

CHAPTER 2

STUDY REGIONS

2.1. OVERVIEW OF THE LOWER ARKANSAS RIVER VALLEY IN COLORADO

The Upstream Study Reach (USR) extends from just west of Manzanola to near Las Animas and is representative of the hydrology, soil, crop, and irrigation conditions upstream of John Martin Reservoir. The Downstream Study Reach (DSR) is representative of the 5 conditions downstream of John Martin Reservoir. It extends from Lamar to the Colorado-Kansas state line. Both study reaches are located in the LARV which starts at the outlet of Pueblo Reservoir, approximately 10.5 km (6.5 mi) miles west of Pueblo, Colorado and extends into Kansas. This study is only concerned with the portions of the Arkansas River and LARV in Colorado. All portions of the LARV in Colorado are within Division 2 of the 10 Colorado Department of Water Resources (CDWR). Division 2 offices are located in Pueblo, Colorado. The CDWR is the state agency responsible for the legal administration of all surface and sub-surface waters in the State of Colorado. Figure 2.1 shows the location of the LARV, USR, DSR, and adjacent irrigated valley lands that contribute to the non-point source (NPS) return flows and loads to the study reaches in this thesis.

15 *Regional Geology of the LARV.*

The LARV is wide, with widths up to approximately 20 km (12.5 mi), but shallow with maximum elevation differences approaching 130 m (425 ft). The un-confined aquifer sits in alluvium made of a series of late Cambrian to Tertiary sedimentary formations (Darton 1906). The bedrock underlying the alluvium consists primarily of marine-derived shales of 20 the Pierre, Niobrara, Carlisle, and Graneros series and limestones for most of the valley. As the river nears the Colorado-Kansas border, the bedrock is Dakota sandstone (Moore and

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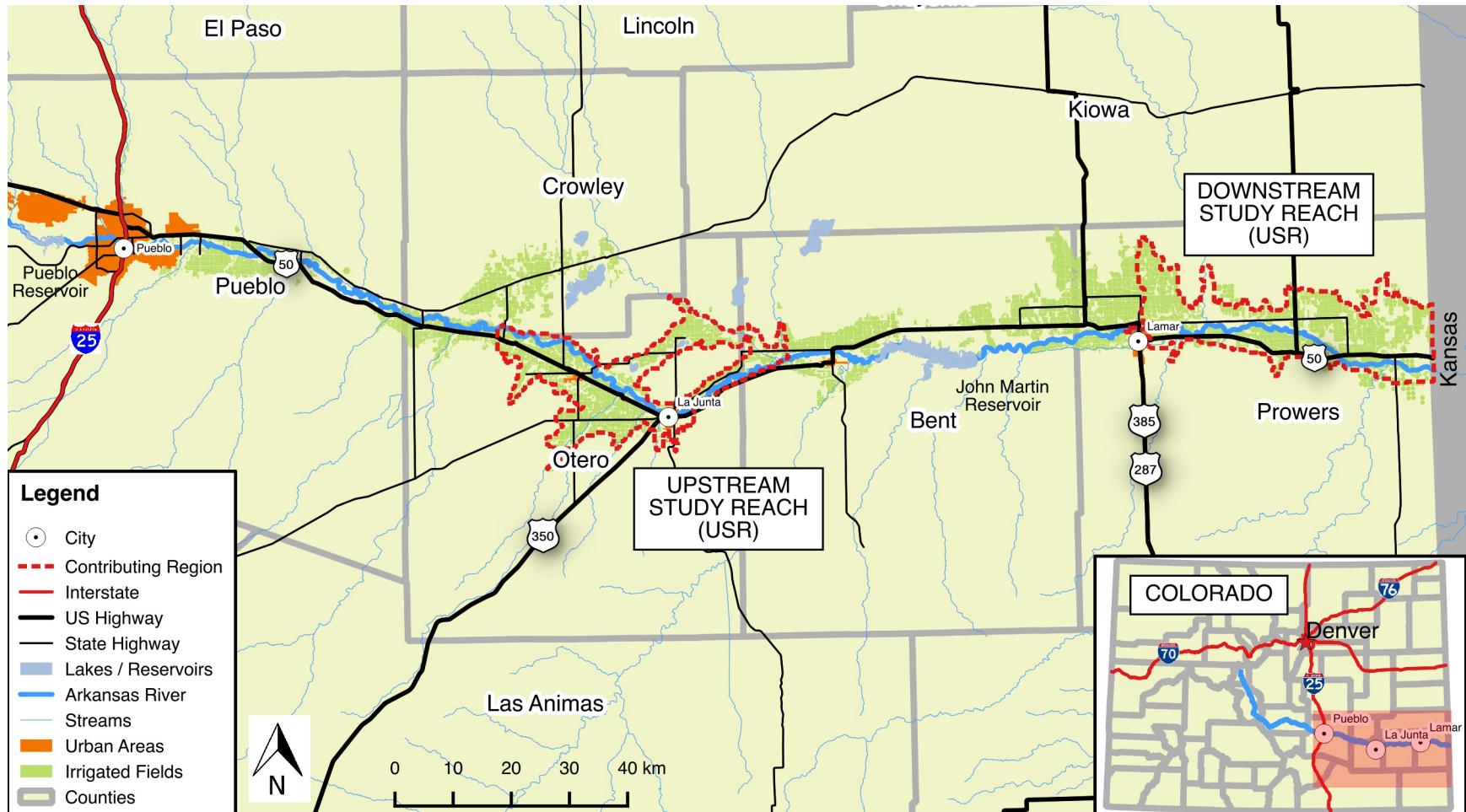


Figure 2.1. Lower Arkansas River Valley.

Wood 1967) . The river is characterized as a shifting sand channel that meanders along the alluvial flood plain which is incised into the flood way. The alluvial aquifer and the Arkansas River and its tributaries have a strong hydraulic connection with the Arkansas River (Konikow and Bredehoeft 1974).

5 Evidence indicates that the marine-derive shale bedrocks that underly most of the LARV and their weathered residuum yield a variety of salts, Se, and U under the dissolving action of natural and irrigation flows (Ryan T Bailey, Hunter, and Timothy K Gates 2012; Timothy K Gates et al. 2009; Zielinski, Sigrid Asher-Bolinder, and Meier 1995; Zielinski, S Asher-Bolinder, et al. 1997). In the US, selenium is readily abundant in some, but not
10 all areas west of the western Dakotas, Nebraska, Kansas, and Oklahoma to the west cost (Painter 1940). Figure 2.2 is a set of geochemical distribution maps developed by the U.S.G.S. Mineral Resources Program that shows the distribution of Se in the conterminous U.S. in the 0 cm to 5 cm layer, the top soil (A horizon) layer, and the parent rock (C horizon) layer (Smith et al. 2014).

15 *Regional Climate and Hydrology of the LARV*

Regionally, the climate is arid with large temperature fluctuations. Most of the rainfall comes during the growing season in the form of heavy thunderstorms. Summers are hot with an average high temperature of 93°F (34°C) and winters are cold, with an average low temperature of 14°C –10°C. Snowfall is usually light, but is prone to drifting with the
20 low humidity and moderately high velocity, steady winter winds.

The historic stream flows show considerable seasonable variability. Most of the total annual flow is influenced primarily by snow melt and runoff in the Upper Arkansas River

Basin, above Pueblo Reservoir. Additionally, groundwater base flow, runoff from precipitation events in the Eastern Colorado plains, and releases from Pueblo and John Martin Reservoirs in compliance with operational rules contribute to flow rates (Miller et al. 2010).

Average annual precipitation within the LARV ranges between 31.52 cm (12.41 in) 5 in Pueblo, and varies eastwardly to 39.65 cm (15.61 in) in Holly. Figure 2.3 is a map of the LARV with the Average Annual Precipitation from 1981 - 2010 as reported by the U.S.D.A N.R.C.S. Average reference ET (ET_{Ref}) during the irrigation season (15 March - 15 November) is 1.3 m (4.25 ft) based on data collected from CoAgMet weather stations over the period 1992 - 2008 (Clifford and N. J. Doesken 2009). The Arkansas River riparian zone 10 in the flood way is primarily characterized by heavy growth of Russian Olive (*Elaeagnus angustifolia*), multiple species of salt cedar (*Tamarix*), willows and other non-native species that are major contributors to regional evapo-transpiration (ET) losses (Nagler et al. 2010).

Anthropogenic Factors for the LARB Study Regions.

Historically, prior to the advent of irrigated agriculture in the Ark River Basin during 15 the 19th century, groundwater recharge in the basin occurred primarily from infiltration of precipitation through the unsaturated zone and from infiltration of surface water from losing streams. By mid-1880s, the waters of the Arkansas R. and its tributaries were fully appropriated for normal or average years (Abbott 1985). In areas where surface water was 20 diverted for irrigation, infiltration of irrigation water from canals and fields became a primary source of groundwater recharge. Natural recharge is about 0.08 inches/year in the southeast corner of the state (Wolock 2003).

The LARV river-aquifer system supplies water to towns and industries through shallow aquifer wells. Water is returned either directly to the river after treatment or into

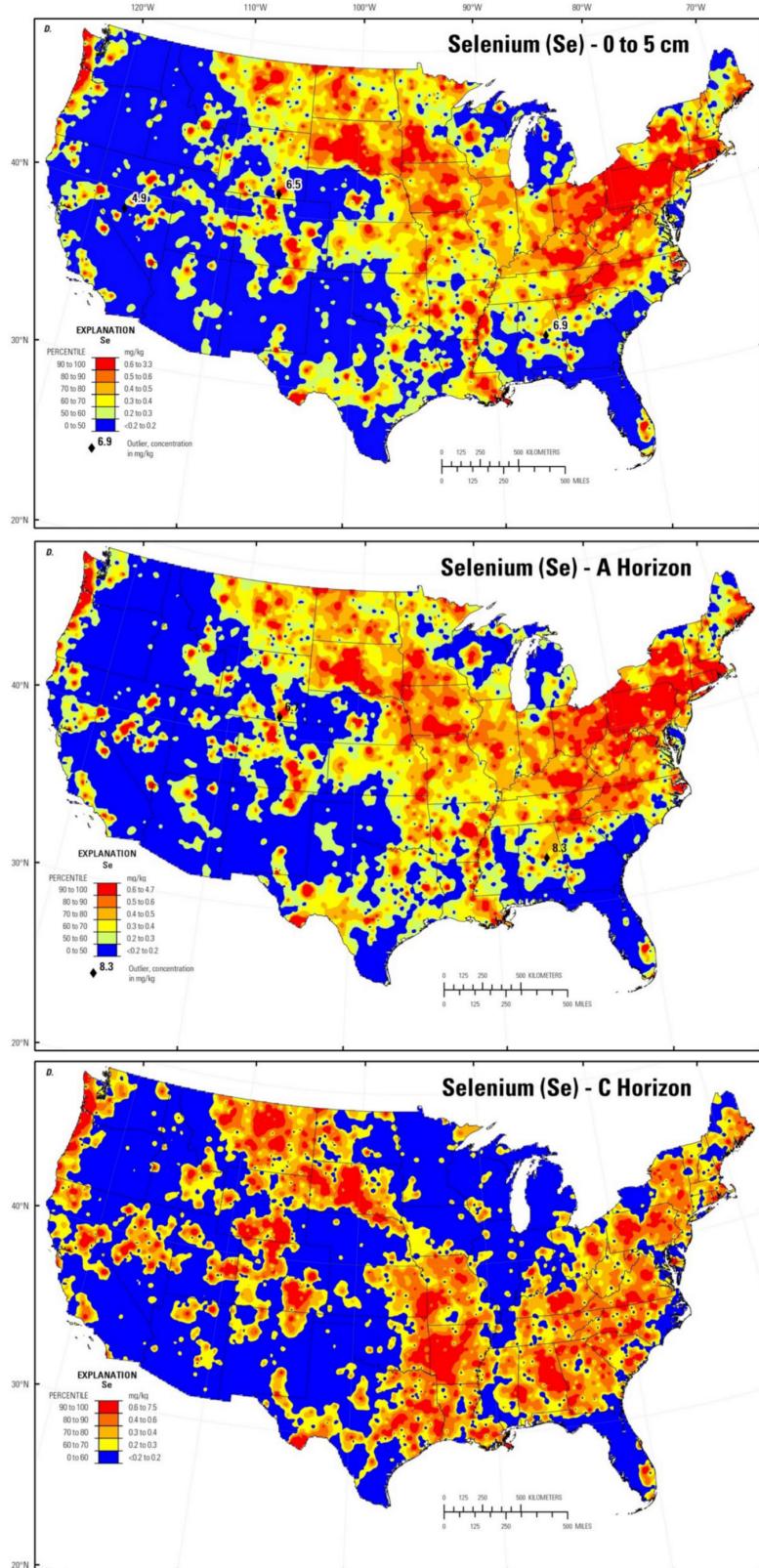


Figure 2.2. Distribution of Se in Soil in the Conterminous United States (Smith et al. 2014). This is a composite of three individual maps.

