SOUTH PLATTE RIVER SALINITY

Sources, Trends, and Concerns – 1995-2018

Colorado Water Conservation Board

South Platte Basin Roundtable

Metro Basin Roundtable

NEIRBO HYDROGEOLOGY

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At the project onset, when it wasn't clear whether salinity was a potential concern for irrigated agriculture, Mark Sponsler championed the cause and secured funding for water-quality sampling through the Colorado Corn Administrative Committee. Mark continued to support the project through the Water Supply Reserve Fund grant process, which included numerous meetings and presentations to obtain Roundtable and Colorado Water Conservation Board approvals.

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EXECUTIVE SUMMARY

South Platte River water is used multiple times as it flows through the basin. Each time the water is used, which can be for many things, including municipal, industrial, irrigated agricultural, and livestock uses, the salinity content can increase. High salinity is a concern for irrigated agriculture because it can reduce crop yields, damage soil structure, and reduce the diversity of crops that can be grown. High salinity can also make water unpalatable for drinking, increase scale deposits, and cause hardness, which may necessitate expensive treatment. Additionally, ecosystems and aquatic species can be affected by high salinity. These concerns prompted an analysis of salinity severity and trends in the South Platte River from 1995 through 2018.

There are many salinity sources in the South Platte Basin, including: 1) municipal and industrial wastewater; 2) geologic formations; 3) irrigated agriculture; 4) livestock; 5) oil and gas operations; 6) highway deicing agents; and 7) stormwater runoff. These sources occur throughout the basin where they comingle along the entire length of the South Platte River.

South Platte River salinity was less than 200 milligrams per liter as the river exits the mountains at Waterton Canyon and it accumulates salts as it flows through the basin. In 2018, the annual average salinity in the reach that includes the upstream part of the Denver Metro area was 569 milligrams per liter (Figure ES-1). Through the Metro area to Kersey, salinity increased to about 700 milligrams per liter. Salinity continued to increase from about 750 milligrams per liter in Reach 7 to 1,165 milligrams per liter in Reach 9 (Figure ES-1).

These elevated salinity concentrations can affect crops and limit water uses. Crop yield reductions for salt sensitive crops like beans, carrots, and onions begin at salinity concentrations of about 500 milligrams per liter. Most crops experience yield reductions in the 1,000 to 2,000 milligrams per liter range. Above 500 milligrams per liter drinking water will develop hardness, scale deposits, discoloration, staining, and salty taste. At increasing salinity concentrations most communities will find treatment necessary for drinking water use.

Salinity in the upper basin has been increasing since the start of the 1995-2018 study period. In the Denver Metro area salinity concentrations began a more dramatic increasing trend in 2005-06 (Figure ES-2, Reach 1). Reaches downstream of the Metro area have had more consistently rising salinity trends since 1995 (Figure ES-2). In the upper basin, salinity has increased from less than 400 mg/l in 1995 to nearly 700 mg/l in 2018. These current salinity levels raise the baseline salinity for water being diverted for agricultural use.

Wastewater effluent from municipal and industrial water treatment facilities are suspected to be major salinity contributors in the Denver Metro area. Salinity concentrations increase from less than 200 milligrams per liter at Waterton Canyon to over 700 milligrams per liter as soon as the river enters the Denver Metro area. River diversions remove freshwater and it is replaced by wastewater effluent.

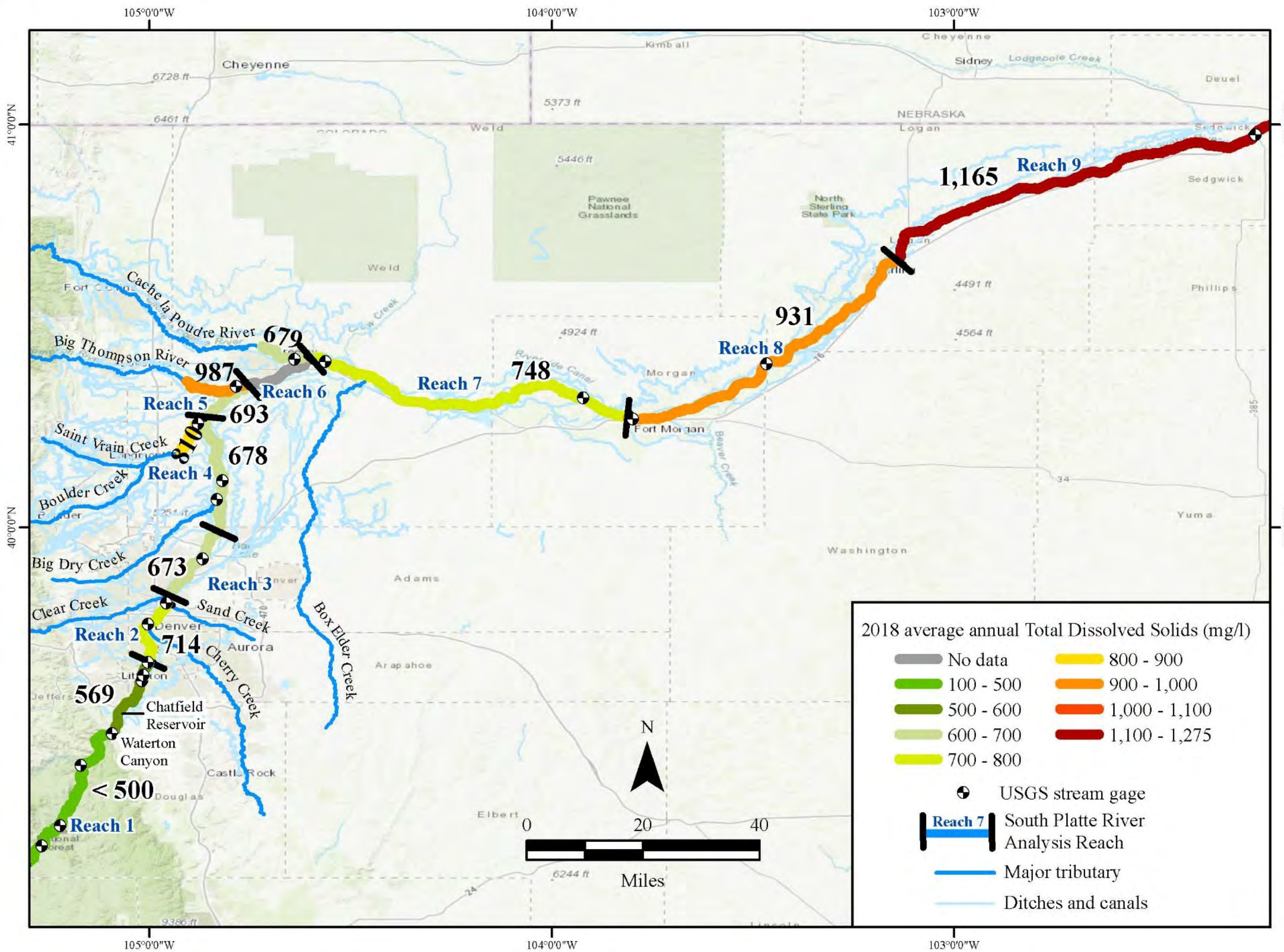

Figure ES-1. Average annual salinity for 2018 in the South Platte River and select tributaries

The importance of wastewater effluent to the river's flow and water quality is magnified because Chatfield Reservoir and diversions remove the natural, low-salinity flow and replace it with higher-salinity effluent. Under normal flow conditions the river's salinity is determined by the many wastewater effluent contributions. During high runoff periods this baseline salinity temporarily decreases due to the high volume of freshwater inflow.

The downstream salinity increases result in the lower basin having the most severe concentrations. Average annual salinity is over 1,000 mg/l with monthly averages exceeding 1,200 mg/l and individual measurements exceeding 1,600 mg/l. However, there has been an apparent decreasing salinity trend since 1995 in the lower basin (Figure ES-3), which was unexpected given the rising salinity in the upper basin. Average annual salinity has decreased 150 to 200 milligrams per liter in the lower basin since 1995. These trends and concentrations, however, are less reliable due to the general lack of data downstream of Fort Lupton. Data collection in the lower basin reaches increased after 2012 and long-term trends will become more defined in the coming years.

The lower basin salinity trends appear to be correlated, at least in part, to the salinity trends in the Saint Vrain, Big Thompson, and Cache la Poudre tributaries. The Big Thompson River, in particular, had high salinity concentrations in the 1990's that have generally been decreasing since 1995 (Figure ES-4). Cache la Poudre River average annual salinity has decreased slightly from 750 to 700 milligrams per liter (Figure ES-4). Average annual salinity in Saint Vrain Creek has consistently been about 750 milligrams per liter. The 2018 salinity in these tributaries were in the 700 to 1,000 mg/l range, which are comparable to or higher than the Denver Metro area concentrations. Other tributaries in the basin also have elevated salinity and from the 1990s into the early 2000's they had generally decreasing trends (Haby, 2011). These trends may reflect water-treatment improvements since the 1990's. Tributaries appear to be significant salt load contributors and their trends influence conditions in the South Platte River.

Salinity on a given day can greatly exceed these monthly averages that mask the extreme salinity conditions. These salinity spikes, that can exceed 1,800 milligrams per liter, can occur during months with high runoff, high average flow, and low average salinity. The impact of these salinity spikes on irrigated agriculture depends on many factors, including the crop type and growth stage at the time high salinity water is applied.

The South Platte River transports hundreds of thousands of tons of salt each year. In the lowest reach analyzed near Julesburg, the long-term annual average salt load was estimated to be over 650,000 tons of salt per year. The river's salt load is being applied to farmland throughout the basin. Farmland irrigated with 24 inches of 1,000 milligrams per liter water over a growing season will have 5,520 pounds of salt deposited per acre every year.

Drought conditions exacerbate salinity problems for irrigated agriculture. River salinity rises due to the lack of freshwater inflow and there is less irrigation water available at a time when crop demand is the highest. Hot and dry conditions increase crop transpiration and evaporation, which increases soil salinity. Applying less water due to restrictions prevents or reduces the flushing of salts from the soil root zone. Multi-year droughts with more salt loading and less salt leaching can lead to salt build-up in soils. Areas with unfavorable water and soil chemistry can be susceptible to permanent soil damage if these conditions persist.

Water law and water-management practices have been consistently evolving over time. Just as the salinity sources mix, evolving water-management practices are constantly mixing and changing as water development continues to expand. Using transbasin water diversions to extinction and prohibiting well pumping without augmentation plans has altered water-rights administration and can result in river calls for South Platte River water on nearly every day of the year. Implementation of water law and water decrees has fundamentally changed the hydrologic system. Streamflow patterns have changed, groundwater levels have risen, groundwater flow paths have been altered, and the magnitude and distribution of salt loads has changed.

All South Platte Basin water users will be impacted if salinity continues to increase. Irrigated agriculture depends on suitable water quality to remain sustainable into the future. High salinity limits crop choices, decreases yields, and can cause permanent soil damage. Costly water treatment may be required for municipal, industrial, and domestic uses. Ecosystems aquatic species and recreational users can also be negatively impacted by deteriorating water quality.

The significant potential impacts from increasing salinity warrants continued attention and active mitigation measures. Improved monitoring and further analyses are recommended to aid in understanding salinity trends, variability, and the role of the many different salt sources. Water-management practices informed by this information can lead to minimizing salinity contributions and its detrimental impacts. This study shows that salinity should be considered explicitly in South Platte Basin water-management policies and projects. Salinity discharge limits, water-treatment strategies, and mitigation controls need to be evaluated and implemented. Without active management to control salinity, northeastern Colorado's most important water resource will likely deteriorate as water demands continue to increase.

