mu\text{g/l}$ was measured, compared with an EPA secondary drinking water regulation of 50 $\mu\text{g/l}$ (EPA 2009).

Laboratory analysis reports of anions and cations yield TDS values also within ranges that reflect high water quality. The primary dissolved constituents that contribute to TDS in the main stem are bicarbonate, sulfate, and calcium in proportions of 51%, 20%, and 17% of the total, respectively. The major contributing constituents in the tributaries are also bicarbonate, sulfate, and calcium in proportions of 58%, 13%, and 18%, respectively. When comparing the contributions of these compounds between sites, the only apparent trend was an inverse relationship between bicarbonate and sulfate. As bicarbonate contribution went up, sulfate contribution went down proportionately and vice versa. The highest average TDS in the study region occurs at the downstream site on the South Arkansas River with a value of 193 mg/l . The lowest average of 40 mg/l occurs at the upstream site on Browns Creek. As expected, TDS values from the main stem of the Arkansas River increase moving downstream, from an average of 84 mg/l at Granite to an average of 116 mg/l at Salida. The relationship of TDS and in-situ measured EC for all 3

sites on the main stem and 10 of the 15 tributary sites showed high correlations, with coefficient of determination values (r^2) above 0.87.

4. Conclusions

Discharge rates in the Arkansas River in Chaffee county and its major tributaries during the study period reflect levels near or slightly less than the long-term averages. In Chaffee County (from Granite to Salida), the Arkansas River discharge increases by 62% and 86% during irrigation and winter seasons, respectively, and the measured tributaries within this reach contribute approximately 70% and 38% of the increases in the irrigation and winter season, respectively. The remaining sources contribute about 90 cfs in both seasons, but this contribution represents a larger percentage in the winter because of the lower discharge rates in the Arkansas River. TDS loads increase through the study region, but greater than half of the relative increase is provided by sources other than the monitored tributaries. Regression analysis of laboratory-calculated TDS to in-situ EC showed high correlation at 13 of 18 sites. Overall, the water quality is good (for all tested characteristics), but the data support continued monitoring of uranium and occasional testing for manganese.

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