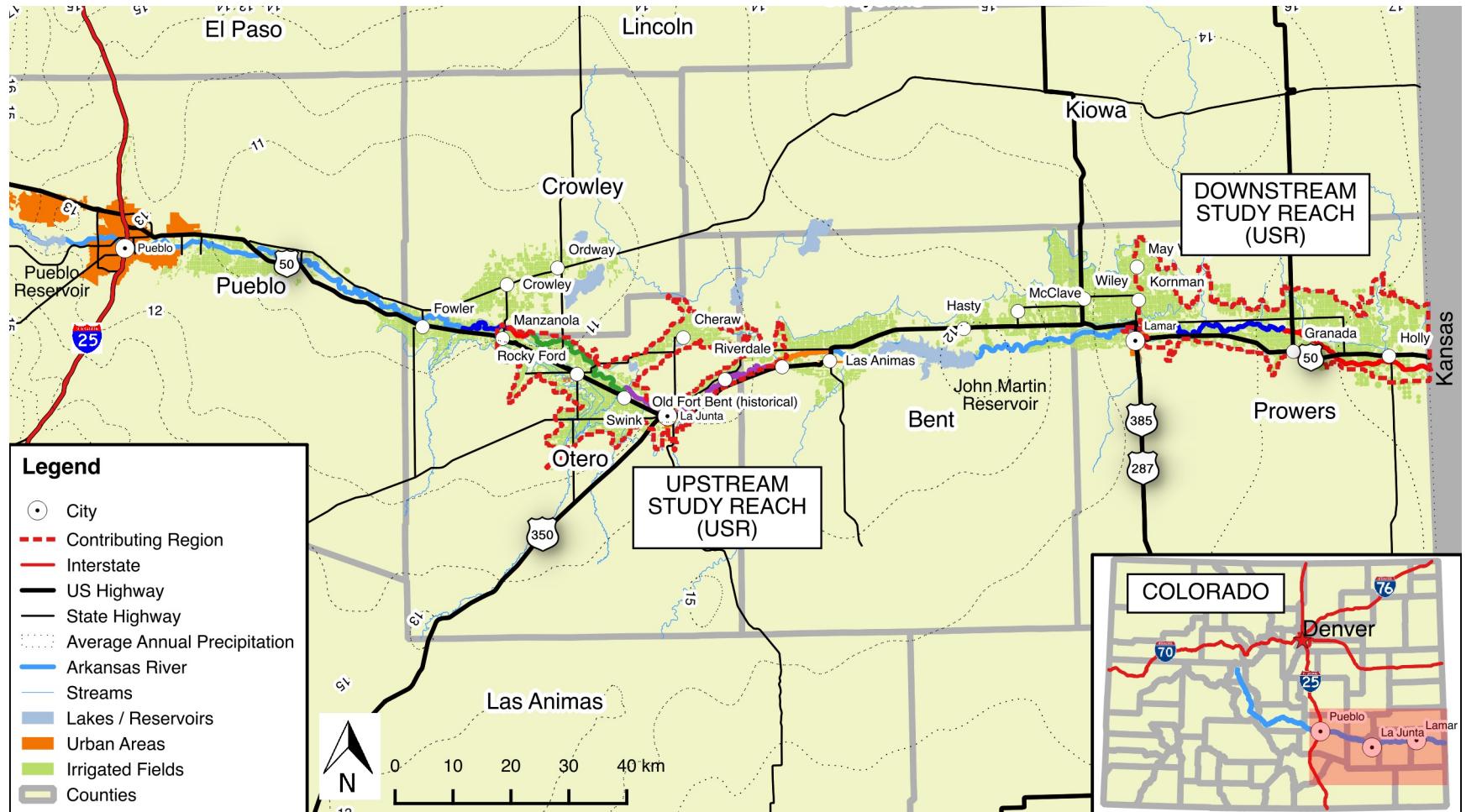


Figure 2.3. Precipitation in the LARV. Values on the isolines are reported as inches of average annual rainfall.

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the aquifer through groundwater seepage from treatment lagoons. Water supplied to these entities is a very small portion when compared to the demand from agriculture in the valley.

Agriculture is the primary industry in the LARV with approx 270,00 acres irrigated (R. T. Bailey, Romero, and T. K. Gates 2015; Miller et al. 2010). There are 25 main irrigation canals in the LARV with diversion structures crossing the river. Many fields near the river drain excess irrigation water directly back to the river (Ryan T Bailey, Hunter, and Timothy K Gates 2012; Morway et al. 2013). There are also about 2,400 groundwater pumping wells that tap into the riparian aquifer, thereby taking water, albeit indirectly, from the river. The floodplain is characterized by heavy agriculture on fertile soils. The region is known for a wide variety of crops including but not limited to alfalfa, corn, grass hay, wheat, sorghum, dry beans, cantaloupe, watermelon, and onions in order of cropped area (USDA NASS Colorado Field Office 2009). There are also a few diaries and cattle feed lots. Most fields are irrigated using surface-irrigation methods with less than about 5% irrigated with sprinklers or drip lines. Surface and sprinkler irrigation efficiencies are varied depending on the crop and location (Ryan T. Bailey 2012) refGates et al 2015

Precipitation in the LARV is substantially insufficient to support crop production by about 0.9 m (3 ft). It has been estimated that appropriated water rights in the LARV exceed the annual native river flow by as much as 40% in a low flow year (Cain 1985; Sutherland and Knapp 1988). Additional water is provided by releases from Pueblo and John Martin Reservoirs which store water during the winter period. Some of this water is provided through trans-basin transfers through the Fryingpan-Arkansas Project.

Seepage from canals contributes significantly to the water quantity and quality in LARV aquifer. Canals are constructed at higher elevations, promoting the surface transport of water over long distances to fields. This elevation difference also places a higher hydraulic

gradient between the canal and aquifer. Canals, as a rule, are not constructed such that groundwater infiltrates into the canal channel. The entire process promotes the movement of water and dissolved constituents, including NO_3^{2-} , Se, U, and salts directly into the aquifer. Additionally, a significantly large quantity of the total canal length in the LARV is located 5 away from the river. This has two results. Since the aquifer is receiving recharge water from the canals, it acts as a reservoir, delaying the return of that water to the river channel. This result is seen during low flow conditions when the river channel still contains water, even though historic conditions would tell us otherwise. The second result is that dissolved constituents are introduced into the aquifer where it is the shallowest, along the edges of 10 the valley. This brings NO_3^{2-} and dissolved oxygen into contact with the Se bearing bedrock before either can be significantly depleted through other redox reactions (Ryan T. Bailey 2012; Morway et al. 2013).

2.2. UPSTREAM STUDY REACH AND SURROUNDING REGION

The upstream boundary of the USR starts immediately downstream of the Catlin Canal diversion dam. The dam is approximately 4.5 miles (mi) (7 km) west of the intersection of U.S. Highway 50 and State Highway 207 in Manzanola and 4.5 mi (7 km) east of the 5 intersection of U.S. Highway 50 and State Highway 164 in Fowler. The USR extends along approximately 61.5 mi (99 km) of the river to where U.S. Highway 50 crosses the Arkansas River north of Las Animas. All portions of the USR are in CDWR Division 2, Water District 17 which extends from Fowler to Las Animas. There are three main tributaries, multiple minor tributaries, five main irrigation canals, and one return canal (for augmentation flow) 10 are present in the USR. Figure 2.4 shows the extent and approximate path of the USR and the irrigated region supplying return flow to the reach.

The USR is separated into five segments given designations from "A" to "E" (Figure 2.4). Segments are geographically separated by irrigation canal diversion dams. Segment B is the only segment that does not contain a stream gauge on the main stem of the river. 15 It is relatively short and has an additional diversion dam within its boundary. Typically, significantly different flows pass through the main channel of the river within each segment. Segments were defined to provide boundaries for river storage volume calculations. Within each segment, except for segment B, the water surface level is determined primarily by flowrate, hydraulic geometry, and hydraulic resistance. Knowledge of the water surface level 20 is necessary for estimating the river storage volume. A discussion of the river geometry analysis and storage volume calculation is provided in sections ?? and ??.

Figure 2.5 is a line diagram representing the major flow paths in the USR. This diagram is not to scale and depicts only the major canals and tributaries. The segments within the reach are color coded. Four canal diversion dams separate the segments. Points in

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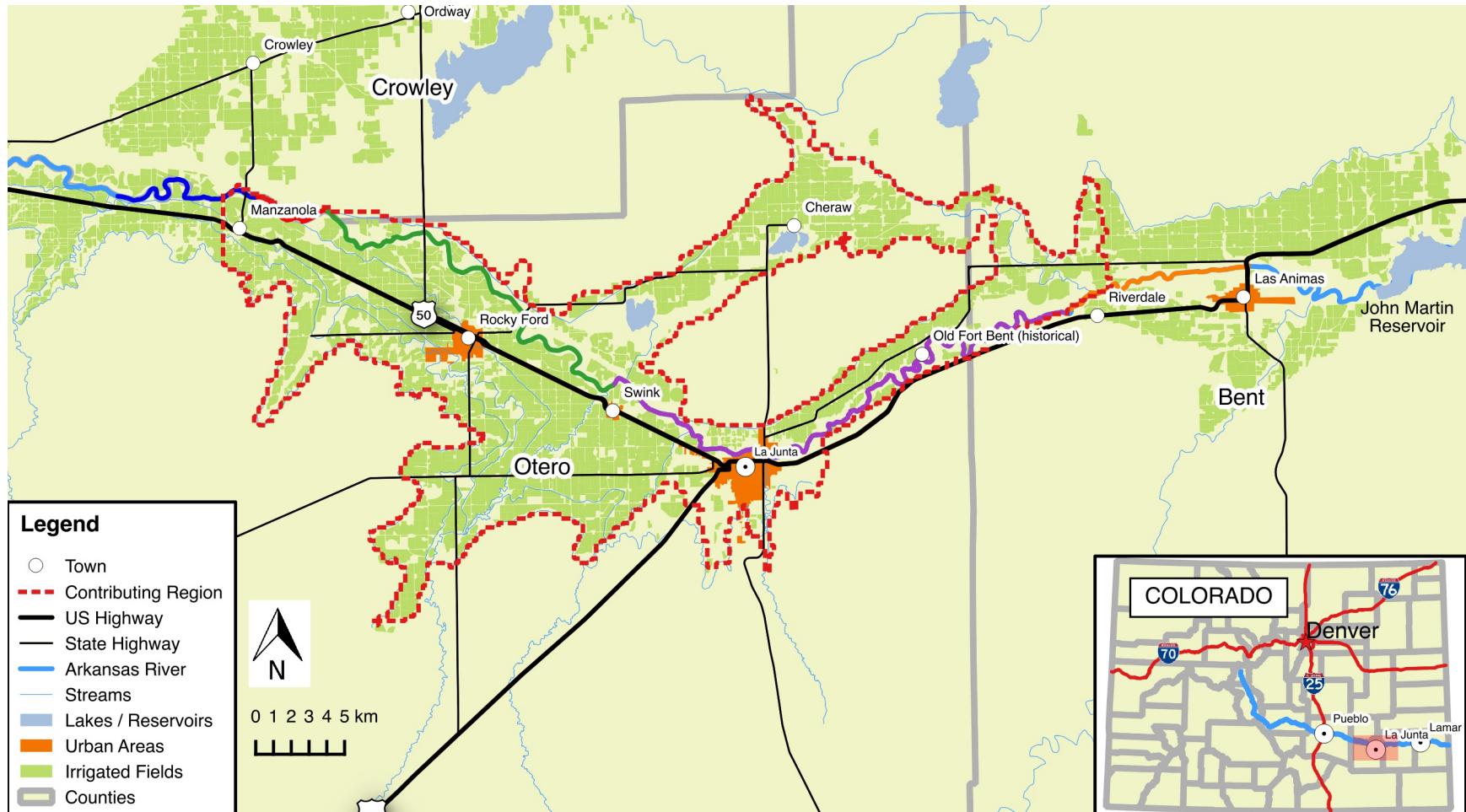


Figure 2.4. Upstream Study Reach. River segments within the USR are color coded.

Figure 2.5 designated as "Water Quality" are locations where CSU field technicians routinely took water samples for analysis. A discussion of the sampling and analysis methods is presented in section 3.1.

The main tributaries are perennial and supply water to the Arkansas River under 5 most conditions. These tributaries are Timpas Creek, Crooked Arroyo, and Horse Creek. Most of the minor tributaries are usually dry and only convey water during larger rainfall events and flood conditions. All three major tributaries have a significant portion of their flows provided by agricultural runoff.

There are two minor tributaries that provide low volume, perennial flows to the 10 Arkansas River: King Arroyo and Anderson Arroyo. King Arroyo is assumed to be primarily fed by La Junta Waste Water Treatment Plant (WWTP) effluent. The La Junta Water Treatment Plant (WTP) effluent spills into Anderson Arroyo. It is currently unknown what groundwater and other flows contribute to the discharge from King or Anderson Arroyos. No discharge data are provided for the La Junta WTP due to the very low discharge rates. 15 The discharge from the La Junta WWTP is included in the models.

Patterson Hollow, a poorly-defined natural drainage, is depicted on the line graph as connected to the Arkansas River. Flows from the upper reach of Patterson Hollow are diverted to the Otero Canal. The reasons for the diversion are unknown, but it is speculated that the majority of the flows upstream of Otero Canal are irrigation returns and the diversion 20 was an attempt to re-use valuable irrigation water. Regardless, since Patterson Hollow, for the most part, was separated from the Arkansas River, it was not included in this study.