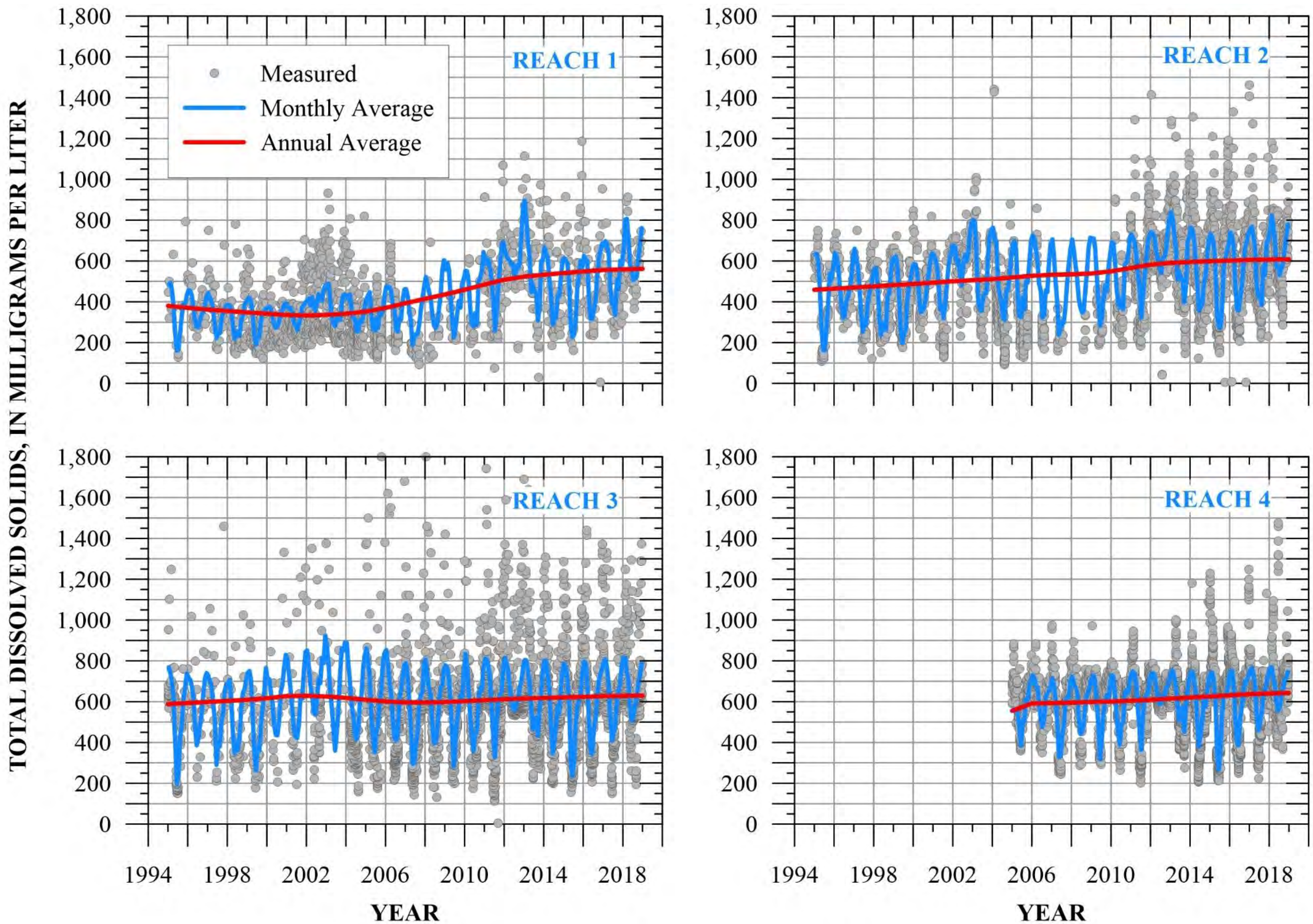

Figure ES-2. Salinity trends in the South Platte River reaches 1 through 4

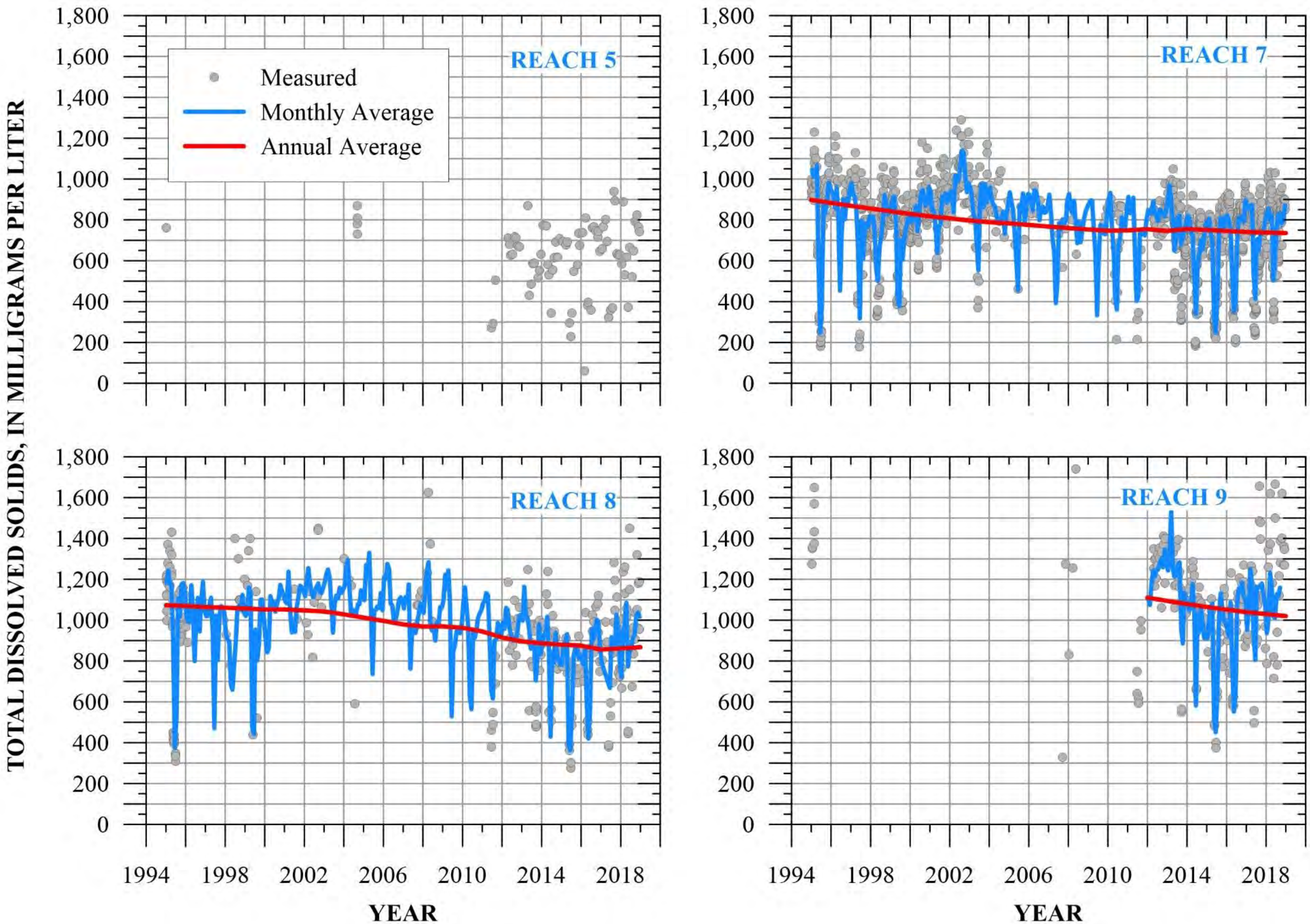

Figure ES-3. Salinity trends in the South Platte River reaches 5, 7, 8, and 9

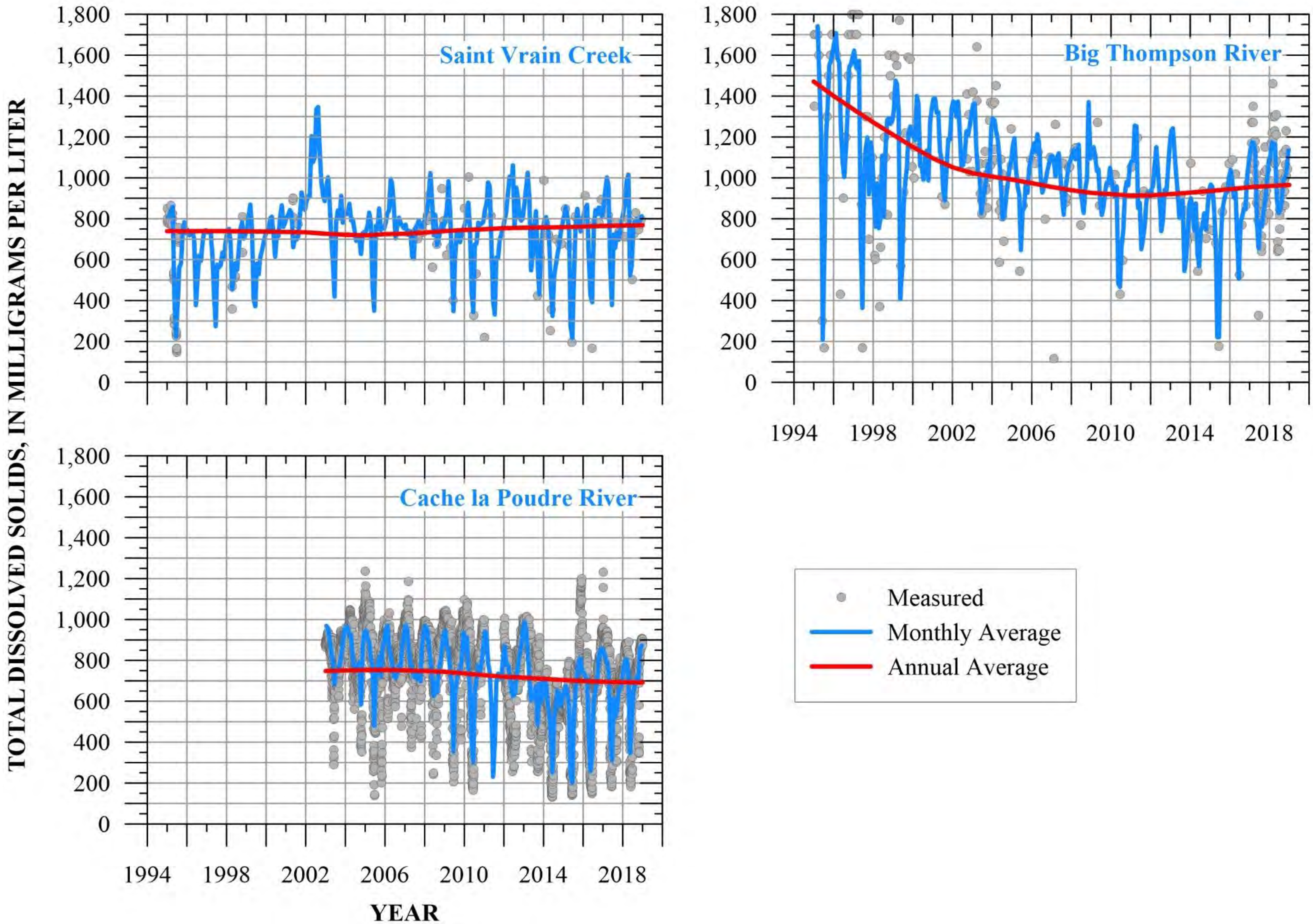

Figure ES-4. Salinity trends in select South Platte River tributaries

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1. INTRODUCTION

The South Platte Basin's projected water-supply gap has received much attention. Water-use efficiencies, including successive use of water, has been improved substantially throughout the South Platte Basin (Figure 1-1). The South Platte River is used and reused many times to meet multiple needs. On average, South Platte Basin water is used seven times successively before it leaves the state at the Nebraska border. Each time water is reused and as it flows through the basin there is the potential for it to accumulate additional chemical constituents. Salts, in particular, are known to accumulate due to municipal, industrial, and agricultural uses as well as from stormwater runoff and geologic formations.

This study investigates salinity in the South Platte River from 1995 through 2018. Population growth, industrial development, and water-management practices in the South Platte Basin have changed considerably since 1995. Salinity is a fundamental water-quality property that can increase with development and water reuse. Salinity severity and trends are potential concerns for irrigated agriculture, municipal and industrial water supplies, and ecological systems.

The Colorado Water Conservation Board (CWCB) recognized that a broader evaluation of water quality would benefit the South Platte Regional Opportunities Water Group (SPROWG) Feasibility Study. The SPROWG study is evaluating four water-supply development concepts that include water-storage facilities and additional conveyance capacity throughout the basin. These water supplies would be delivered to meet municipal, agricultural, environmental, and recreational demands.

The project scope was expanded to support the SPROWG study's evaluation of water-treatment strategies. In addition to salinity, an additional 12 chemical constituents that were requested to assist with water treatment were included. These data were compiled, statistically summarized, and evaluated for trends.

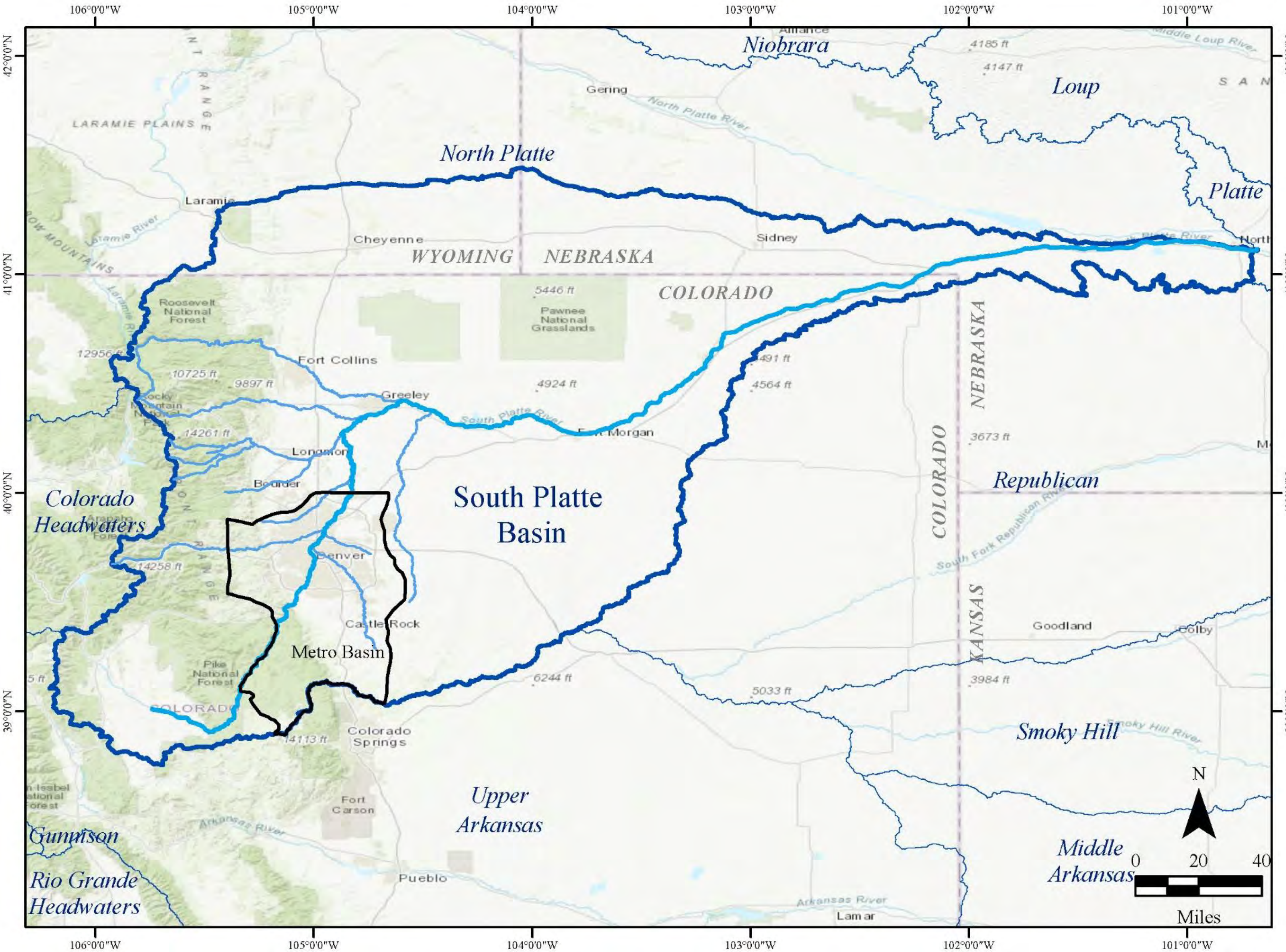


Figure 1-1. South Platte Basin and major tributaries

2. BACKGROUND

Salinity has been a concern for irrigated agriculture since its development by early civilizations. Ancient societies, reportedly as far back as 2400 BC in Mesopotamia and Peru's Viru Valley, were based on irrigated agriculture that initially flourished and then failed due to soil salinization.

Colorado's population has grown from 1 million in 1930 to over 5 million today and it could nearly double by 2050. Although the South Platte Basin has 80-percent of the State's population, and it expected to increase by 2.5 million by 2050, it only has 20-percent of the State's water supply. As the population continues to grow, so do the demands for water. Agriculture, oil and gas, tourism, environmental, recreational, industrial, and municipal uses are all competing for water. Climate change is also expected to disrupt future water availability due to increasingly variable precipitation that could result in significant water-supply shortfalls.

The Colorado Corn Administrative Committee and the Central Colorado Water Conservancy District recognized that salt accumulation in irrigation water can cause soil damage and reduce crop yields. This potential threat to irrigated agriculture in the South Platte Basin led these organizations to support this salinity study with matching funds for a Colorado Water Conservation Board (CWCB) Water Supply Reserve Fund (WSRF) grant. Project funding was provided by the South Platte Basin and Metro Roundtables.

This project initially began in September 2018. At that time, concerns were raised that using transbasin water to extinction, repeated water reuse, and municipal wastewater effluent may be increasing South Platte River salinity to levels that would harm irrigated agriculture. The initial project phase was South Platte River water-quality sampling to obtain a snapshot of the salinity conditions. This sampling showed that Total Dissolved Solids concentrations in the South Platte River were initially 191 milligrams per liter (mg/l) at Waterton Canyon where the river exits the mountains, it increased to about 700 mg/l near Fort Lupton, and reached a maximum of 1,275 mg/l at Julesburg (Figure 2-1). This water-quality sampling confirmed that salinity was a potential problem that warranted further investigation. This report presents the results of a comprehensive evaluation of publicly available South Platte River salinity data.