The five major canals diverting water from the Arkansas River along the USR are Holbrook Canal, Rocky Ford Canal, Fort Lyon Storage Canal, Fort Lyon Canal, and Jones Ditch. The Rocky Ford Return Canal is the only monitored canal returning augmentation

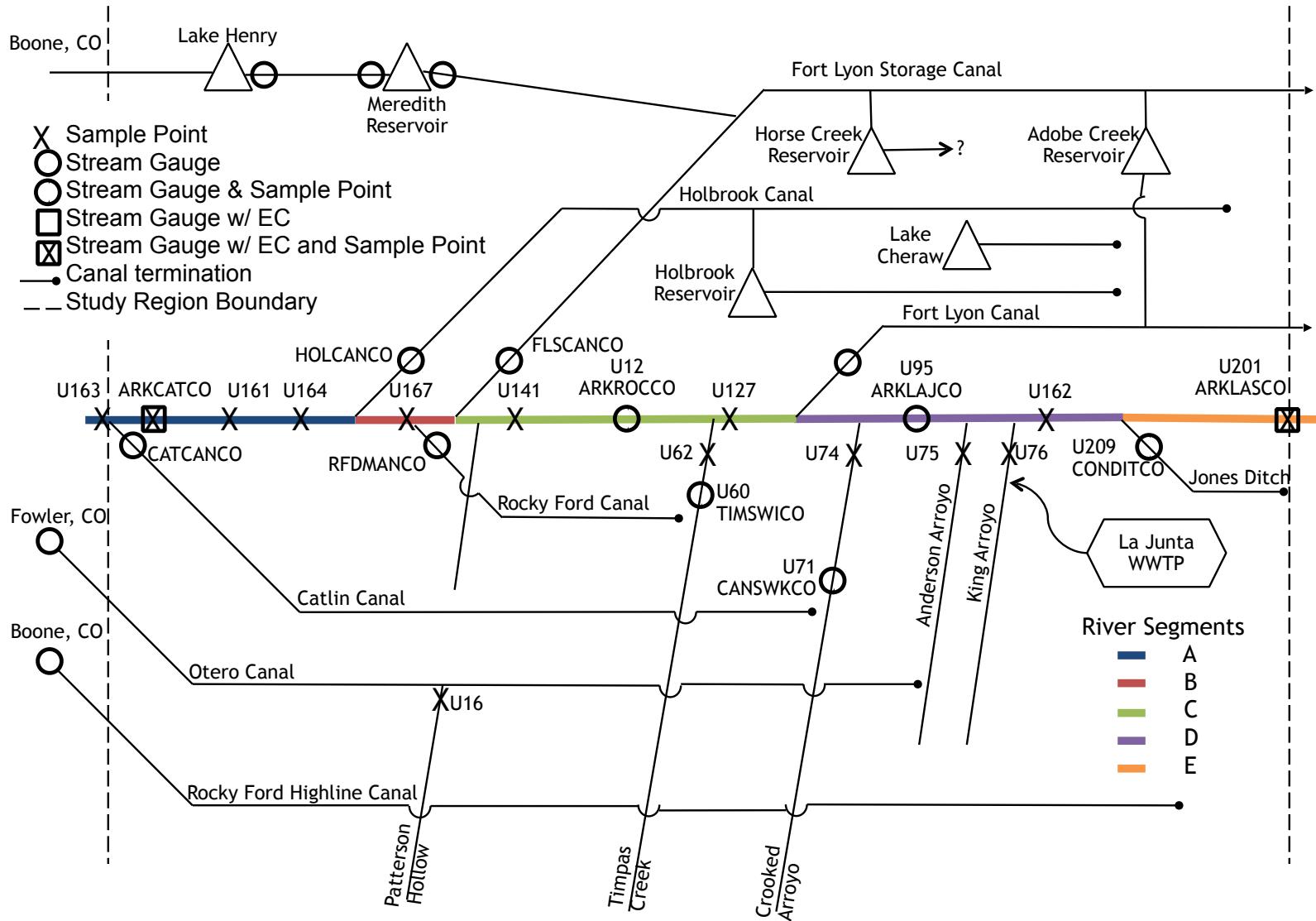


Figure 2.5. Upstream Study Reach Flow Diagram.

water to the Arkansas River in the USR. The Rocky Ford Return Canal diverts water from the Rocky Ford Canal and returns it directly to the Arkansas River. This system is in place to monitor and augment flows in conjunction with trans-basin flows used by the City of Aurora. The Otero and Rocky Ford Highline Canals run parallel to the USR. They divert
5 water from the Arkansas River upstream of the USR upstream boundary. Overflows from these two canals pass through the tributary gauge in Crooked Arroyo.

2.3. DOWNSTREAM STUDY REACH AND SURROUNDING REGION

The DSR begins at the U.S. Highway 50/U.S. Highway 287 Arkansas River crossing in Lamar, Colorado, and extends approximately 71 km to the Colorado/Kansas state line (Figure 2.6). Figure 2.7 is a line diagram representing the flow structure within the DSR.

5 Similar symbology is used on these maps as in Figures 2.4 and 2.5 for the USR. For a period of time, there were four tributaries and drains in the DSR where flows were measured manually gauged on an infrequent basis. The results of the this stream gauging activity do not affect the calculation or analysis of this study, but will be discussed in the conclusion.

The entirety of the DSR lies within CDWR Division 2, District 67 and contains two major

10 tributaries, multiple minor tributaries, and one irrigation canal.

The DSR is separated into Segment F and Segment G as shown in figure 2.6. The diversion dam for the Buffalo Ditch irrigation canal is the boundary between the two DSR segments. Field technicians have observed complete diversion of the Arkansas River at the Buffalo Ditch diversion with small but significant flows reappearing in the Arkansas River

15 channel only a few kilometers downstream. This leads to the speculation that significant portions of the downstream in-channel flow are from groundwater return flow.

The major tributaries within the DSR are Big Sandy Creek and Wild Horse Creek. CSU field technicians have observed that the stream gauge on Big Sandy Creek has been affected by beaver dams constructed downstream of the gauge and upstream of the culvert

20 passing under State Highway 196. The stream gauge on Wild Horse Creek is operated seasonally from April through November. CSU has made many visual flow observations in these creeks outside of the irrigation season. The off season flows are either extremely low or the stream is frozen.



Figure 2.6. Downstream Study Reach. River segments within the DSR are color coded.

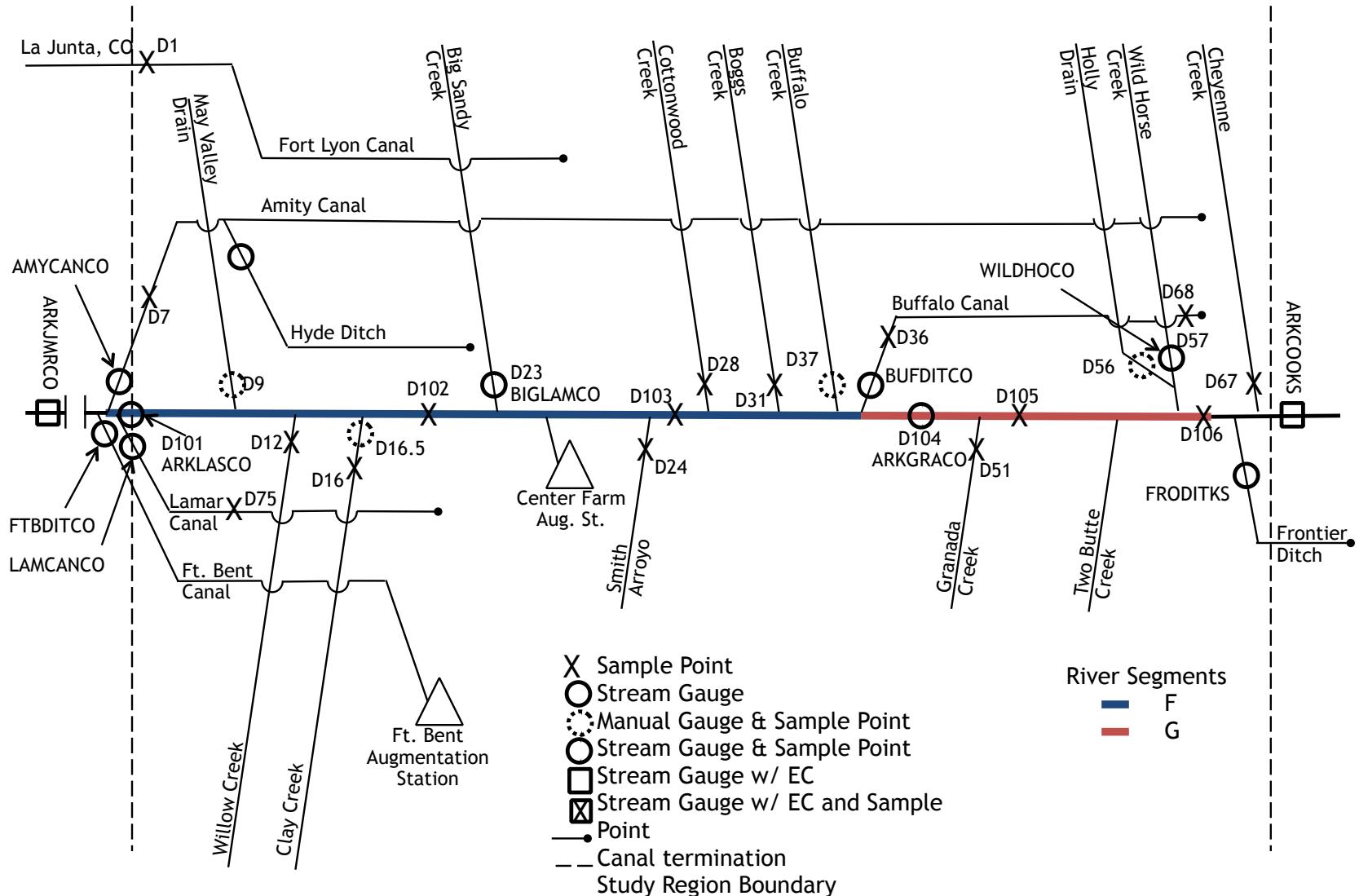


Figure 2.7. Downstream Study Reach Flow Diagram.

Unlike the USR, most of the minor tributaries in the DSR flow most of the year except in drought conditions. The primary source of water in the minor tributaries is irrigation runoff flowing into the streams through surface and subsurface flow paths. Most minor tributaries in the DSR do not have definitive entry points to the Arkansas River channel 5 resulting in doubt as to whether these flows reach the Arkansas River as surface water. It was assumed herein that the minor tributary flows enter the main stem primarily as groundwater. Minor surface return flows that do reach the Arkansas River are not gauged and most are difficult to access.

Buffalo Canal is the only functioning canal diversion within the DSR. There is historical and aerial imagery evidence for another diversion, but the Arkansas River has been 10 routed around the structure and neither the CDWR nor the USGS maintain a flow gauge for the canal serviced by the diversion.

CHAPTER 3

DATA COLLECTION AND COMPIRATION

3.1. WATER QUALITY DATA COLLECTION

From June 2006 to July 2011 and April 2003 to August 2011, water quality samples were taken by CSU field personnel from the Arkansas River, tributaries, and drains in the USR and DSR, respectively. During the Se study periods, 18 surface water sampling trips 5 were made to the USR and 46 trips were made to the DSR. A total of 288 dissolved Se samples were taken and analyzed for dissolved Se and specific ions in the USR and 1,030 in the DSR during their respective study periods. Table 3.3 is a summary of the sample trips, the month and year of the trip, and the number of Se samples taken from the respective locations. Figures 3.1 and 3.2 show the dissolved Se sample locations in the USR and DSR, 10 respectively. Tables 3.1 and 3.2 list the sample locations and their location with the river reach and segment. The location of the sample point within the segment is only listed for samples collected on the Arkansas River with respect to the location of the stream gauge within the river segment. Sample points on tributaries and drains as noted in the tables.

Sample collection trips involved hours of preparation. Before leaving for the study 15 region(s), equipment and supplies were prepared. Peristaltic pumps were used for all surface water sample collection. Two Durham Geo TR-200 PSP peristaltic pumps were taken on each trip. The TR-200 is a single head, bi-directional, 12-volt battery operated, portable sampling pump capable of delivering flow rates up to 500 mL min^{-1} in both directions (Figure 3.3a). The pumps were cleaned, in-situ water quality instruments were calibrated, and sample 20 collection bottles were prepared. Peristaltic pumps were cleaned at the beginning and end of each sampling day and before sampling at each field sampling location. Figure 3.4 is a picture

Table 3.1. Upstream Study Region (USR) Sample Collection Point Information. A value of zero (0) indicates the location of the segment stream gauge. Negative distances indicate the point is upstream of the reference stream gauge location. Segment B does not contain a stream gauge on the river main stem.

River Segment Name	Sample Point	Dist from USR Upstream Boundary		Dist from River Segment Stream Gauge	
		mi	km	mi	km
A	U163	0	0	-2.7	-4.3
	U161	5.8	9.3	3.1	5
	U164	6.8	10.9	4.1	6.6
B	U167	9.2	14.8		
C	U141	14.7	23.7	-5.5	-8.9
	U12	20.2	32.5	0	0
	U60	26.1	42	5.9	9.5
	U127	26.4	42.5	6.2	10
D	U74	30.3	48.8	-3.5	5.6
	U95	33.8	54.4	0	0
	U162	44	70.8	10.2	16.4
	U209	52.8	85	19	30.6
E	U207	55.1	88.7	-6.6	-10.6
	U201	61.7	99.3	0	0

Table 3.2. Downstream Study Region (DSR) Se Sample Location Information. A value of zero (0) indicates the location of the segment stream gauge. Negative distances indicate the point is upstream of the reference stream gauge location.

River Segment Name	Sample Point	Dist from USR Upstream Boundary		Dist from River Segment Stream Gauge	
		mi	km	mi	km
F	D101C	0	0	0	0
	D102C	7.9	12.7	7.9	12.7
	D23	11.6	18.7	11.6	18.7
	D103C	17.6	28.3	17.6	28.3
	D36	23.4	37.7	23.4	37.7
G	D104C	24.9	40.1	0	0
	D105C	31.2	50.2	6.3	10.1
	D57	38.1	61.3	13.2	21.2
	D106C	38.9	62.6	14	22.5

Table 3.3. Summary of USR and DSR Water Sample Events.

Trip #	Date	USR Se Samples		DSR Se Samples	
		River	Trib. & Drain	River	Trib. & Drain
1	April 2003			12	14
2	June 2003			12	15
3	July 2003			7	15
4	July 2003			6	16
5	October 2003			6	15
6	January 2004			6	15
7	March 2004			6	15
8	May 2004			6	15
9	June 2004			6	15
10	July 2004			6	15
11	August 2004			6	15
12	November 2004			6	17
13	January 2005			6	15
14	March 2005			6	15
15	June 2005			6	17
16	July 2005			6	15
17	August 2005			6	17
18	December 2005			6	16
19	January 2006			6	16
20	March 2006			6	16
21	May 2006			6	16
22	June 2006	10	5	6	16
23	July 2006			6	16
24	August 2006			6	16
25	November 2006			6	16
26	March 2007			6	16
27	May 2007	10	5	6	16
28	June 2007			6	16
29	July 2007			6	16
30	August 2007			6	16
31	October 2007	10	4		
32	November 2007			6	16
33	January 2008			6	16
34	March 2008	10	4		
35	May 2008			6	16
36	June 2008	10	5		
37	July 2008			6	16
38	August 2008	10	5		
39	November 2008			6	16
40	January 2009	10	5		

Table 3.3. Summary of USR and DSR Water Sample Events. (Continued)

Trip #	Date	USR Se Samples		DSR Se Samples	
		River	Trib. & Drain	River	Trib. & Drain
41	(No Se Samples)				
42	March 2009			6	16
43	May 2009	10	5		
44	June 2009			6	16
45	July 2009	10	4		
46	August 2009			6	16
47	November 2009	10	4		
48	January 2010			6	16
49	March 2010	10	4	6	15
50	May 2010	9	4		
51	June 2010			6	16
52	July 2010	11	6		
53	August 2010	10	7	6	17
54	November 2010	12	7	8	19
55	March 2011	12	7	8	19
56	May 2011	15	9	8	17
57	July 2011	12	7		
58	August 2011			8	17
Totals		191	97	297	733

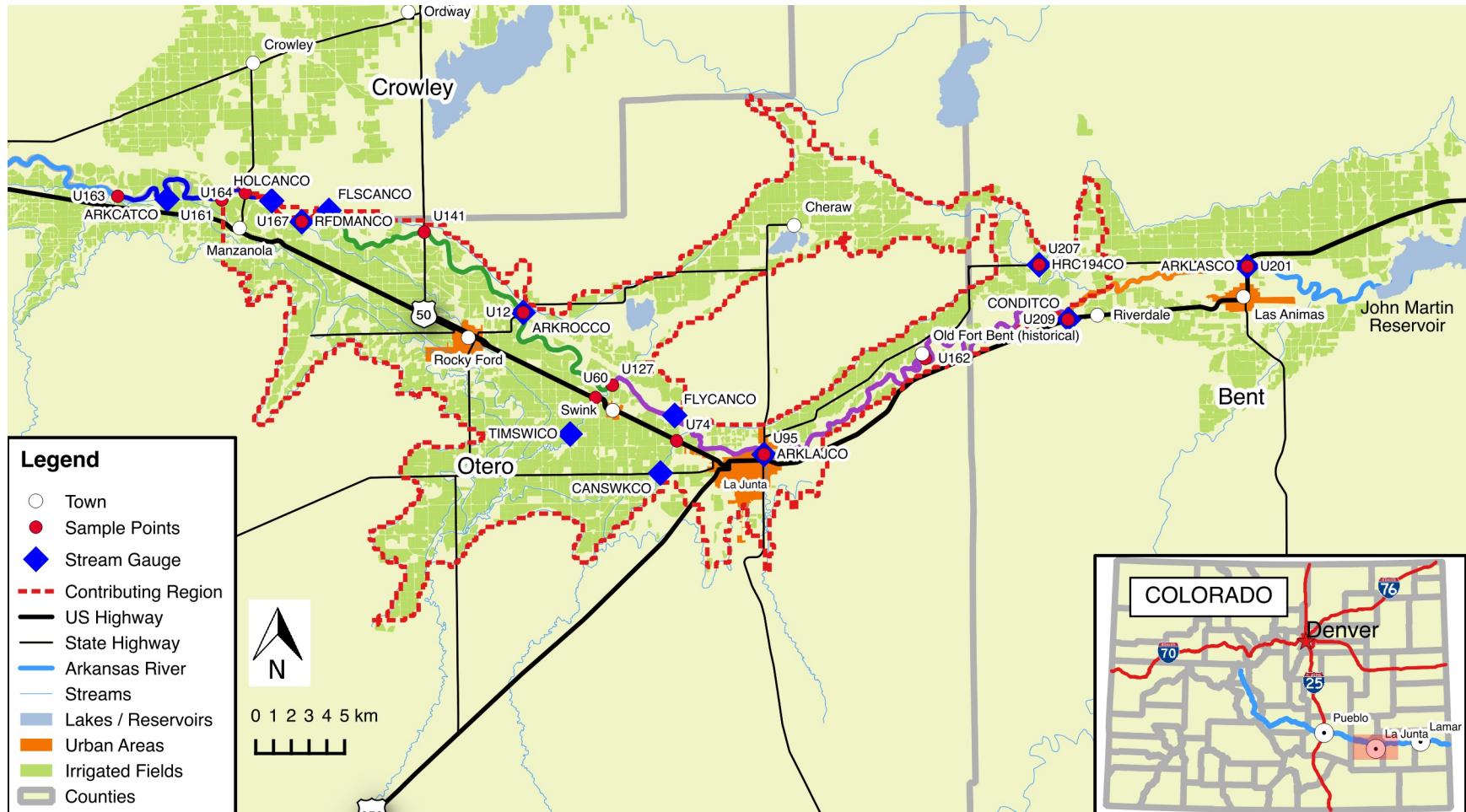


Figure 3.1. Dissolved Se sampling locations in the USR. Samples taken near, but not at stream gauge locations where shown.



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Figure 3.2. Dissolved Se sampling locations in the DSR. Samples taken near, but not at stream gauge locations where shown.

of a typical vehicle setup with cleaning buckets, peristaltic pump, water quality sonde, and various other equipment items. Cleaning consisted of the following listed procedure:

(1) At the beginning of every sampling day, four, 5-gallon (gal) buckets with lids were prepared as follows:

- (a) One bucket filled with approximately 2.5 gal tap water and approximately 20 mL of lab grade hydrochloric acid (HCl).
- 5 (b) One bucket filled with approximately 2.5 gal tap water and approximately 20 mL of LiquiNox®, a lab grade, phosphate and ammonia free, free rinsing detergent.
- (c) Two buckets filled with approximately 2.5 gal deionized water.

(2) The acid solution was run through the pump for two minutes. This disinfected the
10 pump tubing and prevented cross contamination.

(3) The detergent solution was run through the pump for two minutes. This removed any remaining soil particles from the pump tubing.

(4) Water from the first of the deionized water buckets was run through the pump for two minutes followed by the second bucket of deionized water for another
15 two minutes. This rinsed all detergent from the pump tubing.

Two sample types were routinely taken at all locations during each trip. One sample type was for the analysis of specific ion concentrations as a general water quality panel. A 250 mL-wide mouth, high density poly-ethylene (HDPE) bottle was used to collect and ship the specific ion samples. This bottle was pre-cleaned and shipped to CSU by Ward Laboratories, Inc. in Kearney, Nebraska, the laboratory that provided the bulk of the water quality
20 analysis services. The second sample was taken for analysis of dissolved Se concentration using a 125 mL-wide mouth, HDPE bottle. This bottle was procured from multiple sources and pre-cleaned to the US EPA's "Specifications and Guidance for Contaminant Free Sample Containers" (USEPA 1992). Approximately 0.6 mL of a diluted nitric acid solution prepared



(a) Durham Geo TR-200 PSP Peristaltic Pump.



(b) In Situ Water Quality Sonde and Data Logger. Measures temperature, specific conductivity, pH, oxidation-reduction potential, and dissolved oxygen concentration.

Figure 3.3. Water Quality Sampling Equipment.



Figure 3.4. Typical sample vehicle equipped for surface water sampling. Equipment includes peristaltic pump, water quality sonde, pump cleaning buckets, and various other equipment items. This picture is taken at sample site U162 which is on the National Park Service's Bent's Old Fort National Historic Site (fort in background).

with 33 mL of distilled water and 7 mL of ultra-pure nitric acid was added to each bottle using a graduated pipette. This was done to preserve the sample by lowering the pH to less than 2 standard pH units. During the latter half of the sampling periods, samples for

dissolved uranium (U) were gathered during most sampling trips. 250 mL-narrow mouth, pre-cleaned, pre-preserved with nitric acid, HDPE bottles were provided by TestAmerica Inc., the laboratory providing dissolved uranium analysis.

Blank samples of deionized water were prepared in the lab for each sample type before 5 each trip at the beginning of each sampling day for each sample type. Blanks are intended to be free of the analyzed constituent and are used to test the samples for bias due to contamination. Trip blanks were taken in the lab before the begining of the sample trip. They accompanied field personnel during all sampling activities and were then shipped to their respective lab for analysis. Trip blanks were intended to demonstrate that there was no 10 contamination due to transportation activities. Field blanks were taken in the field at the begining of the sampling day. These samples also accompanied the field personnel during sampling activities and were shipped to their respective lab for analysis. Field blanks were intended to demonstrate that there was no contamination in the sampling equipment. Any variation from non-detectable solute concentration in these blanks would indicate possible 15 contamination of the water samples taken that day and further investigation would be required. None of the lab results from field or trip blanks reported values that would indicate sample contamination.

Two YSI, Inc. 600R sondes with attached YSI, Inc. 650 MDS display data loggers were used for in-situ measurements during each sample trip (Figure 3.3b). The sondes were 20 equipped with a Rapid Pulse polarographic dissolved oxygen (DO) sensor capable of measuring DO from 0 mg L^{-1} to 50 mg L^{-1} , $\pm 2\%$; a thermistor capable of measuring temperature from -5°C to 50°C , $\pm 0.15^\circ\text{C}$; a glass combination electrode pH sensor capable of measuring pH in the range of 0 to 14 units, ± 0.2 units; a platinum button oxidation-reduction potential (ORP) sensor capable of measuring in the range of -999 mV to 999 mV , $\pm 20 \text{ mV}$; and a

four electrode, autoranging cell capable of measuring electrical conductivity (EC) as specific conductance at 25 °C in the range of 0 $\mu\text{S cm}^{-1}$ to 100 000 $\mu\text{S cm}^{-1}$, $\pm 0.5\% + 1 \mu\text{S cm}^{-1}$. The equipment was serviced and calibrated by CSU field personnel before every trip to the study reaches and at the end of every sampling day. Sondes were sent to Geotech Environmental Equipment, Inc. annually for maintenance checks. Geotech Environmental Equipment, Inc. is an authorized dealer and service provider for YSI equipment with an office in Denver, Colorado.

At least one set of duplicate water samples was taken per sampling trip to the USR and/or DSR. Duplicate, or replicate, samples were marked as 'A' and 'B' samples. The 'A' sample results were kept with the main data set and were used as the primary data set. 'B' sample results were kept separate and were used to determine the combined sampling methodology and lab analysis uncertainty. The sampling standard procedure was to take one duplicate set of surface water samples per day with a minimum of two duplicate surface water samples per sampling trip.

Each sampling event began with recording the site data on a form (log) similar to the one in Figure 3.5. In-situ water quality measurements were then taken using the YSI sonde. The data logger was used to read the data, but was not used as a recording device. All data were recorded on the form shown as an example in Figure 3.5. The ranges at the bottom of the form are maximum acceptable ranges of values determined from previous sampling trips. Values outside of these ranges would indicate to field personnel that the equipment was damaged, had lost calibration, or operational error had occurred. The YSI sonde was allowed to rest in the water for a minimum of three minutes before recording values. Usually, the sonde would rest in the water while water quality samples were taken. Samples were pumped through a disposable, in-line 0.45 micron, polyethersulfone filter into

the sample bottles. Peristaltic pumps were used to extract all water samples from surface water sources. No air space was permitted in any of the sample bottles. Figure 3.6a shows a trained sample collector at location U12 in the USR which is north of Rocky Ford on a bridge over the Arkansas River. The YSI sonde is not in this image, but is suspended in the river during sample collection. Figure 3.6b is the same sample collector at sample location U73 in the USR recording readings from the YSI sonde. Samples were stored on ice or in a refrigerator until they were shipped to their respective labs. Data was recorded onto the data form from the YSI sonde immediately after collecting the water samples. The sonde was left in the water for an additional two to three minutes. Any changes in readings were recorded as a second entry. An example of a completed log is shown in Figure 3.7

Specific ion lab results from Ward Laboratories and dissolved U lab results from TestAmerica were not used directly in the analysis reported in this thesis. The Oscar E. Olson Biochemistry Laboratories (Olson Labs) at South Dakota State University (SDSU) performed dissolved Se analysis using Official Methods of Analysis of AOAC International, 17th Edition, test number 996.16, Selenium in Feeds and Premixes. This test, a fluorometric test initially designed for testing animal feeds, provides repeatable analysis for dissolved Se near criteria levels. Double tests were completed on each sample and the average was reported. The minimum reportable value was $0.4 \mu\text{g L}^{-1}$.