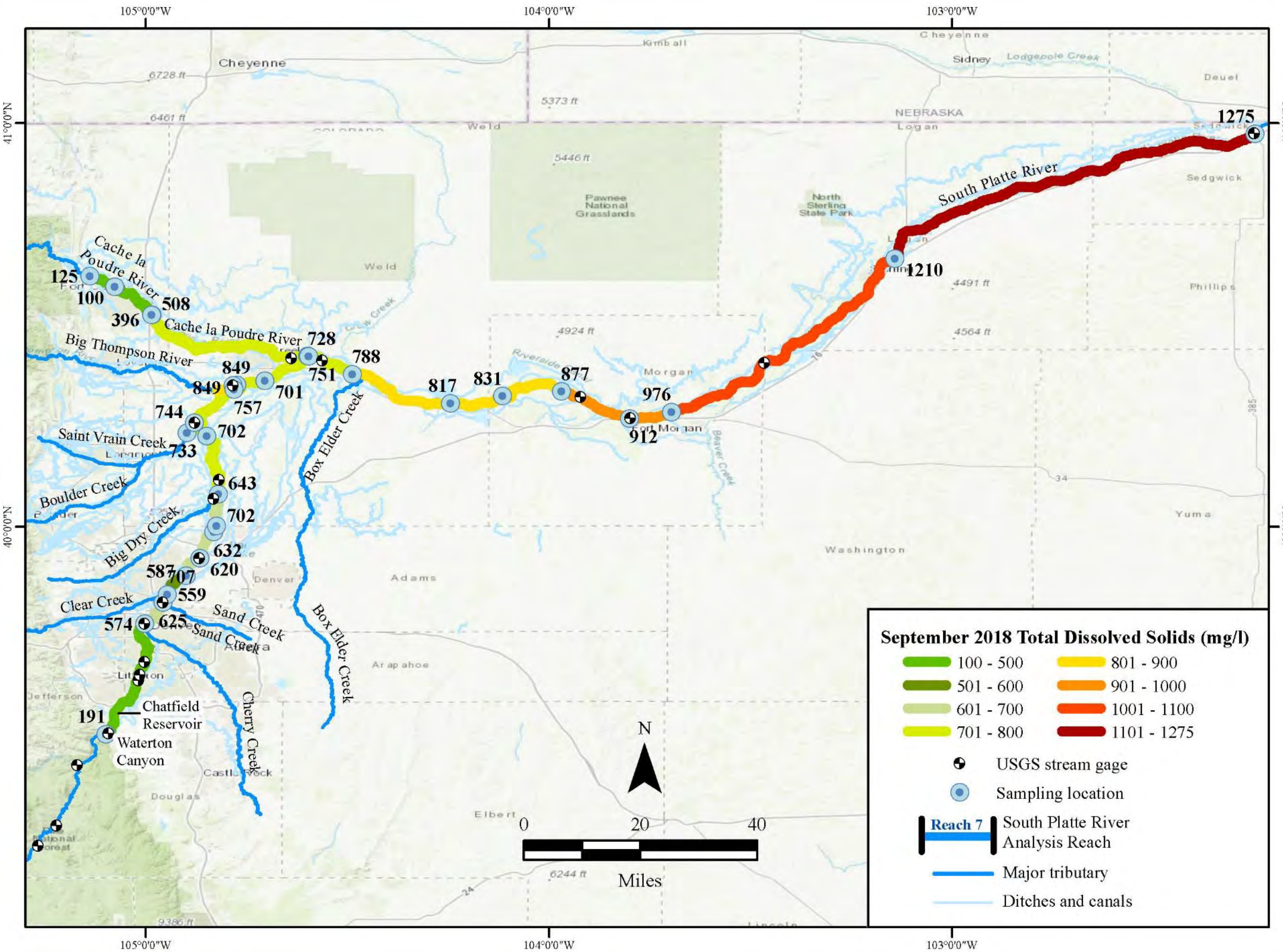


Figure 2-1. Salinity measured in the South Platte River and select tributaries, September 11-13, 2018

3. THE SALINITY PROBLEM

Elevated salt concentrations in water can cause a variety of problems depending on how the water is being used. Adverse crop effects from salinity, as measured by Total Dissolved Solids (TDS) concentrations, begin at about 500 mg/l as shown in Table 3-1 and Table 3-2. Crop yield reductions for salt sensitive crops like beans, carrots, and onions begin at TDS concentrations of about 500 mg/l (Table 3-2). Most crops experience yield reductions in the 1,000 to 2,000 mg/l range and TDS concentrations over 3,000 mg/l make the water unusable for most crops.

The U.S. Environmental Protection Agency (EPA) has set a secondary drinking water standard of 500 mg/l for TDS (Table 3-1). Above 500 mg/l users will notice hardness, scale deposits, colored water, staining, and salty taste. At increasing concentrations most communities will find it necessary to treat the water for drinking water use. For drinking water purposes, TDS between 600 and 900 mg/l is considered fair palatability; 900-1,200 mg/l is poor; and above 1,200 mg/l is unacceptable. Industrial water users have industry specific TDS criteria and they can be among the most limiting of the potential uses.

Healthy freshwater ecosystems need to maintain salinity concentrations that are within tolerable ranges of the local aquatic species and habitat. Salinity can affect organisms by increasing stress or causing mortality, which can produce structural changes in freshwater species density, richness, and diversity. Higher salinity tends to favor predators and filter feeders that can alter the ecosystem balance (Cañedo-Arg elles and others, 2013).

Table 3-1. Salinity effects on drinking water, irrigated agriculture, and ecosystems

<table>
<tr><th>Total Dissolved Solids (mg/l)</th><th>Category</th><th>Drinking Water</th><th>Agriculture</th><th>Ecosystems</th></tr>
<tr><td>0 to 500</td><td rowspan="2">Fresh</td><td>EPA secondary standard</td><td>Acceptable for most crops</td><td rowspan="2">Acceptable for fresh-water species</td></tr>
<tr><td>500 to 1,000</td><td>Hardness; deposits; colored water; staining; salty taste</td><td>Crop yield reductions for sensitive crops</td></tr>
<tr><td>1,000 to 2,000</td><td rowspan="2">Fresh to brackish</td><td rowspan="5">Treatment needed</td><td>Crop yield reductions for most crops</td><td rowspan="2">Aquatic organisms adversely affected</td></tr>
<tr><td>2,000 to 3,000</td><td rowspan="2">Can be used on salt tolerant crops on permeable soils</td></tr>
<tr><td>3,000 to 5,000</td><td>Brackish</td><td rowspan="3">Unacceptable for freshwater species</td></tr>
<tr><td>5,000 to 35,000</td><td>Saline</td><td rowspan="2">Unacceptable</td></tr>
<tr><td>above 35,000</td><td>Hyper-saline</td></tr>
</table>

3.1 Salt Effects on Plants

Evaporative salinization happens due to water evaporation and plant transpiration that remove the freshwater and leave most of the salts in the soil. These salts can accumulate if they aren't flushed out by excess water (rainfall, snowmelt, and irrigation water) that moves the salts below the root zone. In some cases, however, excess water can lead to a high saline water table. When the groundwater table is near the surface, water can be drawn to the surface through capillary action. Near the surface, the water evaporates, leaving behind salts that had previously been flushed from the surface or that occur in groundwater (Bohn and others, 1985). This produces the visible salt deposits sometimes seen in low-lying areas. Mineral solubility largely regulates the extent to which salts accumulate or dissolve. Over time, these processes can result in salt accumulation that hinders seed germination, vegetative growth, crop yields, and crop quality (Tanji and Wallender, 2012).

Anyone that has tried to get table salt out of a wet shaker knows that salt absorbs water. Salts behave the same in soil. The salt absorbs much of the water that would normally be available to plant roots. Even though there is adequate soil moisture, high amounts of salt can result in a drought-like environment for plants. The plants become unable to extract as much water as they need and can wilt even though there is adequate soil moisture. This can slow or stop plant growth due to the increased energy needed to pull water from the soil. In an agricultural crop setting, a reduction in plant growth can result in an economic loss for the producer.

Saline conditions also restrict the ability of crops to take up water and nutrients, because the plants uptake water through a process of 'osmo-regulation.' When salt concentrations within the plant are higher than the soil, water moves from the soil into the plant root. When the soil-water salinity is greater than the internal plant salinity, the plant water uptake is restricted.

Researchers have also observed that when branching roots in some plants encountered saline soil or water, they entered a dormant growth phase. This is thought to be a biological response to prevent plant damage (Duan and Dinneny, 2015).

When salt dissolves in water, the ions separate, and plants absorb the chloride ions. They accumulate at the growth points and can build up to toxic levels. Stunted yellow foliage, premature fall coloration, leaf scorch, and twig dieback are common symptoms. Excessive sodium in the soil also obstructs the availability of important nutrients. Many of these symptoms occur after bud-break in the spring and well into the growing season (Smith, 2007).

If salts that have a high level of sodium compared to the concentration of calcium and magnesium accumulate in the soil, the hydraulic properties of the soil can be negatively affected. Excess sodium reduces the stability of the soil aggregate and causes dispersion or swelling of soil particles. This impedes water infiltration and drainage. Sodic soils can be extremely difficult to cultivate, and when they are, yields can be greatly reduced due to restricted transport of water and oxygen to the root system (USDA, 1958).

Table 3-2. Reduction in crop yield with increasing salinity

Percent Yield Reduction	0		10		25		50	
Vegetable and Row Crops	EC_w (dS/m)	TDS (mg/l)	EC_w (dS/m)	TDS (mg/l)	EC_w (dS/m)	TDS (mg/l)	EC_w (dS/m)	TDS (mg/l)
Bean	0.7	448	1.0	640	1.5	960	2.4	1,536
Carrot	0.7	448	1.1	704	1.9	1,216	3.0	1,920
Radish	0.8	512	1.3	832	2.1	1,344	3.4	2,176
Onion	0.8	512	1.2	768	1.8	1,152	2.9	1,856
Lettuce	0.9	576	1.4	896	2.1	1,344	3.4	2,176
Sweet potato	1.0	640	1.6	1,024	2.5	1,600	4.0	2,560
Corn	1.1	704	1.7	1,088	2.5	1,600	3.9	2,496
Potato	1.1	704	1.7	1,088	2.5	1,600	3.9	2,496
Corn, sweet	1.1	704	1.7	1,088	2.5	1,600	3.9	2,496
Tomato	1.7	1,088	2.3	1,472	3.4	2,176	5.0	3,200
Cucumber	1.7	1,088	2.2	1,408	2.9	1,856	4.2	2,688
Broccoli	1.9	1,216	2.6	1,664	3.7	2,368	5.5	3,520
Soybean	3.3	2,112	3.7	2,368	4.2	2,688	5.0	3,200
Wheat, durum	3.8	2,432	5.0	3,200	6.9	4,416	10	6,400
Wheat	4.0	2,560	4.9	3,136	6.3	4,032	8.7	5,568
Sorghum	4.5	2,880	5.0	3,200	5.6	3,584	6.7	4,288
Sugarbeet	4.7	3,008	5.8	3,712	7.5	4,800	10	6,400
Barley	5.3	3,392	6.7	4,288	8.7	5,568	12	7,680

EC_w (dS/m): Electrical Conductivity of irrigation water in deciSiemens per meter
TDS (mg/l): Total Dissolved Solids in milligrams per liter or parts per million

Adapted from "Quality of Water for Irrigation." R.S. Ayers. Jour. of the Irrig. and Drain. Div., ASCE. Vol 103, No. IR2, June 1977, p. 140.

3.2 Historical Examples of Salinity's Effect on Irrigated Agriculture

Irrigated agriculture has been plagued for centuries by the accumulation of salt in soils. Historical records reveal that numerous societies based on irrigated agriculture have failed. One of the most highly publicized is ancient Mesopotamia, which is now Iraq. This once-productive land appears to have suffered salt damage from about 2400 to 1700 B.C. (Tanji and Wallender, 2012). Flooding, seepage, over irrigation, and siltation resulted in a rising water table, which led to excessive soil salinity (Gelburd, 1985). The crop records show that production of wheat was phased out over time and replaced by more salt-tolerant barley, but the yields of barley gradually declined to 10 bushels per acre. After 1,000 to 1,500 years of successful irrigated agriculture, the Sumerian civilization declined. Similar problems developed in the Indus Plain region, which includes parts of modern-day India and Pakistan. The Harappa civilization began irrigation about 2,000 years ago and serious salinity and drainage problems developed within the last 150 years (Taylor, 1965).

The inhabitants of Viru Valley, on the coast of Peru, developed an irrigation system between 400 B.C. and the start of first Century A.D, (Willey 1953). By the year 800 the population of the Viru Valley reached its peak and after 1200 the population dramatically decreased. Evidence shows that people relocated from the previously densely settled valley bottoms to the upper narrows of the valley. Historians attribute this relocation to increasing soil salinity and rising water tables from lack of drainage (Armillas 1961).

The Hohokam Indians, who lived in the Salt River region of what is now Arizona, practiced a form of flood irrigation, similar to that practiced by the farmers in the Viru Valley. This civilization flourished from about 300 B.C. through the year 900. Historical records are sparse until about 1275, when this region, along with much of the southwestern United States, suffered a drought (Willey 1953). After 1450 no evidence of the Hohokam civilization exists. Records indicate that waterlogging and salt accumulation in the valley floor caused crop failures.

The lesson from history is that fertile farmland can be productive for hundreds of years and drive the growth and prosperity of civilizations. However, if changing salinity conditions are not actively managed, it can lead to crop failures and agricultural collapse. It is advisable to monitor salinity conditions and control salt loading before it impacts economic conditions and causes permanent soil damage.

3.3 Salinity Measurements

Laboratories and reports use various terms for salinity hazards, including salts, salinity, electrical conductivity (EC), specific conductance, and total dissolved solids (TDS). These terms are all comparable and all quantify the amount of dissolved "salts" (or ions, charged particles) in a water sample (Bauder and others, 2014).

Total Dissolved Solids is a direct measurement of all the dissolved constituents in water and is measured by evaporating a water sample and weighing the residue. Specific conductance, also referred to as electric conductivity, measures the ability of a substance to conduct an electrical current. In water, specific conductance increases in proportion to the quantity of mineral salts dissolved in the water. Specific conductance, therefore, is an indication of the concentration of dissolved solids (salinity). EC is easily measured in the field with a handheld meter. For convenience and consistency in this report, EC and specific conductance measurements have been converted to TDS using the conversion factors provided in Table 3-3.

The term "salinity" is frequently confused with common table salt or sodium chloride (NaCl). However, EC and Total Dissolved Solids, measures salinity from all the ions dissolved in a sample. This includes negatively charged ions (e.g., Cl^-, NO^-_3) and positively charged ions (e.g., Ca^{++}, Na^+). There are several measurement units used with EC_{water}, but deciSiemens per meter (dS/m) is the preferred unit. Other EC units include millimhos per centimeter (mmho/cm) and micromhos per centimeter (µmho/cm). TDS is measured in milligrams per liter (mg/l). Factors used to convert between units are provided in Table 3-3.

There are many different types of salt with different chemical compositions. It is not possible to distinguish the specific salt form with EC and Total Dissolved Solids (TDS) measurements. Water samples need to be analyzed for their chemical ion concentrations to determine the water's specific salt forms.