Late in 2011, the Olson Labs was closed by SDSU for funding reasons. Staff at Olson Labs assisted CSU staff in finding a new lab capable of continuing analyses using the same methods and to the same level of quality. South Dakota Agricultural Laboratories (SDAL) was chosen. Most of the staff and equipment from Olson Labs were employed at the new SDAL providing CSU staff with ample reason to move all dissolved Se analyses to the new lab. Both Olson Labs and SDAL were certified by the USEPA for drinking water

Colorado State University
 Department of Civil Engineering
 Arkansas River Assessment

Surface Water Sampling Log

Station No.:				Date:	
Location:				Time:	
	Left	Center	Right	Sample collector(s):	
Upstream				Pumping Note:	
Downstream					
Location Note:					
<input type="checkbox"/> Dry <input type="checkbox"/> Stagnant/Frozen <input type="checkbox"/> No Access _____					
Time (min)	Temp (°C)	Conductivity ($\mu\text{S}/\text{cm}$)	DO (mg/L)	pH	ORP (mv)
Range	(0-35)	(400-8000)	(0-18)	(4.8-10)	(-250-400)

Figure 3.5. Example water quality sample form.

and subscribed to the proficiency testing and check sample programs for the USEPA for wastewaters .

ref. How?

The same procedures and techniques for sample gathering and analysis were used during the entire sampling periods. Newer or different techniques or procedures were considered, but was determined to have the possibility to compromise the consistency of the gathered data. Results from all lab analyses were recorded in a master database at CSU for later data extraction and analysis. The data includes results from over 4,500 sample sets. Approximately 95 and 1,035 of these sample sets were taken from surface water sites in the USR and DSR, respectively. Each sample set included in-situ measurements, a dissolved



(a) Sample location U12. The Se sample bottle is being filled with a peristaltic pump through a 0.45 micron filter. The specific ion sample bottle is filled, laying next to the pump.



(b) Sample location U73. Personnel is hand logging data from the YSI sonde.

Figure 3.6. Personnel performing water sample collection.

Se sample, a general specific ion panel, and a possible dissolved U sample. In-situ EC and temperature measurements taken at stream gauge sites with permanent water quality instrumentation were compared with the measured values reported at those sites. These sites record and report EC and water temperature measurements every 15-minutes. Minor deviations were expected due to instrument drift and calibration error, yet EC and temperature differences were found to be less than 1% for all in-situ measurements.

The water and mass balance models included in this study are among the many lines of research that have used this data. Because of the multiple uses of large data sets, great care has been taken to ensure that data entry errors are rare. Data were copied into the

Colorado State University
 Department of Civil Engineering
 Arkansas River Assessment

Surface Water Sampling Log

Station No.: [U201]			Date: <i>16 May 16</i>		
Location: Arkansas River			Time: <i>1302</i>		
	Left	Center	Right	Sample collector(s): <i>KHM</i>	
Upstream				Pumping Note:	
Downstream		<i>X</i>			
Location Note:					
<input type="checkbox"/> Dry <input type="checkbox"/> Stagnant/Frozen					
<input type="checkbox"/> No Access _____					
Time (min)	Temp (°C)	Conductivity (µS/cm)	DO (mg/L)	pH	ORP (mv)
<i>4</i>	<i>19.40</i>	<i>1676</i>	<i>7.92</i>	<i>8.08</i>	<i>67.4</i>

Figure 3.7. Example completed water quality sample form.

database and randomly checked for transcription errors. Original lab reports were retained on file.

3.2. RIVER CROSS-SECTION GEOMETRY SURVEY

The Arkansas River was surveyed at twenty-one and thirteen locations in the USR and DSR, respectively. At these locations, cross-sections were surveyed and the data analyzed to determine the spatial distribution of the river geometry. The cross-sections are not equally spaced along the river segments. Cross-sections were surveyed at the extreme upstream and downstream end of each river segment. Intermediate cross-sections were located where both the landowner permitted access and the river was reasonably accessible. Additionally, the intermediate cross-sections were located where different cross-section profiles existed. This was done to capture a broadest possible range of cross-section profiles, thereby allowing for a more realistic characterization of the river geometry. Figures 3.9 and 3.10 show the locations of the surveyed cross-sections in the USR and DSR, respectively. Tables 3.4 and 3.5 describe the location of the survey point with respect to the river reach and segment. Survey locations within a river segment are with respect to the segment stream gauge location.

Industry standard survey techniques were used whenever possible. It was not possible to properly locate the instrument location in either the horizontal and vertical plane with respect to a local datum due to the remote location and the lack of available time. All data was collected with a total station (Figure 3.8a) and hand recorded into survey log books. Two back-sights were used at every surveyed cross-section. Both back-sights and the instrument location were located by using a hand held global positioning satellite (GPS) receiver (Figure 3.8b). The receiver was capable of determining the horizontal location to within ± 1 m and the vertical location to within ± 2 m. Licensed surveyors were not hired, retained, or consulted for this study.

Higher location and orientation accuracy could have been obtained by using survey grade GPS equipment or by referencing the instrument survey to an established benchmark.

Table 3.4. Upstream Study Region (USR) Survey Point Information. A value of zero (0) indicates the location of the segment stream gauge. Negative distances indicate the point is upstream of the reference stream gauge location. Segment B does not contain a stream gauge on the river main stem.

River Segment Name	Survey Point	Dist from USR Upstream Boundary		Dist from River Segment Stream Gauge	
		mi	km	mi	km
A	USS1	0	0	-2.7	-4.3
	USS2	2.7	4.3	0	0
	USS3	5.8	9.3	3.1	5
	USS4	7.8	12.6	5.1	8.2
B	USS6	9.2	14.8		
	USS7	9.3	14.9		
	USS8	10.2	16.4		
C	USS10	13.4	21.6	-6.8	-10.9
	USS11	18.1	29.1	-2.1	-3.4
	USS12	20.2	32.5	0	0
	USS13	24.4	39.3	4.2	6.8
	USS14	29.3	47.2	9.1	14.6
D	USS16	30	48.3	-3.8	-6.1
	USS17	32.6	52.5	-1.2	-1.9
	USS18	33.8	54.4	0	0
	USS19	35.9	57.8	2.1	3.4
	USS21	44	70.8	10.2	16.4
	USS22	46.4	74.7	12.6	20.3
	USS23	50.3	81	16.5	26.6
E	USS26	55.7	89.6	-6	-9.7
	USS27	61.7	99.3	0	0

For almost all surveyed cross-sections, benchmarks were not located within a reasonable distance. Attempting to tie into these benchmarks would result in an order of magnitude or more increase in the time required to complete the survey. There were also doubts as to whether the horizontal and vertical accuracy could be maintained due to the distance

- 5 between the nearest benchmarks and the survey sites and the surveyor's skill. Survey grade GPS equipment could have been used, but would have required either a larger team or a significantly increased risk of equipment tampering or theft. The available survey grade

Table 3.5. Downstream Study Region (DSR) River Cross-Section Survey Location Information. A value of zero (0) indicates the location of the segment stream gauge. Negative distances indicate the point is upstream of the reference stream gauge location.

River Segment Name	Survey Point	Dist from USR Upstream Boundary		Dist from River Segment Stream Gauge	
		mi	km	mi	km
F	DSS1	0	0	0	0
	DSS4	7.9	12.7	7.9	12.7
	DSS5	10.3	16.6	10.3	16.6
	DSS6	14.9	24	14.9	24
	DSS7	17.6	28.3	17.6	28.3
	DSS8	20.5	33	20.5	33
	DSS9	23.4	37.7	23.4	37.7
G	DSS10	23.5	37.8	-1.4	-2.3
	DSS13	29.3	47.2	4.4	7.1
	DSS14	31.2	50.2	6.3	10.1
	DSS15	33.9	54.6	9	14.5
	DSS16	37	59.5	12.1	19.5
	DSS17	38.9	62.6	14	22.5
	DSS20	46.2	74.4		



(a) Pentax PCS-315 Total Station.



(b) TopCon GMS-2 Sub-meter handheld GPS.

Figure 3.8. Survey Equipment.

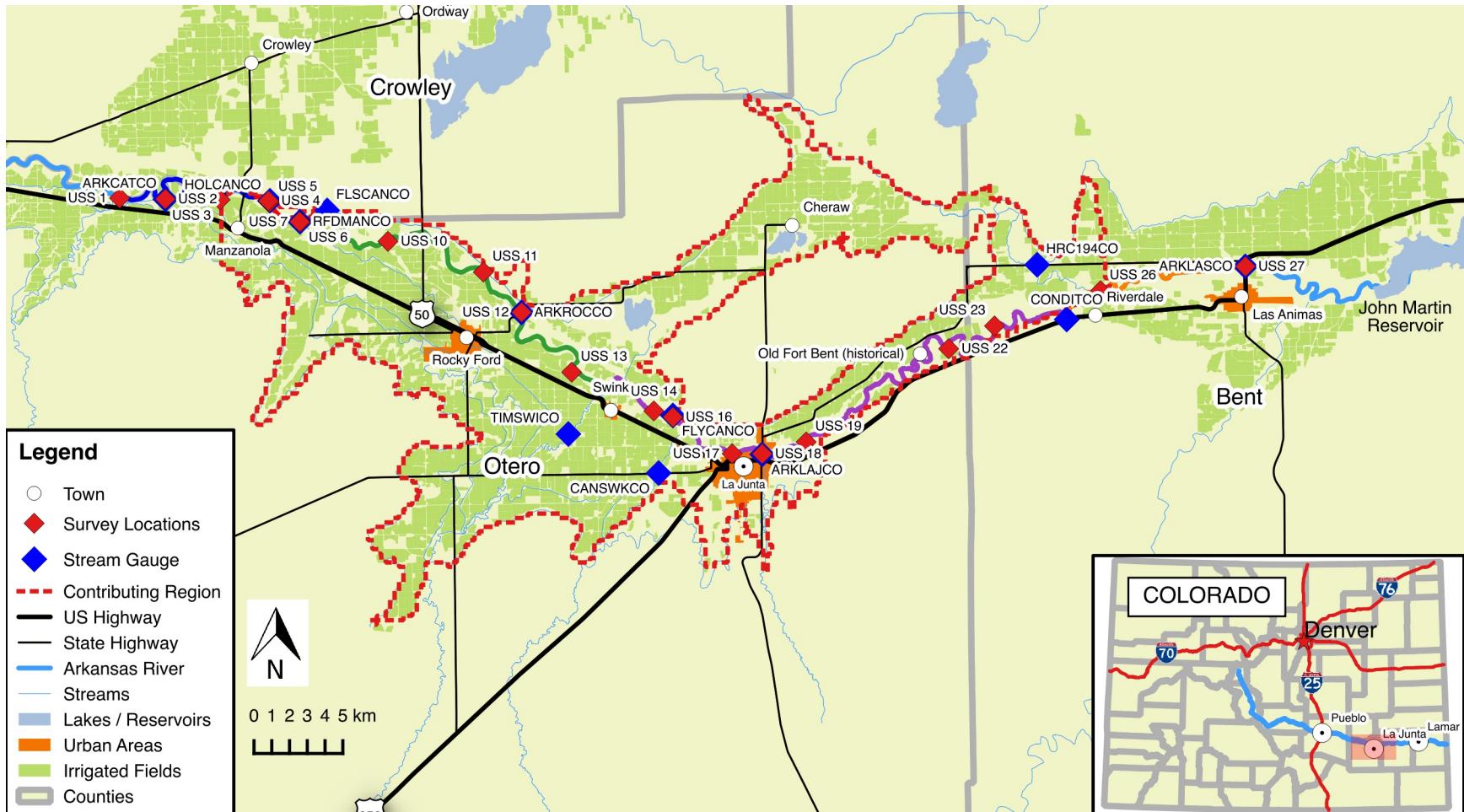


Figure 3.9. USR River Cross-section Survey Locations. Cross-sections are taken above and/or below the diversion structure and near gauge locations.