Table 3-3. Salinity measurement units and conversion factors for water-quality analyses

Component	To Convert	Multiply By	To Obtain
Water nutrient or TDS	mg/l	1.0	ppm
	TDS, ppm	~2.72	TDS, lb/ac-ft
Water salinity hazard	dS/m	1.0	1 mmho/cm
	mmho/cm	1,000	1 µmho/cm
	µmho/cm	0.001	dS/m
	µmho/cm	0.001	mmhos/cm
	mS/m	0.01	dS/m
	dS/m	100	mS/m
	ECw, <5 dS/m		
	dS/m	640	TDS, mg/l
	mS/cm	640	TDS, mg/l
	mS/m	6.4	TDS, mg/l
	µS/cm	0.64	TDS, mg/l
	ECw, >5 dS/m		
	dS/m	800	TDS, mg/l
	mS/cm	800	TDS, mg/l
	mS/m	8.0	TDS, mg/l
	µS/cm	0.8	TDS, mg/l
Water NO_3N, SO_4-S, B applied	ppm	0.23	pound per acre inch of water
Irrigation water	acre inch	27,150	gallons of water
Wastewater effluent	million gallon/day	1.547	cubic foot/second

dS/m: deciSiemen per meter; mg/l: milligram per liter; ppm: parts per million; mmho/cm: millimho per centimeter; µmho/cm: micromho per centimeter; TDS: Total Dissolved Solids

4. HYDROLOGIC CONDITIONS

The headwaters of the South Platte River originate at an elevation of about 11,500 feet. The South Platte River emerges out of the mountains through Waterton Canyon southwest of the Denver Metro region. The river flows through the Denver metropolitan urban area, and then enters the High Plains Region. The elevation at Waterton Canyon is about 5,500 feet and over about 250 miles it drops to 3,400 feet at the Colorado-Nebraska state line. Major tributaries to the South Platte River include Clear Creek, Cherry Creek, Dry Creek, Saint Vrain Creek, Big Thompson River, and the Cache la Poudre River. Numerous other drainages contribute flow with higher discharges resulting from stormwater runoff.

Water development in the South Platte River Basin began in 1870 when the first irrigation ditches were dug in the vicinity of Greeley. In 1993, there were hundreds of structures withdrawing more than 3 million acre-feet of water from streams each year, dozens of water storage reservoirs stored more than 2 million acre-feet of water each year, 12 trans-mountain diversions imported 400,000 acre-feet of water into the basin each year, and several thousand wells pumped an estimated 1 million acre-feet of water each year (Dennehy and others, 1993). Water diversion structures and storage projects have continued to be developed and more are planned.

The South Platte River Basin has been the focus of research for many years. Many of the issues today were issues in the 1990's. For example, a study of conditions from 1992-95 found that large water withdrawals from streams for agricultural and urban use resulted in less water to dilute contaminants in streams (Dennehy and others, 1998). Reuse of surface and groundwater for irrigation had resulted in increased salinity in the lower South Platte River and the alluvial aquifer. It was found that wastewater-treatment plant effluent at times was contributing almost all the South Platte River flow downstream from Denver (Dennehy and others, 1998; Litke, 1998). Groundwater return flows were a major nonpoint source of nitrate, dissolved solids, and pesticides (atrazine and prometon) in the lower reaches of the South Platte River.

Alterations of the natural hydrologic system also have resulted in less water in the river during spring snowmelt runoff and more water in the river during fall and winter. Historically, the South Platte River ran dry in the plains when the supply of mountain snowmelt was exhausted. Now, irrigation water seepage from ditches and fields replenishes the alluvial aquifer during spring and summer, and the aquifer slowly drains during fall and winter by discharging groundwater to the South Platte River. This altered flow regime has changed native aquatic habitat along the river (Dennehy and others, 1998).

A substantial part of the water that is removed from the river for irrigation infiltrates into the alluvial aquifer and eventually returns to the river. Surface water diverted out of the river downstream from Kersey during April 1994 (1,485 cubic feet per second, cfs) was replaced by a similar amount of groundwater discharged to the river (1,430 cfs) (Litke, 1996). The South Platte River acts as a drain for irrigation return flows from adjacent agricultural lands, and the return flow affects water quality in the river (Dennehy and others, 1993).

The South Platte River is a gaining river throughout much of its length; with groundwater inflow as large as 15 cfs per mile (Litke, 1998). Synoptic streamflow measurements have been used to estimate the volume of water continuing flow to the South Platte River. Near Kersey, the median gain in stream flow was about 3 cfs per mile (Litke, 1996). Median inflow increased to about 15 cfs per mile just downstream from Kersey and then generally decreased downstream to about 1 cfs per mile. These estimates were consistent with previous estimates for groundwater discharge to the river (Hurr and others, 1975; Ruddy, 1984; Wind, 1994). The downstream variability in streamflow could be due to aquifer morphology and the proximity of irrigation canals, irrigation reservoirs, and groundwater augmentation ponds to the river (Litke, 1996). These streamflow conditions indicated that the South Platte River downstream from Kersey is essentially recycled water.

Wastewater treatment facilities (WWTF) discharge effluent into the South Platte River and its tributaries. Some WWTF have the option of discharging into irrigation ditches and in some cases, ditches may remove effluent before it reaches the South Platte River. It was estimated that about 67 percent of the total estimated effluent to the South Platte River occurred upstream from Henderson, Colorado. In the Henderson to Kersey reach of the South Platte River another 28-percent of the total estimated effluent input occurred. This effluent originates from Saint Vrain Creek, the Big Thompson River, and the Cache La Poudre River drainages. From Kersey to North Platte, Nebraska, there are few WWTF effluent inputs and they account for 5-percent of the total effluent (Litke, 1996).

Urban storm runoff in the Denver metropolitan area contains elevated concentrations of nitrogen and phosphorus, but storms are of short duration so that annual storm-runoff contributions to instream nutrient loads are small (Litke, 1996). Ellis and others (1984) estimated that storm runoff contributed 5 percent (80 tons) of the total nitrogen load and 6 percent (22 tons) of the total phosphorus load at a site on the South Platte River downstream from the Denver metropolitan area during the April through September 1981 storm season.

5. STUDY METHODS

This study started as a one-time water sampling event to determine if salinity concentrations were a potential concern for irrigated agriculture in the South Platte Basin. The sampling at 33 sites in the South Platte River from Waterton Canyon to Julesburg, select diversions, and the Cache la Poudre River, was conducted from September 11-13, 2018. This snapshot of salinity concentrations showed that TDS concentrations in the South Platte River were initially 191 mg/l at Waterton Canyon where the river exits the mountains, increased to about 700 mg/l near Fort Lupton, and reached a maximum of 1,275 mg/l at Julesburg. These results are similar to the historical concentrations presented in Section 8, SALINITY TRENDS.

These sampling results indicated a 500 mg/l increase as the river flows through the heavily populated upper basin. Although the lower basin from Kersey to Julesburg is much less populated, there was also a 500 mg/l increase in this reach. These salinity concentrations raised concerns for irrigated agriculture, municipal water supply, and ecosystems. This historical salinity analysis was initiated to put the September 2018 sampling results into context and to investigate potential trends.

5.1 Data Compilation

Municipal wastewater treatment facilities became operational during the early to mid-1990's, which caused a major change in the South Platte River's water quality. The analysis period for this study was 1995 through 2018, since earlier data would not be representative of modern conditions. Long-term trends that may be related to the evolving water-management practices and due to climate variations occur during this period.

The major data sources used in this study are provided in Table 5-1. The "Water quality portal" (WQP) is a cooperative service sponsored by the United States Geological Survey (USGS), the Environmental Protection Agency (EPA), and the National Water Quality Monitoring Council (NWQMC). This portal serves data collected by state, federal, tribal, and local agencies. The EPA's STORET database and the USGS's National Water Information System (NWIS) database are major contributors to the WQP.

The most continuous and comprehensive dataset was obtained from the Metro Wastewater Reclamation District (MWRD) water-quality office. This data set included bi-monthly water-quality sampling of the MWRD wastewater treatment plant effluent and multiple locations along the South Platte River for 1995 through 2018. Central Colorado Water Conservancy District (CCWCD) electrical-conductivity data has been collected since 1995 at varying frequency and in most years. The CCWCD has four (4) sites on the South Platte River and numerous other sites on canals and tributaries. The South Platte River sites were measured quarterly during 2018.

Northern Water provided EC data collected every 15-minutes at the mouth of the Cache la Poudre River and three lower basin (Reach 7) locations for 2006-2017 (Figure 5-3 and Figure 5-4). This monitoring program included 12 sites in total, on the Cache la Poudre and South Platte Rivers. These were the highest frequency salinity measurement data available. Northern has not published these data and they were not included in this analysis. When quality-control procedures are completed and these data are released, they may provide valuable insights into salinity variability and loading in the basin.

Table 5-1. Water-quality data sources

Entity / Database	Source	Contributor(s)
Water quality data portal	https://www.waterqualitydata.us/portal/	USGS, EPA, cities, counties, CDPHE, and others
Colorado Department of Public Health and Environment (CDPHE), Discharge permits	http://environmentalrecords.colorado.gov/HPRMWebDrawer/search	CDPHE
Denver MWD Urban Waters Tool	http://exploremetrodenverwaterquality.org	Denver Metro Water District
Metro Wastewater Reclamation District (MWRD)	Water-quality Office - personal communication	MWRD
Central Colorado Water Conservancy District (CCWCD)	http://www.ccwcd2.org/Central/welcome	CCWCD
Northern Colorado Water Conservancy District (Northern Water)	http://www.northernwater.org/DynData/WQDataMain.aspx and personal communication	Northern Water

US Environmental Protection Agency (EPA); US Geological Survey (USGS),

All available water quality data within the South Platte Basin from these data sources were obtained. The dataset used for analysis was a refined by selecting data based on the following criteria:

a) Sampling locations within 1-mile of the South Platte River (this accounts for inaccuracies in location coordinates);
b) South Platte River sampling only[1];
c) Stream and river samples only, no lakes, ponds, canals, or groundwater;
d) Dissolved and total concentrations, no suspended or bedload sediments; and
e) Obvious anomalous data were removed.

[1] See discussion in Section 5.2 River Reaches regarding inclusion of sampling locations at the mouth of Saint Vrain Creek, Big Thompson River, and the Cache la Poudre River.

This dataset evaluation indicated that data were not uniformly distributed along the South Platte River. The upper basin reaches from the Denver metropolitan (metro) area to Fort Lupton had numerous sampling locations. The reach from Fort Lupton to Julesburg had sparse, widely spaced locations. Additionally, even though the Metro area had many locations, the individual locations did not contain continuous datasets that spanned the analysis period.

5.2 River Reaches

Long-term trend analysis requires water-quality analyses obtained over many years. Since there are few sampling locations that provide adequate data, the river was subdivided into nine reaches. Sampling locations within each reach were aggregated and collectively analyzed.

The South Platte River was subdivided into nine reaches for analysis. The start of most reaches coincided with the inflow of a major tributary and/or wastewater treatment facility. The reaches with major tributaries, wastewater treatment facilities, sampling locations, and stream gages are shown on Figure 5-1 through Figure 5-4. Descriptions of each reach are provided in Table 5-2. Most reaches had at least one stream gage that is operated by the US Geological Survey or the Colorado Department of Water Resources.

It was assumed that all sampling locations within a reach were representative of that reach. No attempt was made to account for tributary inflow that occur within reaches. Diversions affect the river's flow, but they do not affect the river's water quality. Groundwater inflow and its water quality contribution to the South Platte River were not considered.

It was also assumed that the stream gage used for analysis within each reach was representative of flows for that reach. No attempt was made to account for tributary inflow or diversion outflows that occur within reaches.

Reaches 5 and 6, from the South Platte River's confluence with Saint Vrain Creek to the Cache la Poudre River confluence, had little water-quality data and no stream gages. Tributary flows and water-quality from Saint Vrain Creek, Big Thompson River, and the Cache la Poudre River where added as analysis locations to better understand their contributions to the South Platte River.

Table 5-2. Descripion of South Platte River reaches used for analysis

Reach	Description
1	From confluence of the South and Middle Fork of the South Platte River to upstream of the Littleton-Englewood wastewater treatment facility. Includes USGS Englewood stream gage (Figure 5-2).
2	Downstream of the Littleton-Englewood wastewater treatment facility to upstream of the Metro wastewater treatment facility. This reach includes inflow from Cherry Creek and the USGS Denver stream gage (Figure 5-2).
3	Downstream of the Metro wastewater treatment facility to upstream of the MWRD's Northern wastewater treatment facility. This reach includes inflow from Sand Creek and Clear Creek and the USGS Henderson stream gage (Figure 5-2).
4	Downstream of the MWRD's Northern wastewater treatment facility to upstream of the confluence with Saint Vrain Creek. This reach includes inflow from Big Dry Creek and the USGS Fort Lupton stream gage (Figure 5-3).
5	Downstream of the confluence with Saint Vrain Creek and upstream of the confluence with the Big Thompson River. The South Platte River does not have a stream gage in this reach, but the Saint Vrain Creek flow is monitored by the Platteville gage (Figure 5-3).
6	Downstream of the confluence with Big Thompson River and upstream of the confluence with the Cache la Poudre River. The South Platte River does not have a stream gage in this reach, but the Big Thompson River flow is monitored by the La Salle gage (Figure 5-3).
7	Downstream of the Cache la Poudre River confluence and upstream of the Fort Morgan wastewater treatment facility. The South Platte River flow is monitored by the Kearsey, Masters, and Weldona gages (Figure 5-3).
8	Downstream of the Fort Morgan wastewater treatment facility and upstream of the Sterling wastewater treatment facility. The South Platte River flow is monitored by the Fort Morgan and Balzac gages (Figure 5-4).
9	Downstream of the Sterling wastewater treatment facility to the Colorado-Nebraska State line. The South Platte River flow is monitored by the Julesburg gage (Figure 5-4).

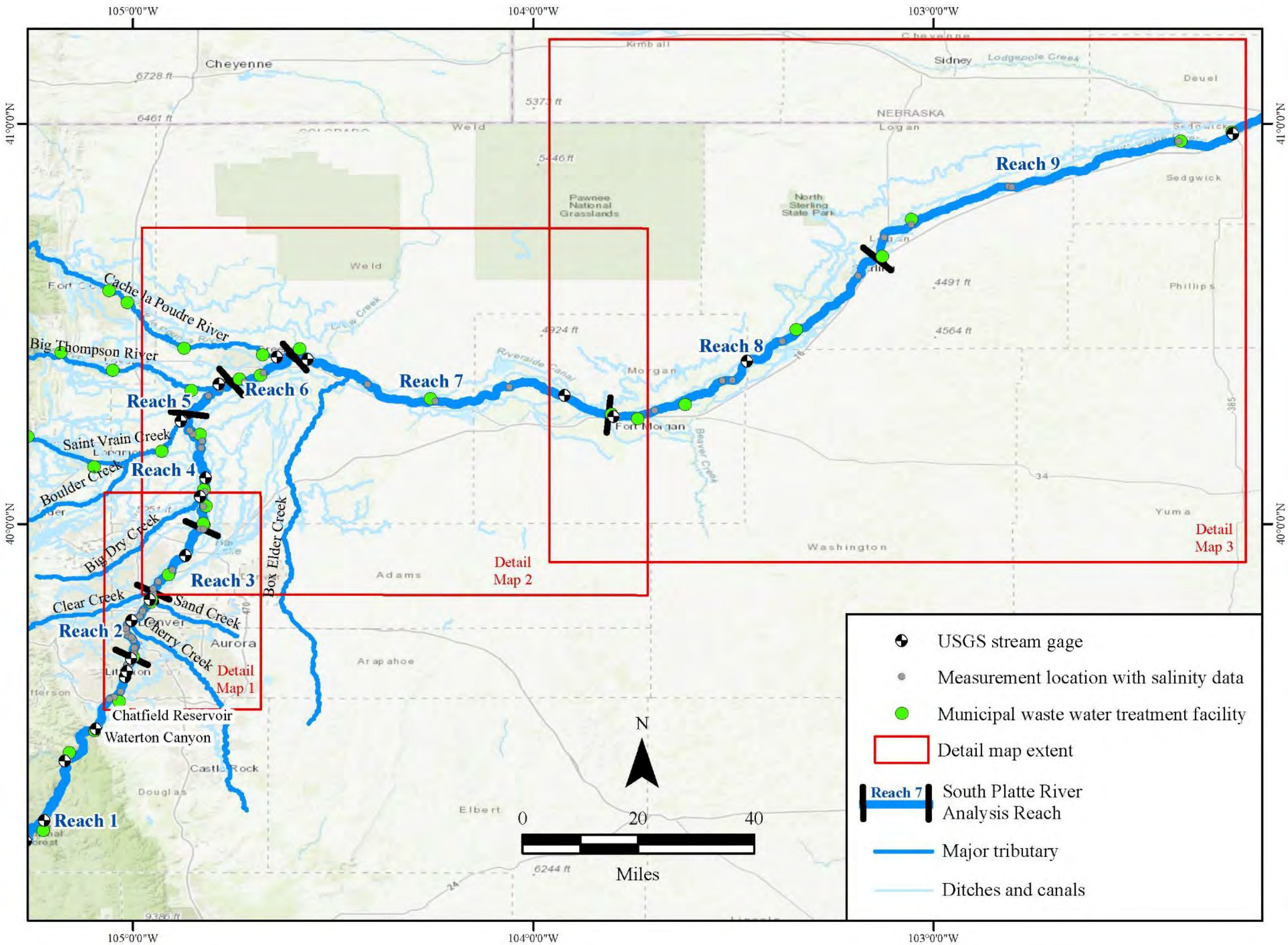


Figure 5-1. South Platte River, major tributaries, and index to detailed maps

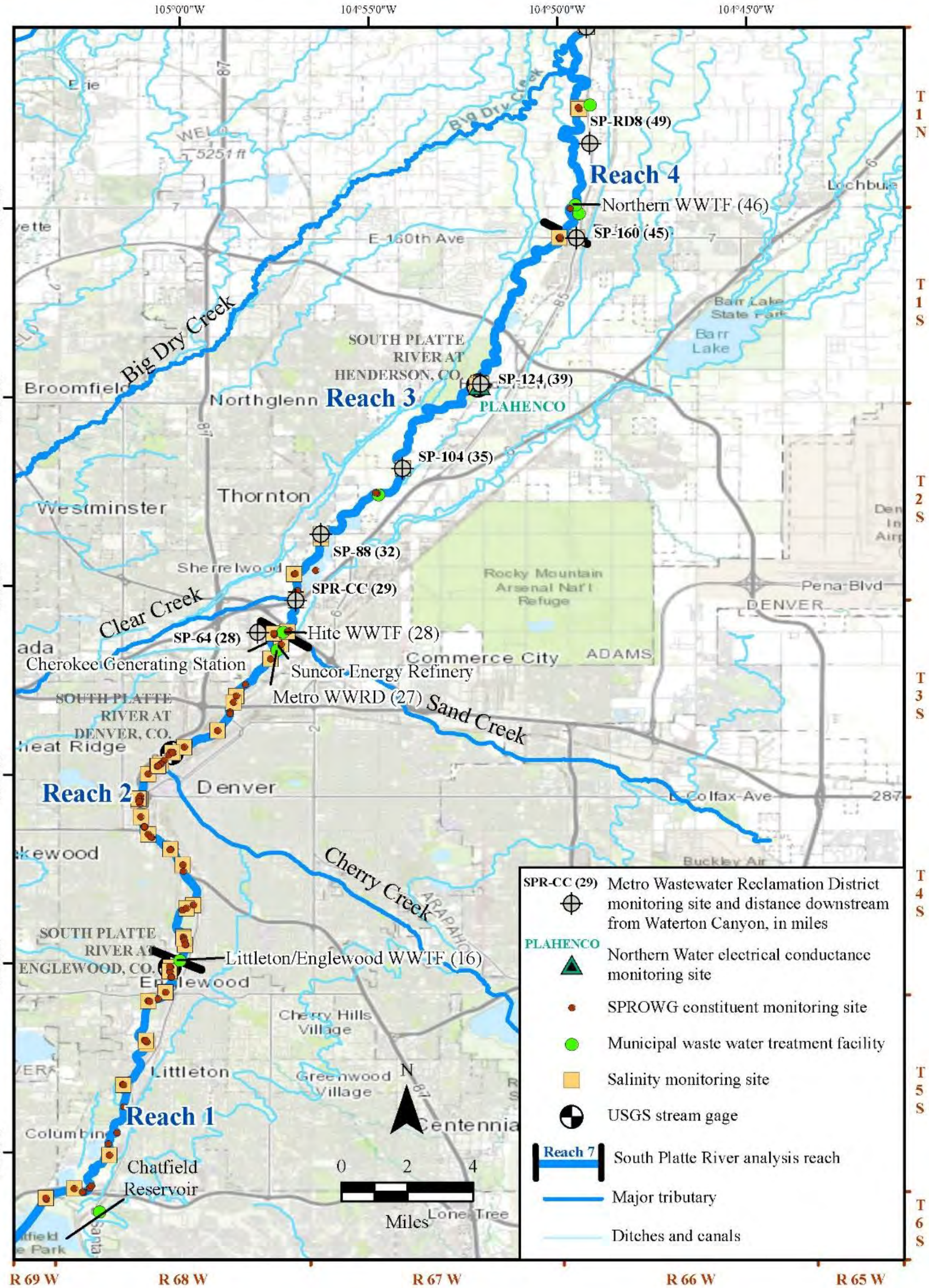


Figure 5-2. Upper South Platte River upper basin reaches 1, 2, and-3

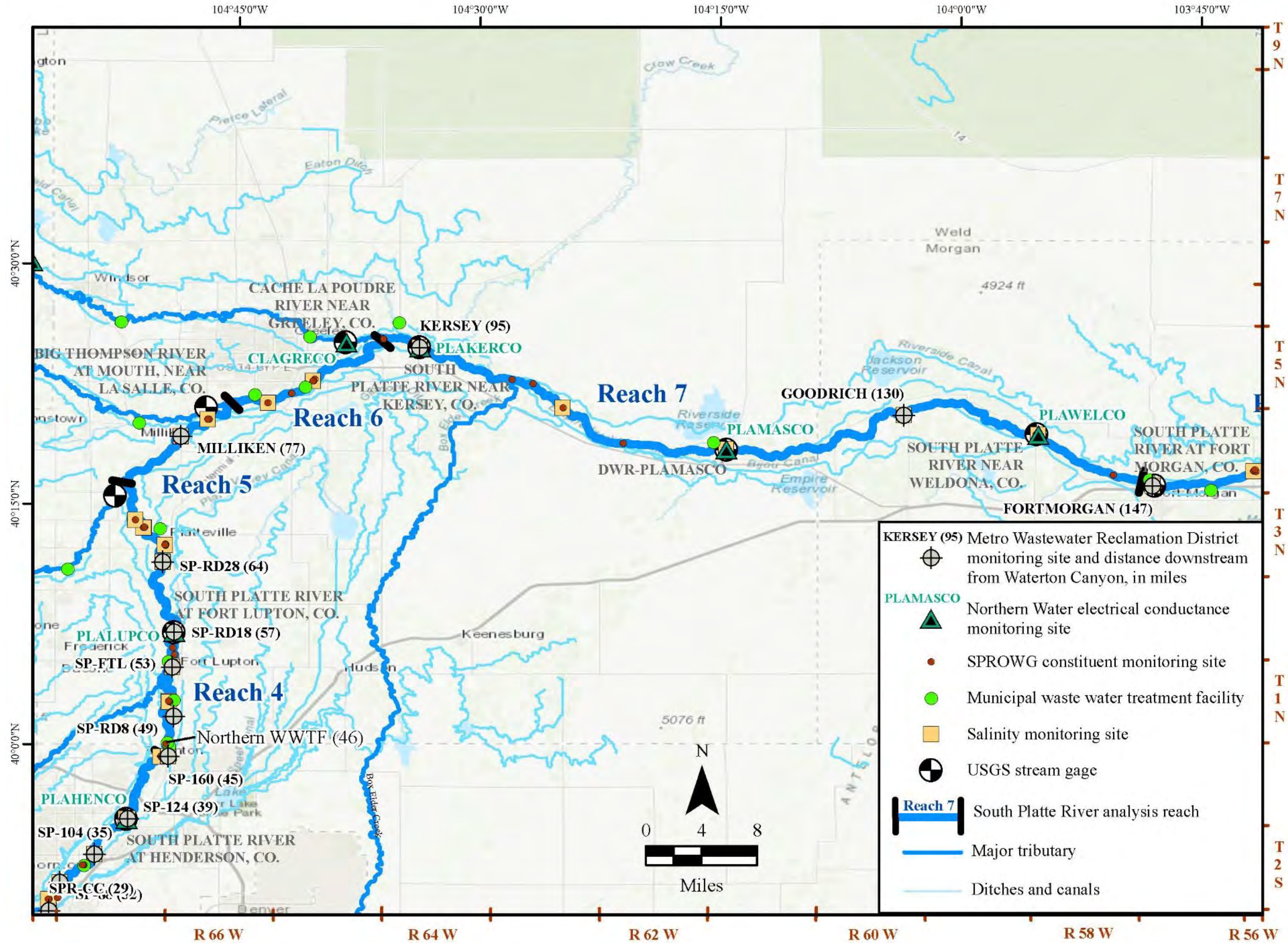


Figure 5-3. South Platte River reaches 4, 5, 6, and 7

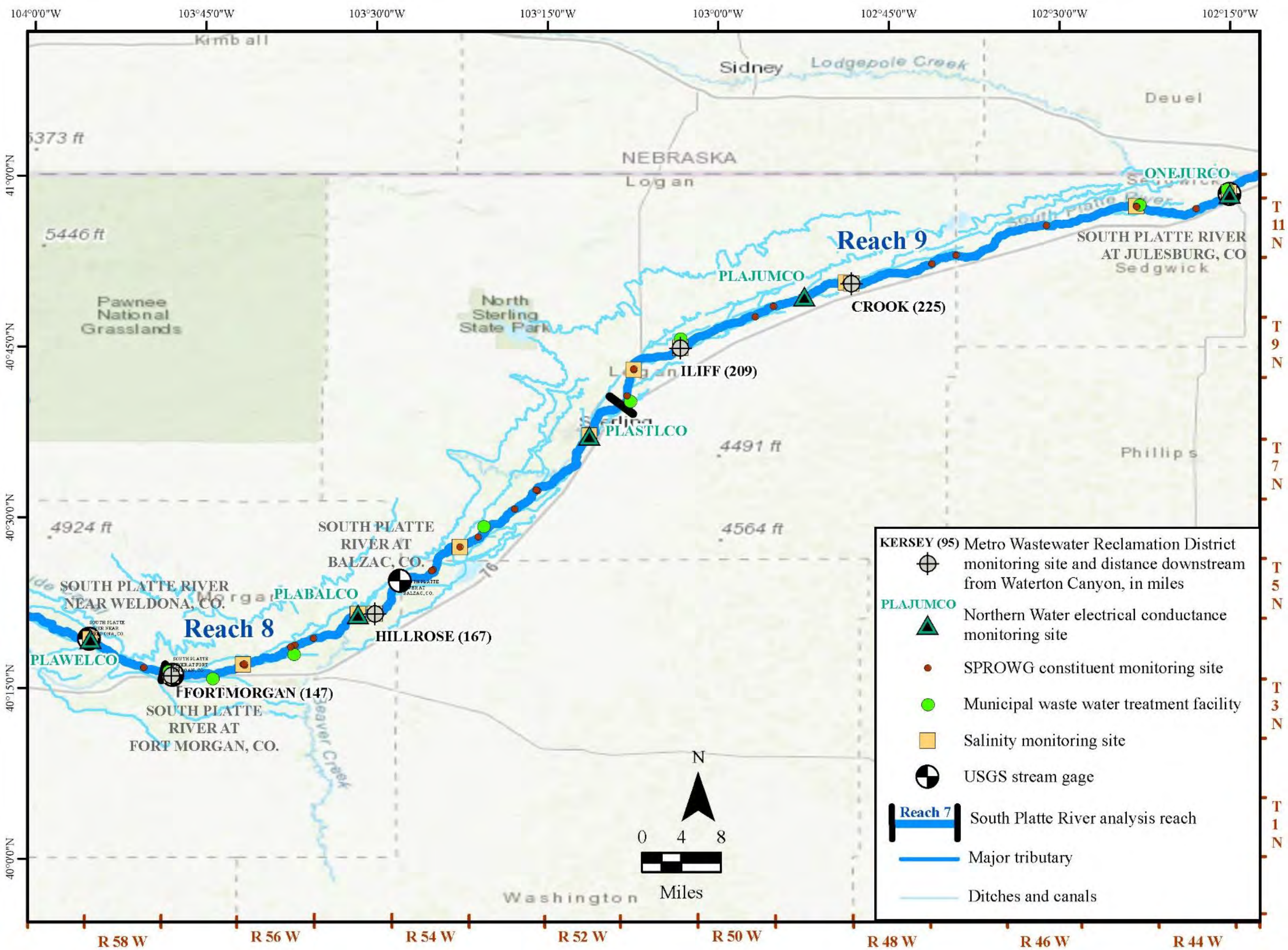


Figure 5-4. South Platte River lower basin reaches 8 and 9

5.3 Trend Analyses Methods

Most chemical concentrations in surface waters show strong seasonal patterns. Streamflow varies greatly between seasons due to variations in precipitation and temperature, which affects precipitation type (rain or snow) and evapotranspiration rates. Some of the observed seasonal variation in water quality may be explained by accounting for this seasonal variation in discharge (Hirsch and others, 1982). However, seasonality often remains even after discharge effects have been removed.

Seasonal water-quality patterns can also be caused by biological activity and water management for flood control, water supply, and irrigated agriculture. For example, nutrient concentrations vary with seasonal application of fertilizers and the natural pattern of uptake and release by plants. Other effects are due to different sources of water dominant at different times of the year, such as snow melt versus intense rainfall. Seasonal rise and fall of groundwater can also influence water quality. A given discharge in one season may derive mostly from groundwater while the same discharge during another season may result from surface runoff or quick flow through shallow soils. The chemistry and sediment content of these sources may be quite different (Helsel and Hirsch, 2002).

The measured salinity and the flow-adjusted salinity were analyzed in this study. All selected data within a reach were used to calculate monthly average salinity. Monthly averages reduce the variability and provide a reasonable estimate of the overall water quality. If seasonal trends are present, monthly averages would reflect these changes. Monthly average concentrations for each constituent and each reach were calculated and they are presented on scatter plots. LOcally Weighted Scatterplot Smoothing (LOWESS, Cleveland, 1979) lines were then added to aid in the visualization of the data's general nature and trends.

The WRTDS (Weighted Regressions on Time, Discharge, and Season) analysis method was used to characterize the status and trends in water-quality concentration and flux (Hirsch and others, 2010). This trend analysis was implemented with EGRET, which stands for Exploration and Graphics for RivEr Trends (Hirsch and De Cicco, 2015). EGRET was used to explore the variations in river discharge, analyte concentrations, and analyte fluxes. EGRET is best described as "exploratory data analysis" (Tukey, 1977) rather than statistical inference or hypothesis testing.

The water-quality analyte concentrations and fluxes are interpreted in relation to discharge, seasonality, long-term trend, and a random component. Annual and seasonal summaries of concentration and flux over time and flow-normalized estimates of concentration and flux that are designed to remove the influence of year-to-year variations in discharge. This provides insight on underlying changes in the behavior of the watershed.