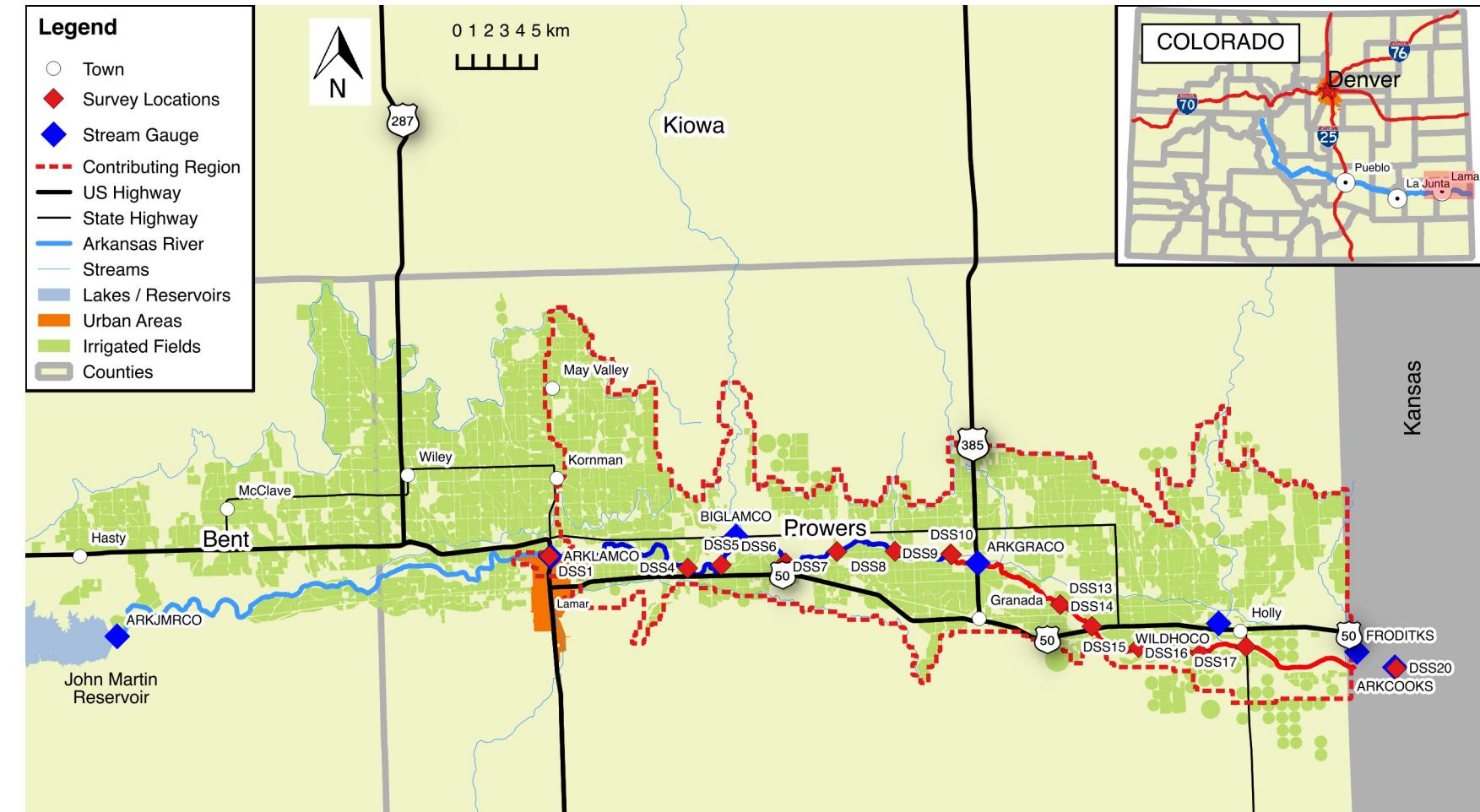


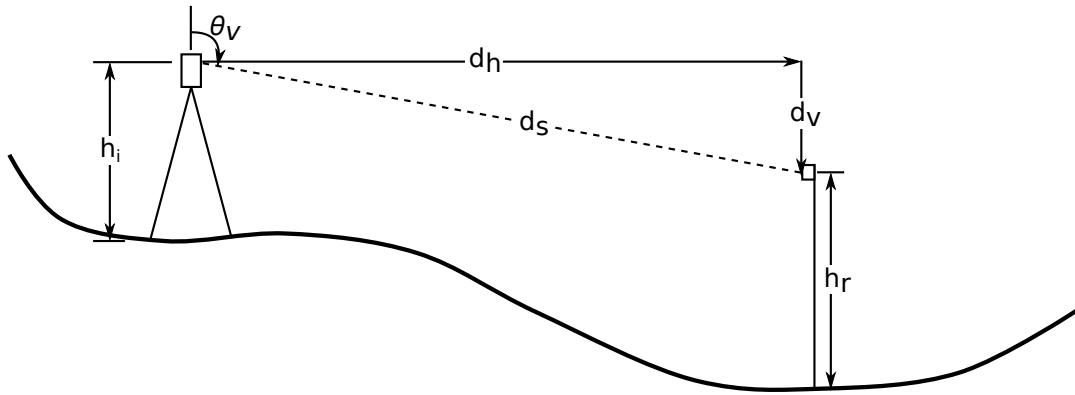
Figure 3.10. DSR River Cross-section Survey Locations. Cross-sections are taken above and/or below the diversion structure and near gauge locations.

GPS base station also had a limited range compared to the range required to access many of the locations. Since the goal of the survey was to determine the relationship between the depth and width of the river, it was determined that locating and orienting the survey data correctly was a secondary goal. For these reasons, it was determined that the level of 5 location and orientation accuracy obtained by using the hand held GPS receiver would be sufficient.

The data was collected in the form of horizontal angle, vertical angle, sight distance, rod height, and instrument height. The survey data was downloaded from the total station and entered into a spreadsheet for conversion to horizontal and vertical location relative to 10 the instrument. Values in the spreadsheet were checked against the survey log book. Points collected but not used to calculate the cross-section, such as the back-sight points, were marked so that they were not used in the cross-section analysis. These excluded points were used for other survey related calculations. The rod height for each measurement and the instrument height for the survey was transferred from the log book to the spreadsheet.

15 Coordinate geometry (COGO) techniques were used to convert from angle, sight distance, rod height, and instrument height measurements to horizontal and vertical distance measurements relative to the instrument as shown in figure 3.11. Vertical angles were measured using decimal degrees such that zero degrees (0°) was located above the instrument and 90° was horizontal. Horizontal angles were measured using decimal degrees such that 20 0° was located when the instrument was facing the first back-sight and positive angles were measured clockwise when viewed from above. The sight distance was measured using the instruments integrated laser distance measuring tool from the optics of the instrument to the rod prism with sub-millimeter accuracy. Horizontal and vertical distances to the ground location of the survey point from the ground location of the instrument were calculated as

shown in equations 1 and 2, respectively. The horizontal location was calculated as northing and easting with the line between the instrument and the first back-sight as the reference. Northing and easting distances were calculated with respect to the horizontal line between the instrument and the first backsight. Corrections were made to orient the points to the coordinate system, but this step was not necessary to provide the necessary results.



$$d_h = d_s \cdot \sin(\theta_v) \quad (1)$$

$$d_v = h_i - h_r + d_s \cdot \cos(\theta_v) \quad (2)$$

d_h = Horizontal distance from the instrument to the surveyed point.

d_v = Vertical distance from the instrument to the surveyed point.

d_s = Sight distance from the instrument optics to the rod prism.

θ_v = Vertical angle from the sight optics to the rod prism

Figure 3.11. Survey Measurement Definitions.

GPS location data for the instrument and back-sights was collected in the form of northing, easting, and elevation. Colorado State Plane-South, North American Datum 1983 (NAD83), U.S. feet was used as the horizontal datum and North American Vertical Datum 1988 (NAVD88) was used as the vertical datum. All survey units are U.S. Feet. Survey errors, also known as closing errors, were corrected for all points. Most survey locations were on soft soils. It was assumed that survey error would primarily consist of instrument location drift. Measurements were taken to both back-sights at the beginning and end of the

site survey. The northing, easting, and elevation difference between the measurements taken at the beginning and end of the site survey were spread equally and successively among all points. Since two back-sights were used, the total closing error was taken as the average of the closing errors for the two back-sights.

5 Correction of closing errors was required to obtain accurate stream depth and river top width values. Location and orientation error correction was not required and was only performed as a manner of good survey practice. Survey data points were translated from their position relative to the instrument to their position relative to the State Plane coordinate system by adding the northing, easting, and elevation values collected by the GPS receiver
10 at the instrument site. Orientation error corrections to make instrument North coincide with true North were made by adding a positive horizontal correction angle such that the corrected angle to the first back-sight, which was the zero back-sight, matched the angle between the two corresponding GPS northing and easting coordinate sets. Final survey locations should always have the most correct location and elevation relative to a given datum. Both the
15 back-sights and instrument location were marked with steel reinforcement bar (re-bar) and plastic caps (Figure 3.12), it may be possible for future surveys to be conducted at the same locations with the same back-sights.



Figure 3.12. Typical plastic cap on rebar used to locate instrument location and back-sights.

A least squares fit linear regression equation was fit to the relative location of all points along the surveyed cross-section (Figure 3.13). It was reasoned that a straight line through the data points would allow for a better approximation of the river's cross-section than connecting the points. The straight line would represent a true cross-section, whereas connecting the points would exaggerate the distance across the cross-section. The relative locations of the points as projected onto the best-fit line were entered into computer aided design and drafting (CADD) software (Figure 3.14). Horizontal lines, spaced 0.03 m (0.1 ft) apart from the bottom of the channel to 1.5 m (5 ft) from the bottom, were drawn from edge of bank to edge of bank. The vertical location of these lines was taken as the flow depth and the length of the line was taken as the river top width.

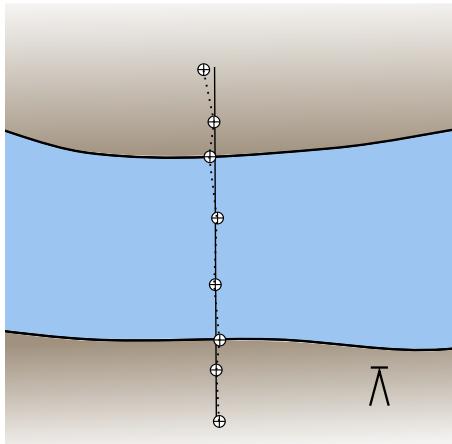


Figure 3.13. Depiction of the conversion of River Survey Locations to Linear Cross-Section. The crossed circles are the surveyed points. The instrument (total station) is in the lower right-hand corner. The dotted line depicts the cross section if no correction were made to linearize the survey cross section locations. The solid line is the cross-section line created from the best-fit line through the surveyed points. Surveyed points were translated perpendicular to the cross-section line to lie on the cross-section line across the river.



Figure 3.14. River Cross-Section as Draw in CADD Software. The black line is the channel cross-section with the left side representing the north bank of the Arkansas River (water flow is into the page). The blue horizontal line is the lowest point in the surveyed channel. All elevations were shifted such that the bottom point had a stream depth of zero. This particular cross section is at cross-section USS1. The horizontal and vertical scales are identical.

3.3. DATA COMPILED FROM OTHER SOURCES

The data collected in the field constituted a small portion of the total data required to perform water and mass balance calculations. Additional data were obtained from three sources: the USGS, the CDWR, and the Colorado Climate Center (CCC).

5 The USGS operates and maintains the largest network of stream gauges in the United States. USGS gauges in the LARV in Colorado are operated and maintained by the USGS Colorado Water Science Center. Their main office is Lakewood, Colorado, with one of their satellite offices in Pueblo, Colorado. Of the gauges listed in Tables 3.6 and ?? and shown in Figures 3.16 and 3.17, five are operated by the USGS. There is additional sensing
10 equipment owned and maintained by the USGS at some stream gauges owned and operated by the CDWR. Water temperature, air temperature, precipitation, and EC are the additional parameters typically measured and recorded by this equipment. EC is reported as specific conductance standardized to 25 °C and is the standard for EC used throughout this thesis. EC values are reported in units of micro-siemens per centimeter ($\mu\text{S cm}^{-1}$) and are converted
15 to units of deci-siemens per meter (dS m^{-1}).

The USGS and CDWR do not have typical gauge sites in the LARV. Gauge housing and locations vary as show in Figure 3.15. These figures are not all inclusive and other variations occur in the LARV. Both agencies were consistent in the flow measuring equipment deployed to the gauge sites. During the Se sampling time frame, all stream gauges were constant flow bubblers as described in the USGS Techniques of Water Resources Investigations
20 (TWRI) Report, Book 3, Section A, Chapter 7 (Sauer and Turnipseed 2010). After all Se sampling was completed, the USGS and CDWR began upgrading some of the gauge sites with radar non-contact water level sensors. It is unknown how this will affect the comparison of the results of this thesis with any future work.

Table 3.6. Upstream Study Region (USR) Stream Gauge Information. Segment stream gauges record flow depth for surface area and river volume change calculations. A value of zero (0) indicates the location of the segment stream gauge. Negative distances indicate the point is upstream of the reference stream gauge location. Segment B does not contain a stream gauge on the river main stem.

River Segment	CDWR Stream Gauge Name	USGS Stream Gauge Name	Dist. from USR Upstream Boundary		Dist. from River Segment Stream Gauge	
			mi	km	mi	km
A	ARKCATCO		2.7	4.3	0	0
	HOLCANCO		7.8	12.6	5.1	8.2
B	RFDMANCO		9.2	14.8		
	FLSCANCO		10.2	16.4		
C	RFDRETCO		11.7	18.8	-8.5	-13.7
	ARKROCCO		20.2	32.5	0	0
	TIMSWICO	7121500	26.1	42	5.9	9.5
	FLYCANCO		29.3	47.2	9.1	14.6
D	CANSWKCO		30.3	18.8	-3.5	-5.6
	ARKLAJCO		33.8	54.4	0	0
	CONDITCO		52.8	85	19	30.6
E	HRC194CO		55.1	88.7	-6.6	-10.6
	ARKLASCO	7124000	61.7	99.3	0	0

Table 3.7. Downstream Study Region (DSR) Stream Gauge Information. River segment stream gauges record flow depth for surface area and river volume change calculations. A value of zero (0) indicates the location of the segment stream gauge. Negative distances indicate the point is upstream of the reference stream gauge location. Stream gauges ARKJMRCO, FRODITKS and ARKCOOKS although required for analysis, are not within the DSR.

River Segment	CDWR Stream Gauge Name	USGS Stream Gauge Name	Dist. from DSR Upstream Boundary		Dist. from River Segment Stream Gauge	
			mi	km	mi	km
	ARKJMRCO	07130500	-22	-35.4		
F	ARKLAMCO	07133000	0	0	0	0
	BIGLAMCO	07134100	11.6	18.7	11.6	18.7
	BUFDITCO		23.4	37.7	23.4	37.7
G	ARKGRACO	07134180	24.9	40.1	0	0
	WILDHOCO	07134990	38.1	61.3	13.2	21.2
	FRODITKS	07137000	43.5	70		
	ARKCOOKS	07137500	43.2	74.4		



(a) HRC194CO.



(b) BIGLAMCO.



(c) TIMSWICO



(d) FRODITKS



(e) ARKCOOKS

Figure 3.15. Range of Stream Gauge Equipment Housings in the LARV.