Limited data availability prevented some reaches and some time periods from being analyzed using EGRET. The results were sensitive to data outliers, short periods of continuous data, and multi-year data gaps. Extremely high and low water-quality values that were not physically possible and were obviously erroneous were removed from the datasets.

6. STREAMFLOW

The concentration of many water-quality constituents vary with changes in streamflow. For example, when streamflow increases in the South Platte River due to stormwater runoff or snow melt runoff Total Dissolved Solids concentrations decrease. The runoff water has lower TDS concentrations than the river, which results in a dilution effect. Water-quality trends can be obscured, misleading, or mis-interpreted if the stream discharge-concentration relationships are not considered. For example, an apparent increasing salinity trend could be due to lower precipitation and lower streamflow rather than an increase in salinity loading to the river. Streamflow data were, therefore, compiled and analyzed to illustrate streamflow variability and to define discharge-concentration relationships.

Historically, before wide-spread irrigated agriculture, the South Platte River flow would stop after spring runoff. Now, there are upper basin diversions that can remove most of the flow for municipal and agricultural use. When natural spring runoff decreases the river may be sustained entirely by WWTF effluent. In the lower basin, the river can be sustained by irrigation return flows.

High flows occur during spring snowmelt runoff in April, May, June, and following rain-storm runoff during July and August. The magnitude and duration of these high flows depends on winter snow accumulations in the mountains and summer rain patterns. Lower flows occur during the Fall and Winter months. This seasonal and annual streamflow variability during 2015-2018 is illustrated by the Kersey gage in Figure 6-1. The long-term streamflow variability in mean daily and average monthly flow at Kersey is illustrated in Figure 6-2. The Kersey gage is downstream of the major tributary inflow and tends to have the highest flows along the South Platte River.

The two driest years on record were 2002 and 2018, with 2012 also being considered a drought year (Water Education Colorado, 2019). Drought years are noted for their low snowpack and limited spring runoff. Drought is exacerbated when there have been several years of below-average snowpack and above-average temperatures that result in high evapotranspiration, depleted soil moisture, and low surface-water supplies. These conditions during planting and early crop development can be particularly difficult for agriculture. Late season rainfall may increase the annual precipitation total, but it may be too late to benefit crop yields.

The statistical variation at the Kersey gage is shown in the boxplot in Figure 6-3. Wet years have higher mean flows and typically higher extreme flows, whereas dry years have lower mean flows and lower extreme flows. For comparison the Reach 1 and Reach 9 gage statistics are provided in Figure 6-4 and Figure 6-5. The discharge differences are due largely to tributary inflow and diversions that remove flow for municipal and agricultural use. Streamflow data for all reaches are provided in Appendix A.

The South Platte River is entirely contained by Chatfield Reservoir as the river exits the mountains (Figure 5-2) and water releases are highly managed. This maintains consistent mean flows and reduces the flow magnitude and variability at the Englewood gage (Figure 6-4). The Julesburg gage is the last South Platte River gage in Colorado (Figure 5-4). Very high flows were recorded during flood periods in 1995 and 2015 (Figure 6-5). During dry years, like 2000 through 2008, the South Platte River can have very low flows at Julesburg. However, the stream channel can be highly braided in the lower reaches and the stream gages may not always measure all flow.

Several tributary rivers provide additional flow to the South Platte River in the upper basin. This study considered flows from Saint Vrain Creek, Big Thompson River, and Cache La Poudre River. These streams originate in the mountains and then flow through the Front Range communities of Boulder, Longmont, Loveland, Fort Collins, and Greeley. These streams also flow through agricultural areas before joining the South Platte River (Figure 5-3).

Streamflow data for the South Platte River and major tributaries are provided in Appendix A. Graphs with daily and monthly mean streamflow, tabulated statistical flow summaries for each year from 1995 through 2018, and boxplots are included.

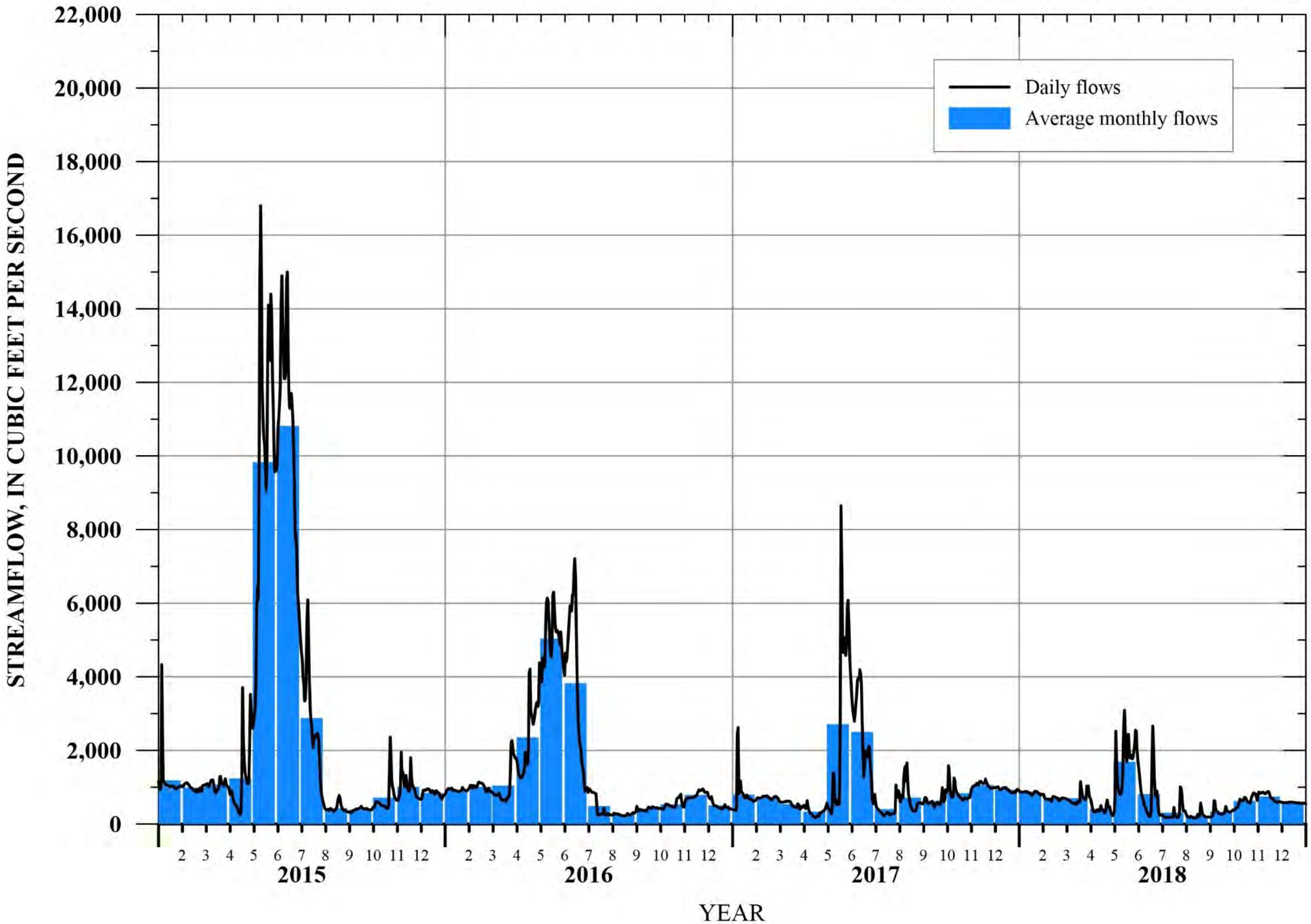


Figure 6-1. Streamflow, 2015-2018, at USGS 06754000, South Platte River at Kersey, Reach 7

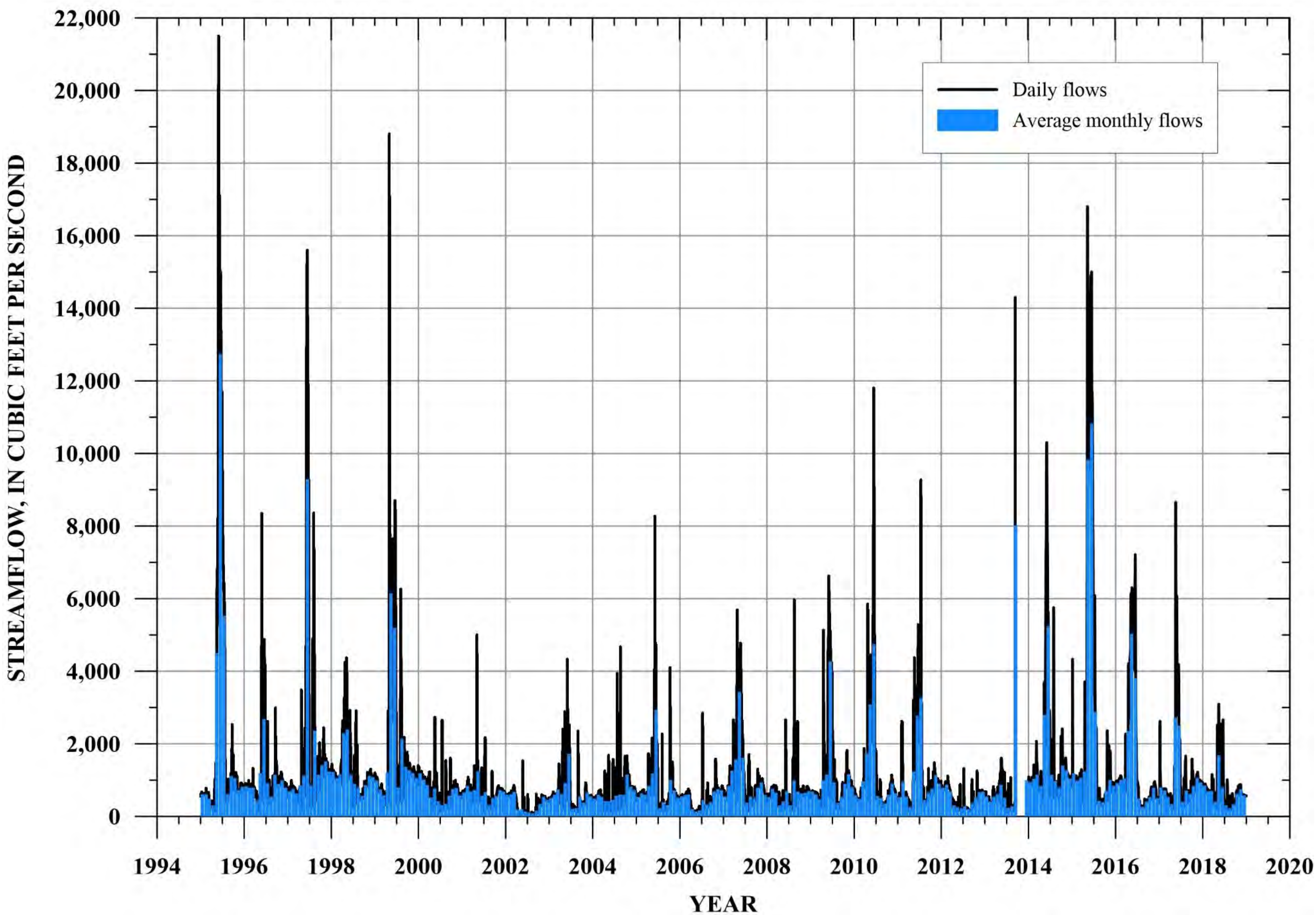


Figure 6-2. Streamflow, 1995-2018, at USGS 06754000, South Platte River at Kersey, Reach 7

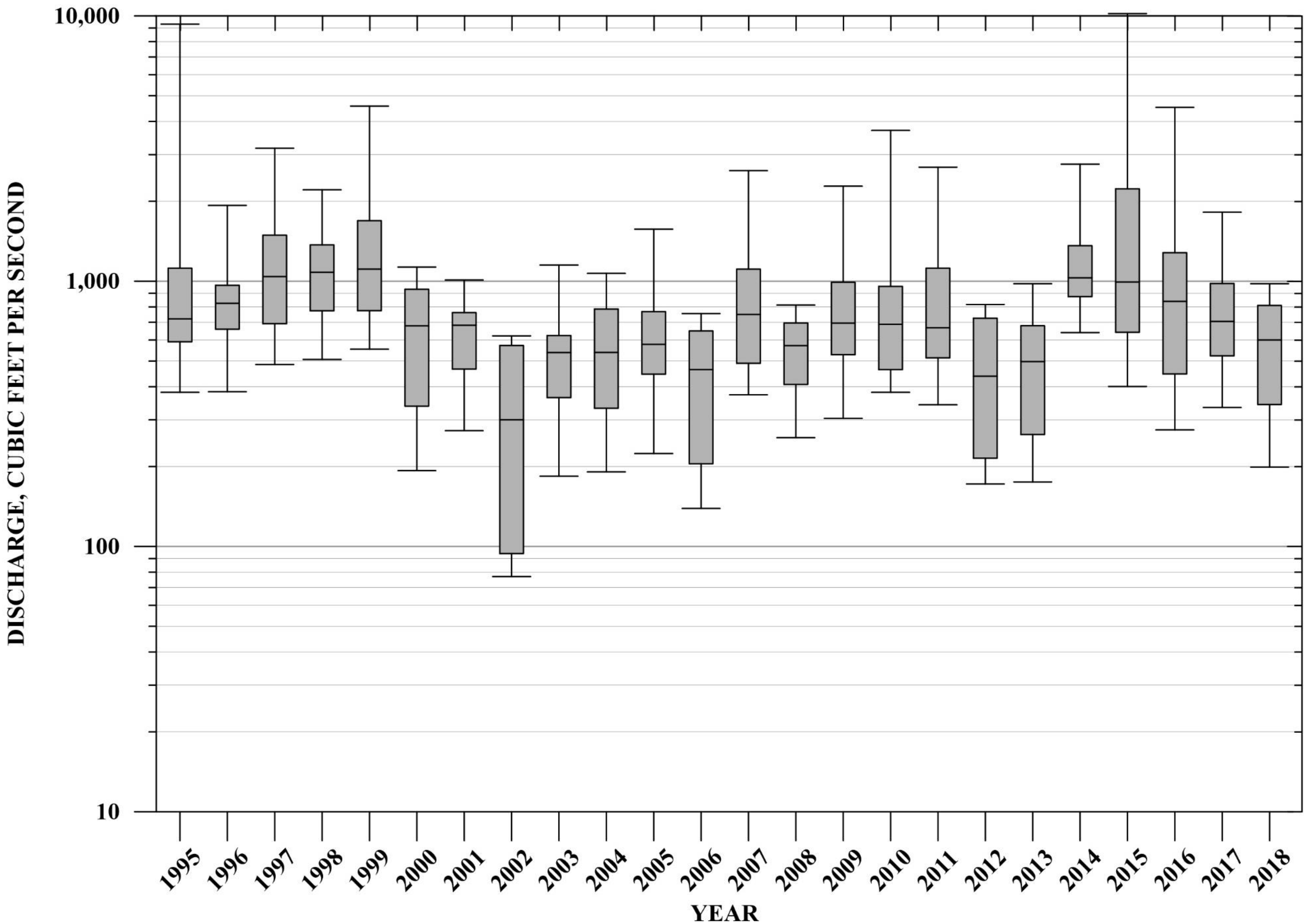


Figure 6-3. Streamflow boxplot, USGS 06754000, South Platte River at Kersey, Reach 7