Data from the CDWR and USGS stream gauges are reported on web sites operated by the two agencies. Table 3.8 lists the gauge sites used in this study and notes the additional data besides streamflow collected at each gauge. Additional data are reported by the agency that owns and operates the gauge site. USGS instruments at a CDWR gauge site are recorded

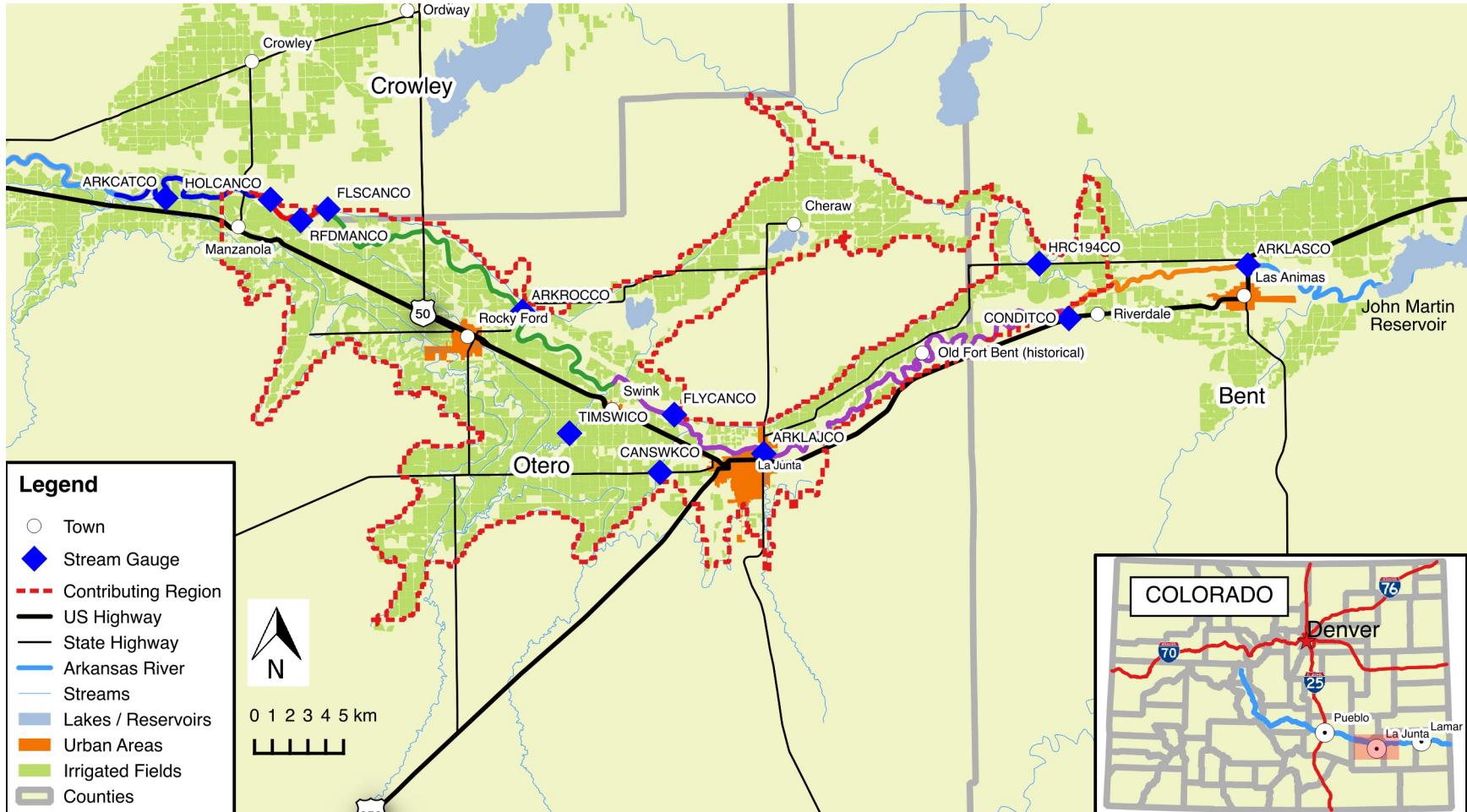


Figure 3.16. USR River River and Tributary Stream Gauge Locations.

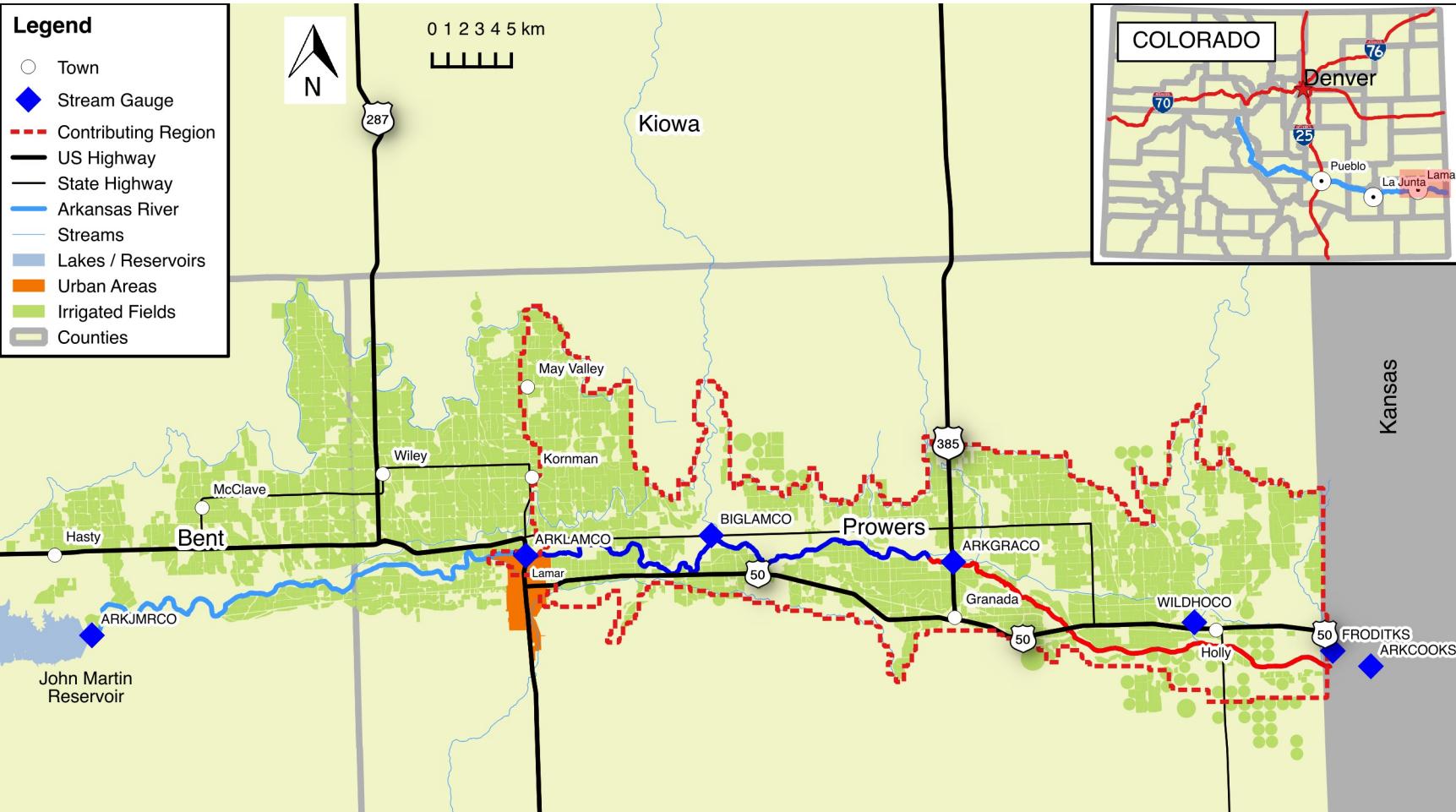


Figure 3.17. DSR River River and Tributary Stream Gauge Locations.

— DRAFT —

February 18, 2015

and reported on the CDWR web site. Note that the CDWR gauge site ARKLAMCO, which is owned by the USGS, does not have any additional data collection instruments.

Table 3.8. Summary of Stream Gauges with Notation of Additional Data Collected.

Study Reach		Stream Gauge ID	Parameter		
	CDWR	USGS	Air Temp.	Water Temp.	EC
USR	ARKCATCO			X	X
	HOLCANCO				
	RFDMANCO				
	FLSCANCO				
	RFDRETCO				
	TIMSWICO				
	FLYCANCO				
	CANSWKCO				
	ARKLAJCO		X		
DSR	CONDITCO				
	HRC194CO				
	ARKLASCO	07124000		X	X
	ARKJMRCO	07130500		X	X
	ARKLAMCO	07124000			
5	BIGLAMCO				
	BUFDITCO				
	WILDHOCO				
	FRODITCKS				
10	ARKCOOKS	07137500		X	X

Stream flow data were obtained as average daily flow for each stream gauge. Some average daily flow records were reported as being estimated or provisional. These data points were removed from the analysis. Average daily flow data were quality checked for unacceptable values. For each gauge, acceptable values were defined as those above zero and below the 99th percentile of all flows recorded at that gauge. Unacceptable values were removed from the data set.

All stream gauges report gauge height which is the vertical distance from the gauge site datum to the water surface (Figure 3.18). Gauge site datum is arbitrarily set, but is tied to a local survey benchmark. Flow depth is the depth from the bottom of the channel

to the water's surface. While both gauge height and flow depth measure the distance to the water's surface, their datums can, and frequently do vary. The Arkansas River is a shifting bed channel and as such, the channel bottom elevation varies with time at a gauge site. The rating table, which is used to convert flow depth to flow rate, is configured such that flow depths below the channel bottom have a flow rate of zero. The table is frequently updated with data obtained from routine re-calibration of the stream gauge.

5

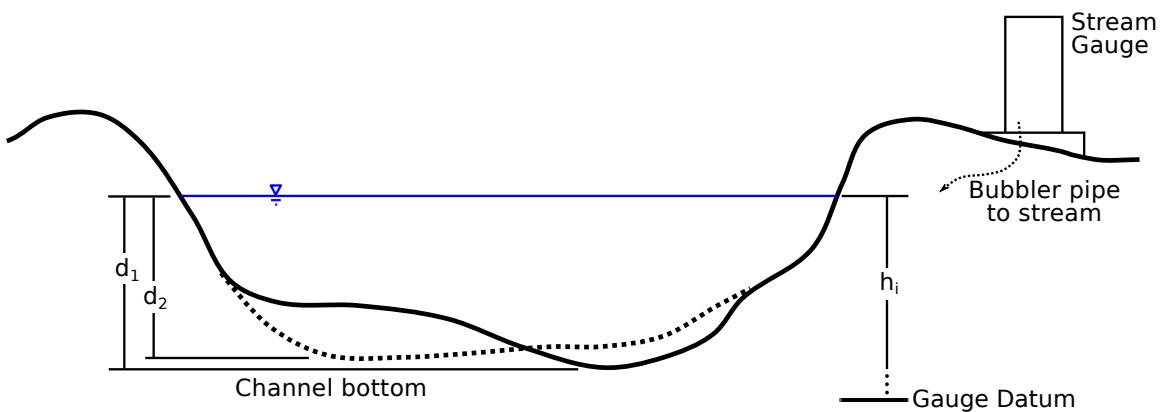


Figure 3.18. Depiction of Variable Channel Bottom and Fixed Gauge Datum. d_1 and d_2 are flow depths at different times. h_i is the stream gauge height measurement at any time.

Gauge height data is the directly measured value that is used to calculate flow rate. Flow rates are calculated from gauge height using a gauge site specific rating table produced in accordance with USGS standards and procedures (Rantz et al. 1982a,b). Gauge heights for 10 the USGS and CDWR gauges were obtained from the respective regional offices. Historical recorded gauge heights are not reported on web sites as these data are considered to be precursors for stream flow rate calculations. Stream gauge data were provided as both average daily gauge height and as recorded gauge height. Recorded gauge height is the gauge height recorded in 15-minute increments during a calendar day. Average daily gauge 15 height is the mean of the recorded gauge heights over a calendar day. All gauge heights were

provided in units of feet above the gauge datum. Gauge height units were converted to SI units of meters for this study to simplify calculations and discussion. Gauge height data were checked for accuracy by the source agency before being released to CSU staff.

Water temperature data were obtained as average daily temperature or as minimum 5 and maximum daily temperatures, depending on the gauge site. Average daily temperature is calculated as the mean of the minimum and maximum daily temperature. Water temperature data were provided in units of °C. Since frozen or partially-frozen river channels do not have the same gauge height to flow rate relationship as free running river channels, data corresponding to water temperatures below zero were removed from the data set.

EC data obtained from USGS and CDWR stream gauge sites were provided as average 10 daily values for each recording gauge station. EC values recorded at the stations were compared to available EC values measured by CSU to cross-validate both data sets. Gauge station recorded EC values were quality controlled by removing the bottom and top 1% of EC values for each gauge. Changes in average daily EC between consecutive days were 15 checked for validity. Changes greater than 33% were analyzed to determine if the EC change was valid. The average daily flow rate and time of year were taken into consideration when determining if the questionable EC values were valid. EC values that exceeded the 33% change but were accompanied by large changes in EC or during peak irrigation seasons were considered valid EC values. Values considered to be invalid were removed from the data set.

20 EC values were provided in units of $\mu\text{S cm}^{-1}$.

Atmospheric data was required to determine the volume of water evaporated from the river's surface. The Colorado Agricultural Meteorological Network (CoAgMet) was chosen as the source for atmospheric data. The National Weather Service station sites in the study regions are located in populated areas or at airports and is only suitable for weather analysis.