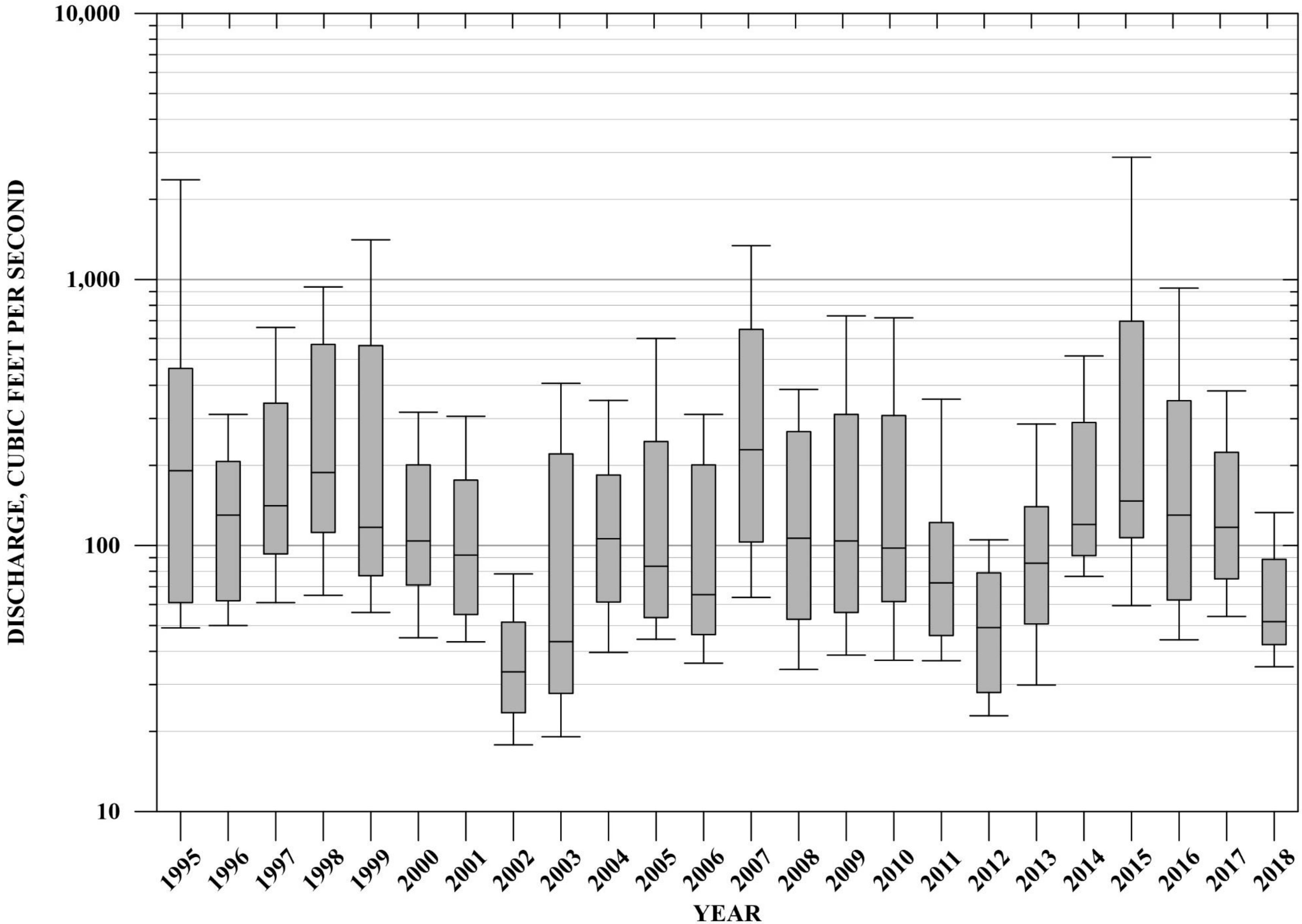


Figure 6-4. Streamflow boxplot, USGS 06711565, South Platte River at Englewood, Reach 1

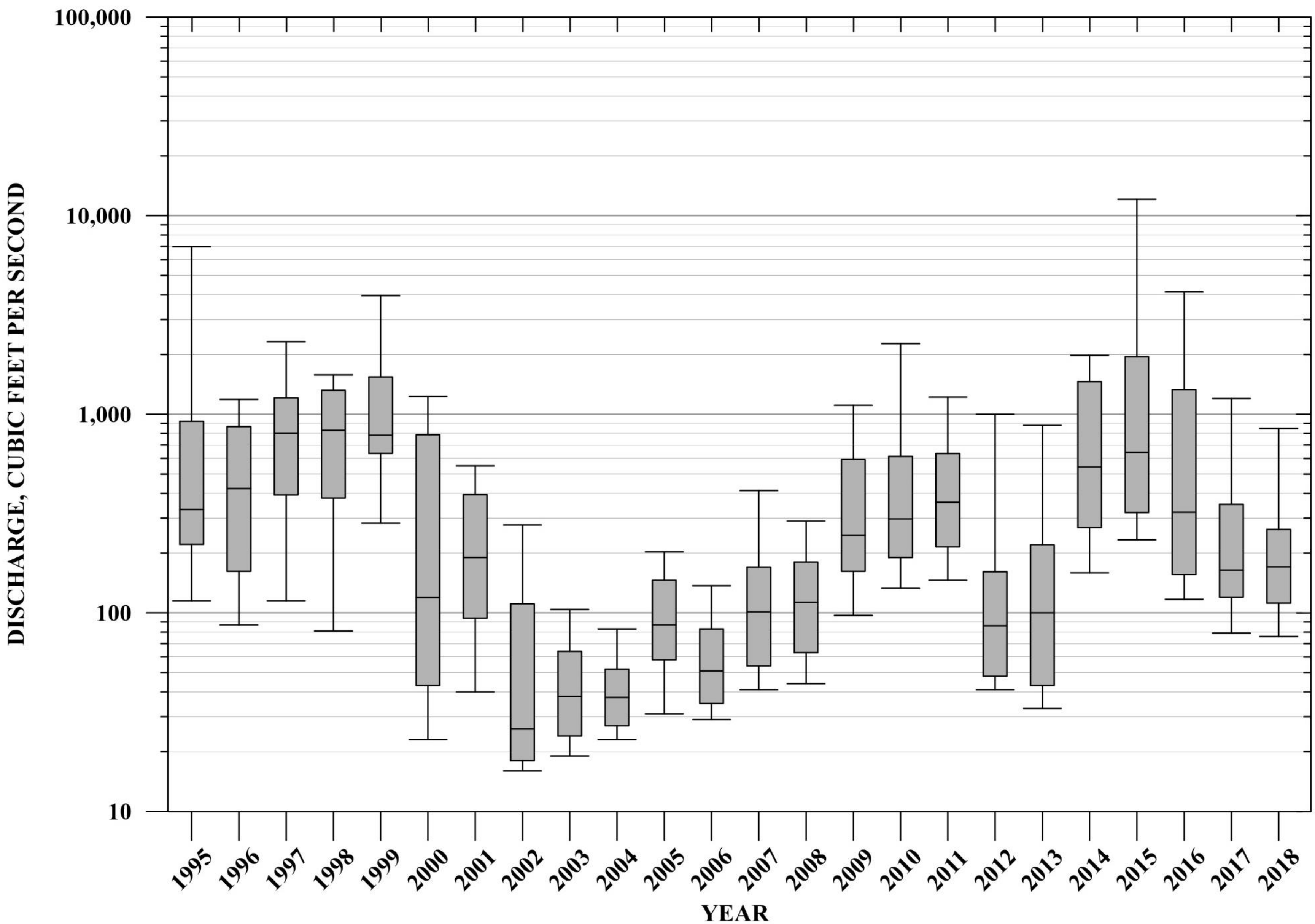


Figure 6-5. Streamflow boxplot, USGS 06764000, South Platte River at Julesburg, Reach 9

7. RIVER SALINITY INFLUENCES

In this report, the general term “salinity” is used when discussing Total Dissolved Solids (TDS) concentrations, which is a measure of all salt forms in water. Specific conductance or electrical conductivity are indirect measures of salinity and are often measured due to low cost and simplicity. Specific conductance measurements have been converted to TDS concentrations to provide a more robust dataset for analysis.

South Platte River salinity as the river exits the mountains is a baseline for evaluating impacts as the river flows through the basin. Natural geologic sources, small volume wastewater discharges, and mine runoff contribute to the baseline salinity. The limited salinity data available in the mountains suggests that the baseline salinity concentrations as the river exits Waterton Canyon are about 200 mg/l.

Human derived sources of salinity occur from municipal wastewater treatment facility (WWTF) sewage effluent, agricultural soil and water amendments, road deicing solutions, livestock waste, produced water from oil and gas development, and industrial sites. Salts from these sources are transported to the South Platte River by tributaries, surface runoff, groundwater flow, and direct discharge.

As the South Platte River flows through the basin it receives municipal WWTF effluent, industrial discharges, agricultural return flows, geologic formations, and surface runoff. Identifying South Platte River salinity sources, that can change daily, is challenging due to the large number of point and non-point sources. Point sources include discharges from a discrete location, for example municipal or industrial facility effluent discharge pipes or water impoundments with discharge structures. Non-point sources include discharges over an area, like urban stormwater runoff, cropland runoff, or groundwater flow.

The Colorado Department of Public Health and Environment (CDPE), Water Quality Control Division (WQCD) is responsible for implement the state water quality statues and rules. The WQCD issues discharge permits and requires effluent discharge and water-quality monitoring.

MWRD routinely measures water quality at several sites in the upper reaches on the same day each month and in the lower river reaches on a different day each month (Table 7-1, Figure 5-2, Figure 5-3, Figure 5-4). Streamflow conditions may be inconsistent between the upper and lower reaches due to runoff between the different sampling days. However, these MWRD data are the best available for assessing water-quality under relatively consistent streamflow conditions from the Metro area to Julesburg.

Salinity concentrations along the South Platte River measured during the spring and summer months of 2017 are shown on Figure 7-1. The overall trend is for increasing salinity levels with downstream distance from Waterton Canyon. The dilution effect of snowmelt runoff can be seen with salinity concentrations initially decreasing in the spring and then rising as the runoff is exhausted. The most upstream sampling location is at 64th Avenue in Denver, which is located immediately upstream of the MWRD’s Robert W. Hite water treatment facility.

The approximately 400 mg/l decrease in TDS concentration between the Weld County Road 28 (mile 63.5) and Milliken (mile 77.1) sites during May (Figure 7-1) was due to a runoff event in

Saint Vrain Creek that occurred between the sampling dates at these sites. This illustrates that the pre-spring runoff TDS concentrations of about 700 mg/l can be reduced significantly by tributary spring runoff. As the runoff dilution effect diminishes over the summer and streamflow decreases, the TDS concentrations steadily rise during June, July, and August, with the greatest increases in the lower basin. The lower basin increases could be due to irrigation return flow from ditches or migrating groundwater reaching the river.

Table 7-1. Metro Wastewater Reclamation District (MWRD) water-quality sampling locations

Monitoring Location	Description	Distance from Waterton Canyon, miles
SP-64	South Platte River at 64th Avenue	27.7
NFE-PC	MWRD North Final Effluent	28.0
SFE-PC	MWRD South Final Effluent	28.0
SPR-CC	South Platte River 100 yards upstream confluence Clear Creek	29.2
SP-88	South Platte River at 88th Avenue	31.5
SP-104	South Platte River at 104th Avenue	34.9
SP-124	South Platte River at 124th Avenue	39.1
SP-160	South Platte River at 160th Avenue	45.5
SP-RD8	South Platte River at County Road 8	48.5
SP-FTL	South Platte River at Colorado Highway 52 in Fort Lupton	53.4
SP-RD18	South Platte River at Weld County Road 18	56.8
SP-RD28	South Platte River at Weld County Road 28	63.5
MILLIKEN	South Platte River at Milliken	77.1
KERSEY	South Platte River at Kersey	95.4
GOODRICH	South Platte River at Goodrich	130.2
FORTMORGAN	South Platte River at Fort Morgan	147. 5
HILLROSE	South Platte River at Hillrose	166.7
ILIFF	South Platte River at Iliff	209.4
CROOK	South Platte River at Crook	225.3

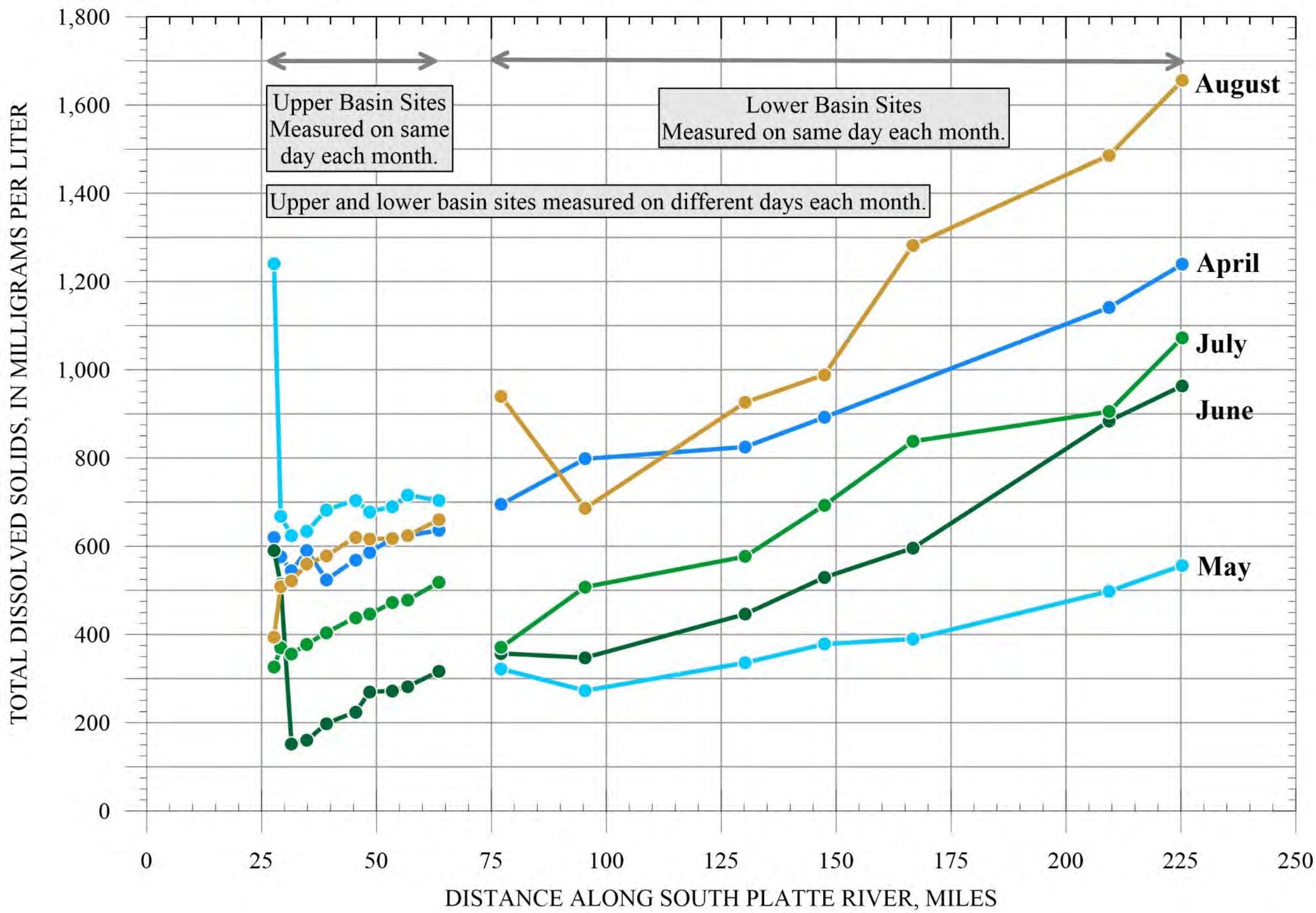


Figure 7-1. Salinity increases with downstream distance during summer months in 2017 (MWRD synoptic data)

7.1 Municipal Wastewater

There are many types of municipal and industrial facilities that discharge water to the South Platte River. Municipal WWTF can be large salinity sources because they can have high effluent discharges, often do not treat explicitly to reduce salinity, and discharge permits may not have salinity limits.