CoAgMet station sites are more numerous, are located in agricultural areas, and are suitably equipped for evaporation and transpiration (*ET*) analysis. An example of one of the weather stations is shown in Figure 3.19. The CoAgMet network is operated by the Colorado Climate Center at CSU and consists of 86 weather stations throughout the state. Some stations
5 are only seasonally operational (Andales, Bauder, and N. Doesken 2009; Colorado Climate Center 2012). Of the full-time sites, three are located in the USR and three are located in the DSR as shown in Figures 3.20 and 3.21, respectively. The CoAgMet weather stations in the USR are located such that they represent the upper, middle, and lower segments of the USR. The CoAgMet stations in the DSR are more tightly grouped toward the upstream
10 end of the reach, but still are considered representative of the study reach. The weather stations are primarily located in agricultural areas to provide agricultural researchers with data used for many different research applications. The data also are available to the public through a web site. This has aided farmers in determining irrigation timing and quantity (Andales, Bauder, and N. Doesken 2009). Table 3.9 is a list of the parameters measured
15 at the CoAgMet stations and the typical instruments used. Not all stations are identical. Instruments were replaced or upgraded by CCC staff when required with instruments that were available and equal to or better in quality than the instrument being replaced.

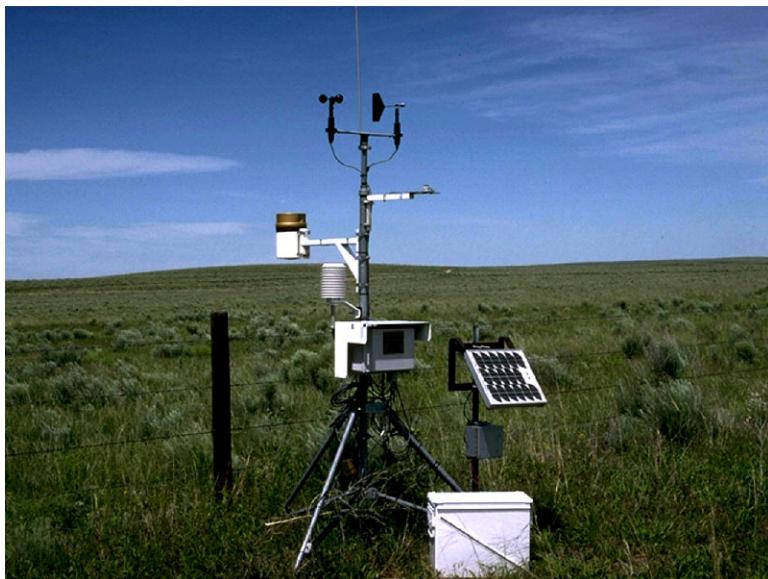


Figure 3.19. Typical CoAgMet Weather Station.

53

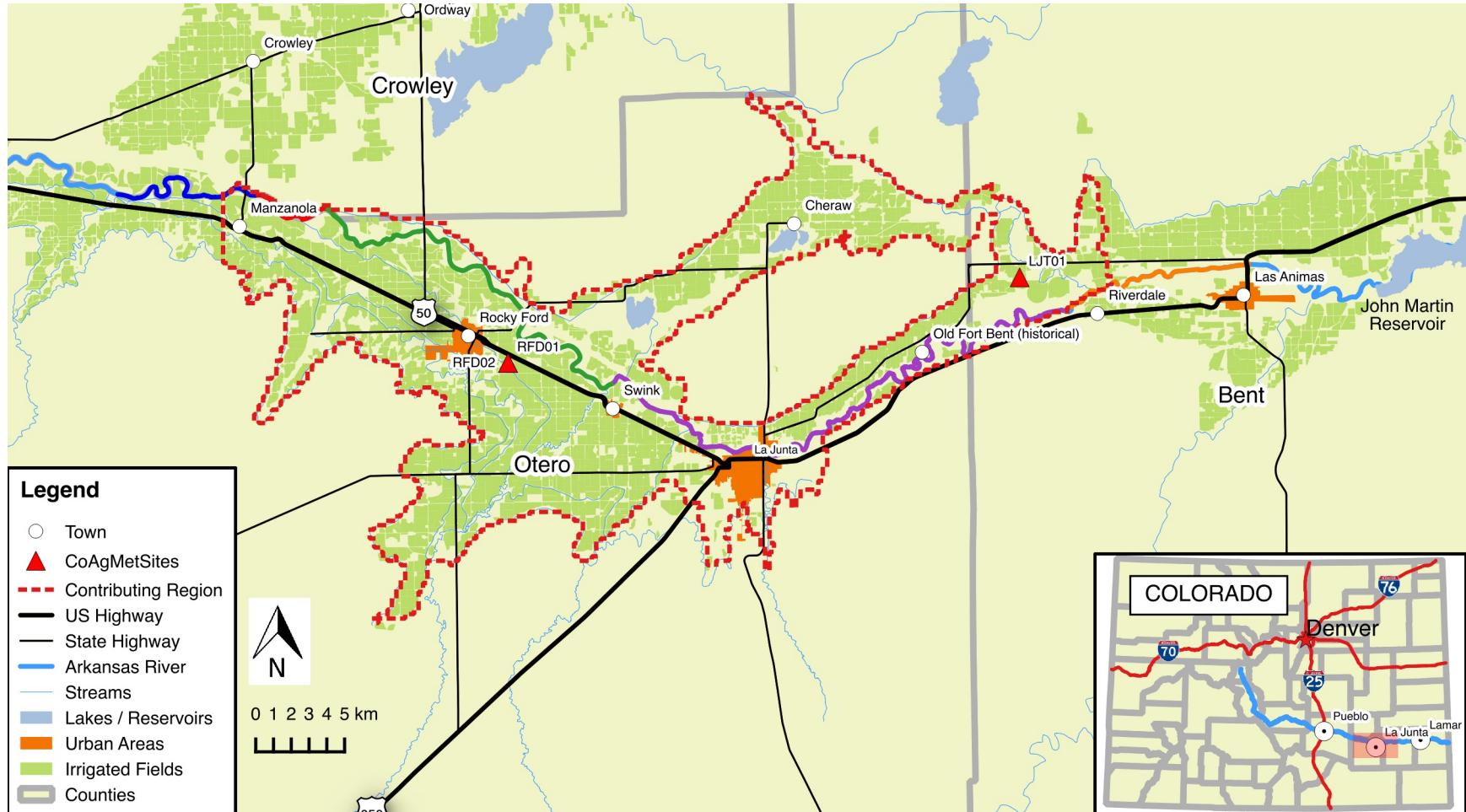


Figure 3.20. USR CoAgMet Weather Station Locations.

54

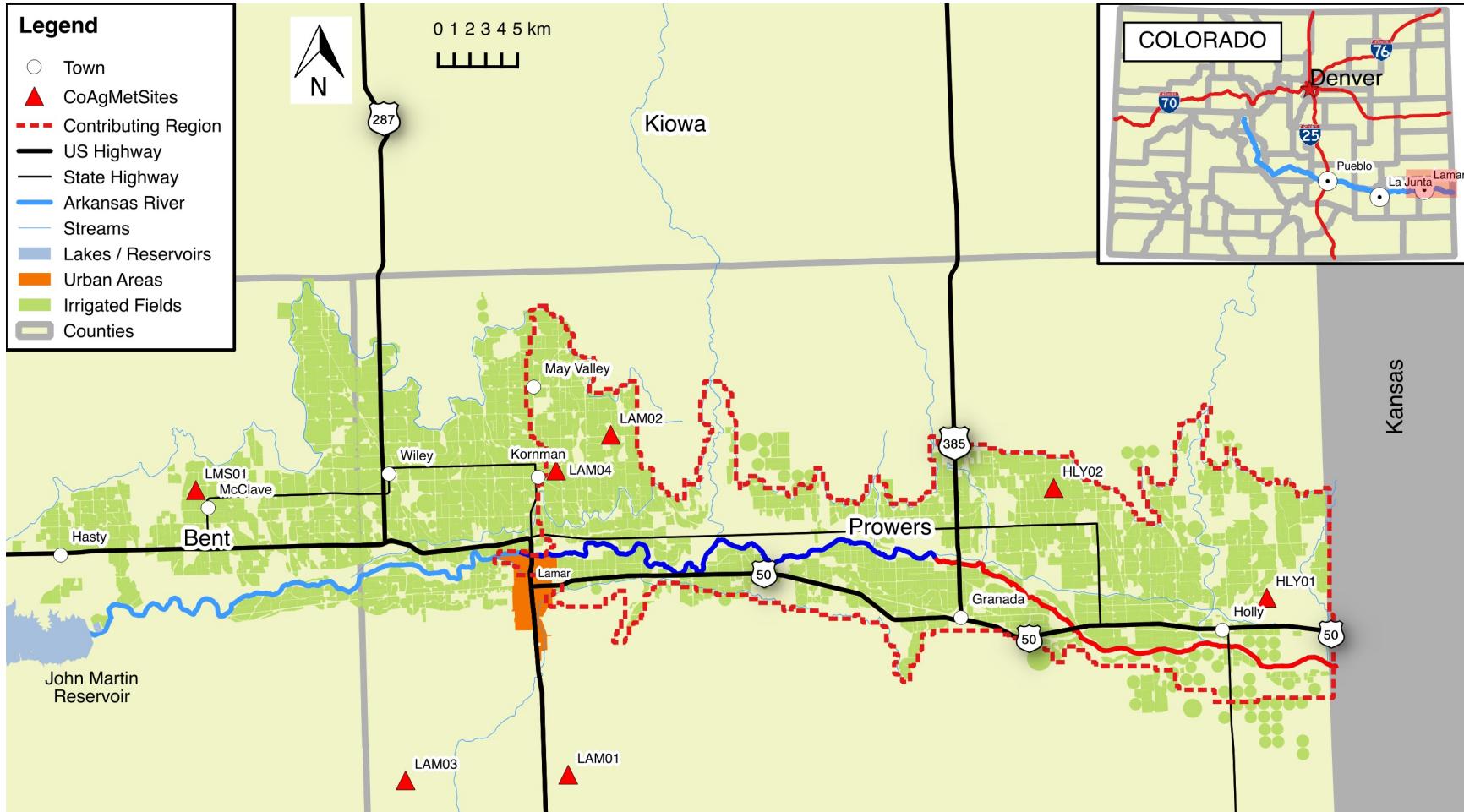


Figure 3.21. DSR CoAgMet Weather Station Locations.

Table 3.9. Typical Instrumentation at CoAgMet Weather Stations.

Measured Parameter	Typical Instrument
Temperature & Relative Humidity	Vaisala HMP45C Probe
Wind	R.M. Young Wind Sentry
Solar Radiation	Licor LI-200X Pyranometer
Precipitation	TE525 tipping bucket raingauge
Soil Temperature	CSI Model 107 Soil Temp Probe (thermistor)
Data Loggers	Campbell Scientific CR10, CR10X, and CR1000

Table 3.10 lists the weather stations in the LARV that were used in this study. This table lists the station name and location, the state of irrigation of the land surrounding the site, the date of first record, and a comparative estimate of the site estimated ET_{ref} to the actual ET_{ref} . The irrigation state of the land surrounding the site is used to determine the 5 comparative estimate of the site estimated ET_{ref} to the actual ET_{ref} . If the monitoring station is on irrigated land then the ET_{ref} values calculated based on site data are expected to be at or near the actual value of ET_{ref} for the site. If the station is on dry, or non-irrigated land, then calculated ET_{ref} values tend to over estimate the actual ET_{ref} .

CoAgMet provides both raw weather data from all weather stations and daily ET_{ref} 10 values calculated for select stations. Daily ET_{ref} values were obtained from the sites in the LARV. The American Society of Civil Engineers (ASCE) Environmental and Water Resources Institute (EWRI) standardized tall crop evapotranspiration reference Penman-Monteith equation was used by the Colorado Climate Center to calculate ET_{ref} . Values are obtained in units of mm d^{-1} .

15 The average daily ET_{ref} for a region surrounding a study reach was calculated as the mean of the stations reporting ET_{ref} for a given day. If a station or group of stations did not have data for a particular day in the study time frame, then those stations were not included in the calculation. An assumption was made that the ET_{ref} over the Arkansas

Table 3.10. CoAgMet Weather Stations used for analysis in the LARV.

Study	Station			Irrigation	Date of First Record	Comparative Est. of Site ET
Reach	ID	Name	Location			
USR	FWL01	Fowler	Fowler Golf Course	Full	17 Mar 2005	—
	LJT01	LaJunta	11 mi NE of LaJunta	Full	17 Mar 2005	Under
	RFD01	RockyFord	CSU Experiment Station, Rocky Ford	Full	6 Apr 1992	—
DSR	HLY01	Holly	5 mi NW of Holly	Part	27 Sep 2001	Over
	HLY02	Holly #2	8.5 mi NW of Holly	Full	21 May 2005	—
	LAM04	Lamar #4	4.5 mi NNE of Lamar	Full	11 May 2005	—

River within a study reach could be approximated as the mean of the reported values within the surrounding region.

The minimum daily relative humidity (RH_{min}) and wind speed at 2 m above ground surface (u_2) data were obtained from the same CoAgMet stations as the precipitation and
5 ET_{ref} data. RH_{min} values were reported as a fraction and values less than zero were removed from the data set. Wind speed values were reported as wind run, which is the total distance the air traveled during the calendar day and is reported in units of km d^{-1} . A small number of the wind run values in the obtained data set were less than zero and were removed. Historical average wind run values were not available to provide a method to sanitize the
10 wind run upper bound values. Wind run values were converted to average daily wind speed in units of m s^{-1} .

Precipitation data were collected from the same network of monitoring stations used to generate average daily ET_{ref} as daily values in units of mm d^{-1} . Data was not sanitized

before publication to the CoAgMet web site. A small number of total daily precipitation values in the obtained data set were less than zero or exceeded reasonable maximum values.

Daily total precipitation values less than zero or greater than 1.5 times the highest average precipitation reported by the National Weather Service were excluded. As with the ET_{ref}

5 data, the mean precipitation value over the surrounding region of a study reach for any given day only included those stations reporting data. Any additional data collected from the CoAgMet system was treated in a similar manner.

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