Municipalities and other water users with rights to transbasin water diversions appear to be increasing the baseline salinity in the South Platte River. Transbasin water imported from Colorado's western slope is 100-percent consumptive, which means that the water can be reused to extinction and the unconsumed portion is not required to return to the river[2]. Municipalities with transbasin water rights that can maintain dominion and control of its effluent, can repeatedly remove an equal volume of water from the river as it replaces with effluent. For example, the low-salinity, transbasin water is diverted, used as a water supply, wastewater is collected, and treated to meet discharge permit requirements. If the effluent is stored in off-channel reservoirs, the water-rights holder gets credit for the volume of treated effluent that is discharged back to the river. The municipality can then remove this credited volume of water from an upstream river reach.

This process intercepts low salinity water and prevents it from flowing through the basin. Freshwater is replaced by higher salinity effluent. Diversions can remove all the river's flow. Streamflow increases downstream of these diversions as tributary streamflow, groundwater inflow, and more effluent flow into the river.

There are hundreds of industrial and municipal WWTF discharging into the South Platte River and its tributaries. Most of these facilities are in the more densely populated areas in the upper basin, but they occur throughout the basin. Municipal wastewater effluent has been reported to increase salinity by a factor of about 1.5 of the source water concentration (Brusseau and others, 2004). This salinity increase appears to be low based on data available for this study.

The Metro Wastewater Reclamation District (MWRD) operates the largest municipal wastewater facilities in the basin. The Robert W. Hite and Northern WWTF are the largest MWRD effluent-discharging facilities. The effluent discharge volume and salinity were analyzed to provide examples of municipal wastewater operations. The Hite facility was in operation for the entire 1995-2018 study period and the Northern facility became operational in 2017. Effluent TDS concentrations for the Hite facility were available for 1995-2018 and effluent discharge rates were available for 2013-2017.

The Hite Facility has north and south plant effluent outfalls that discharge to the South Platte River. The TDS concentrations are typically between 450-600 mg/l, with occasional concentrations of 600-880 mg/l (Figure 7-2). Total effluent discharge is typically 180-220 cubic feet per second (cfs) (116-142 million gallons per day) with periods in 2015-2016 up to 300 cfs. The higher salinity and higher discharges in 2013, 2015, and 2016 are correlated to extended high streamflow periods, but cause-and-effect relationships were not investigated. Assuming the source water had TDS concentrations of about 200 mg/l, these data indicate that municipal water use can result in TDS increases of 250 to 700 mg/l.

[2] City and County of Denver v. Fulton Irrigating Ditch Co., Colorado Supreme Court, 1972

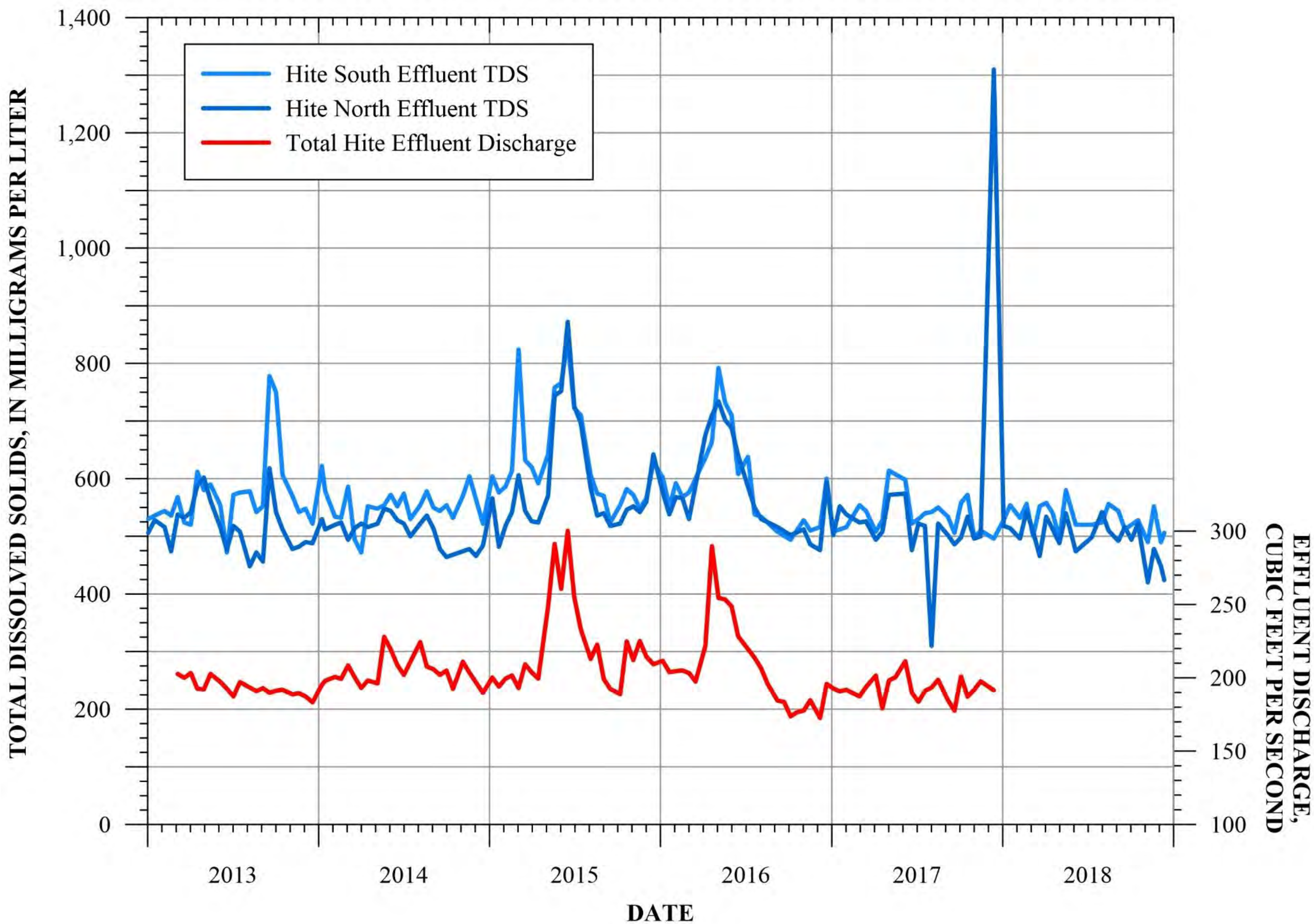


Figure 7-2. Metro Wastewater Hite treatment facility effluent salinity and discharge

The effect of municipal effluent discharge on the South Platte River depends on the relative salinity concentrations and discharges. Adding a small volume of high concentration effluent to a large streamflow volume will have little effect. Whereas, a high relative effluent discharge to low streamflow will have a larger effect. As an example, the MWRD measures salinity up and downstream of its Hite facility. The TDS concentrations downstream of the effluent discharge (Figure 7-3, green line) is consistently lower than the upstream concentrations as shown on Figure 7-3 (brown line). In this example, the effluent salinity is lower than the upstream river and the effluent is lowering the river salinity concentrations. However, the Hite effluent salinity is 200-400 mg/l higher than the river flow at Waterton Canyon.

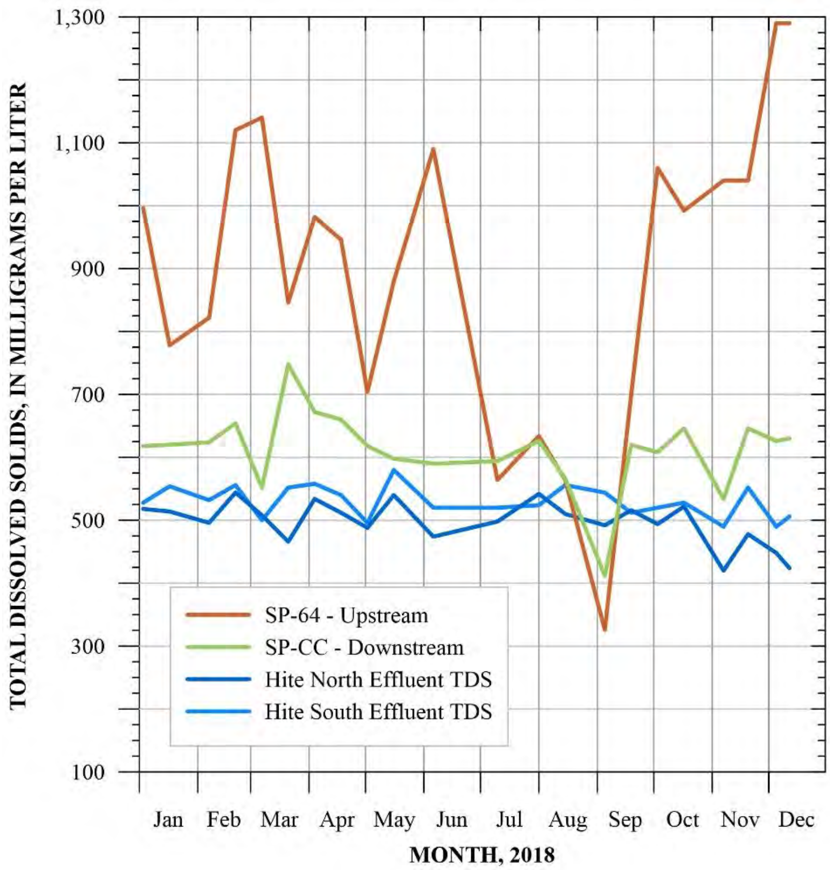


Figure 7-3. South Platte River and effluent salinity upstream and downstream of the Hite facility

Salinity concentrations upstream of the Hite facility (SP-64) are relatively high and variable (Figure 7-3, brown line). There are several municipal and industrial facilities in the area, including the Littleton-Englewood WWTF, the Suncore Energy Refinery, and Xcel Energy’s Cherokee Generating Station. These facilities have point source discharges and potentially non-point source discharges, like groundwater seepage, to the South Platte River that may contribute to the water quality. These types of facilities are present throughout the basin and contribute to the flow and water quality of the streams, rivers, and groundwater.

The effect of municipal wastewater and industrial discharges on the river's water quality depends, in part, on the streamflow. The South Platte River flows are highly variable and can fluctuate between nearly dry and flood stage over a short time. Effluent discharge at the Metro Hite facility tends to be consistent. When river flow is low, effluent discharge can be 95-percent or more of the total streamflow as shown in Figure 7-4.

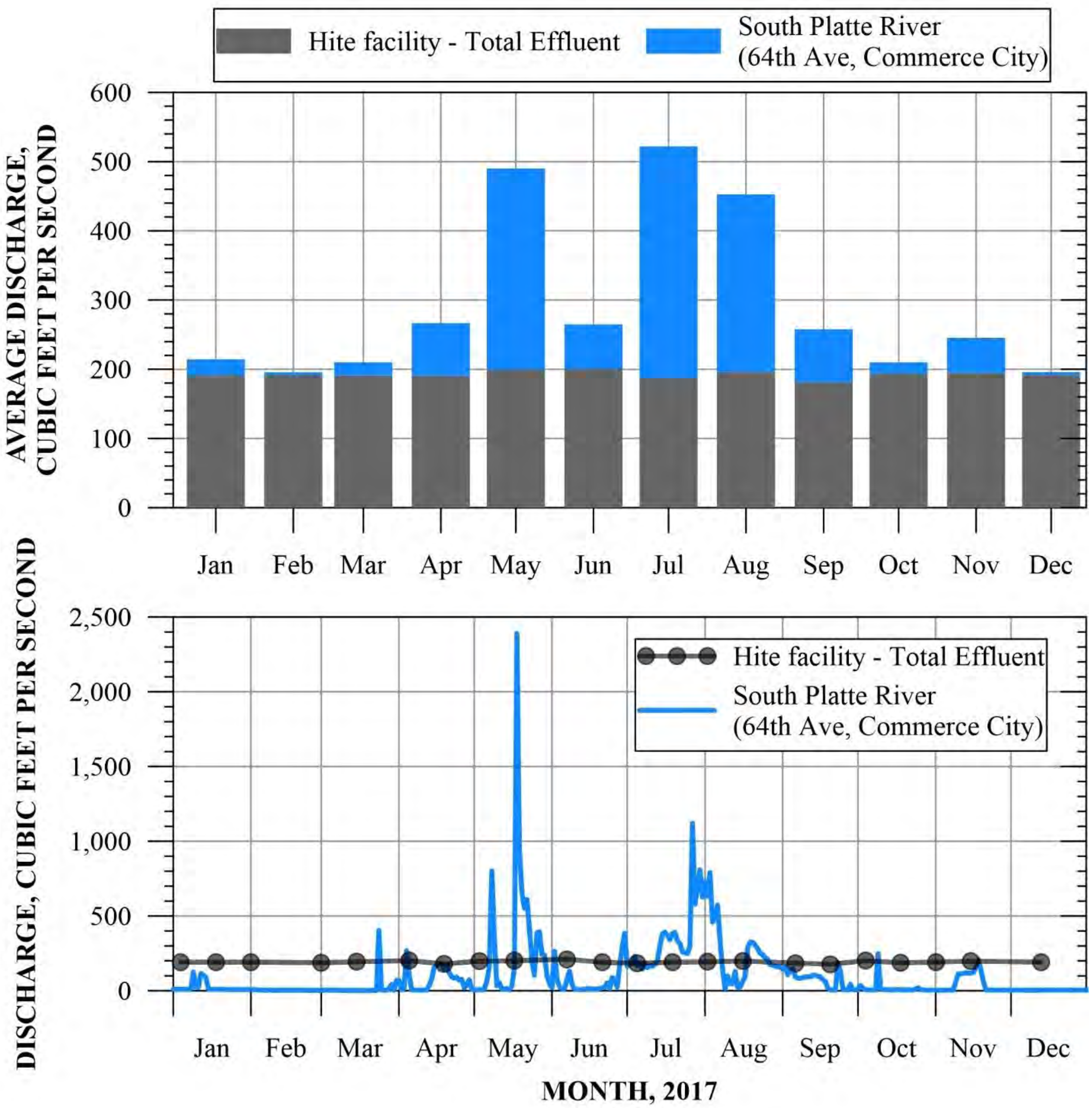


Figure 7-4. South Platte River streamflow can be dominated by effluent during low flow periods

7.2 Geologic Sources

In the South Platte Basin, geologic materials like rocks and soils are the primary naturally occurring salinity sources. Chemical weathering can mobilize the minerals in rocks and soils. The salt types and concentrations the rocks and soils contribute depend largely on the mineral composition, the mineral solubility, and the exposure to water.

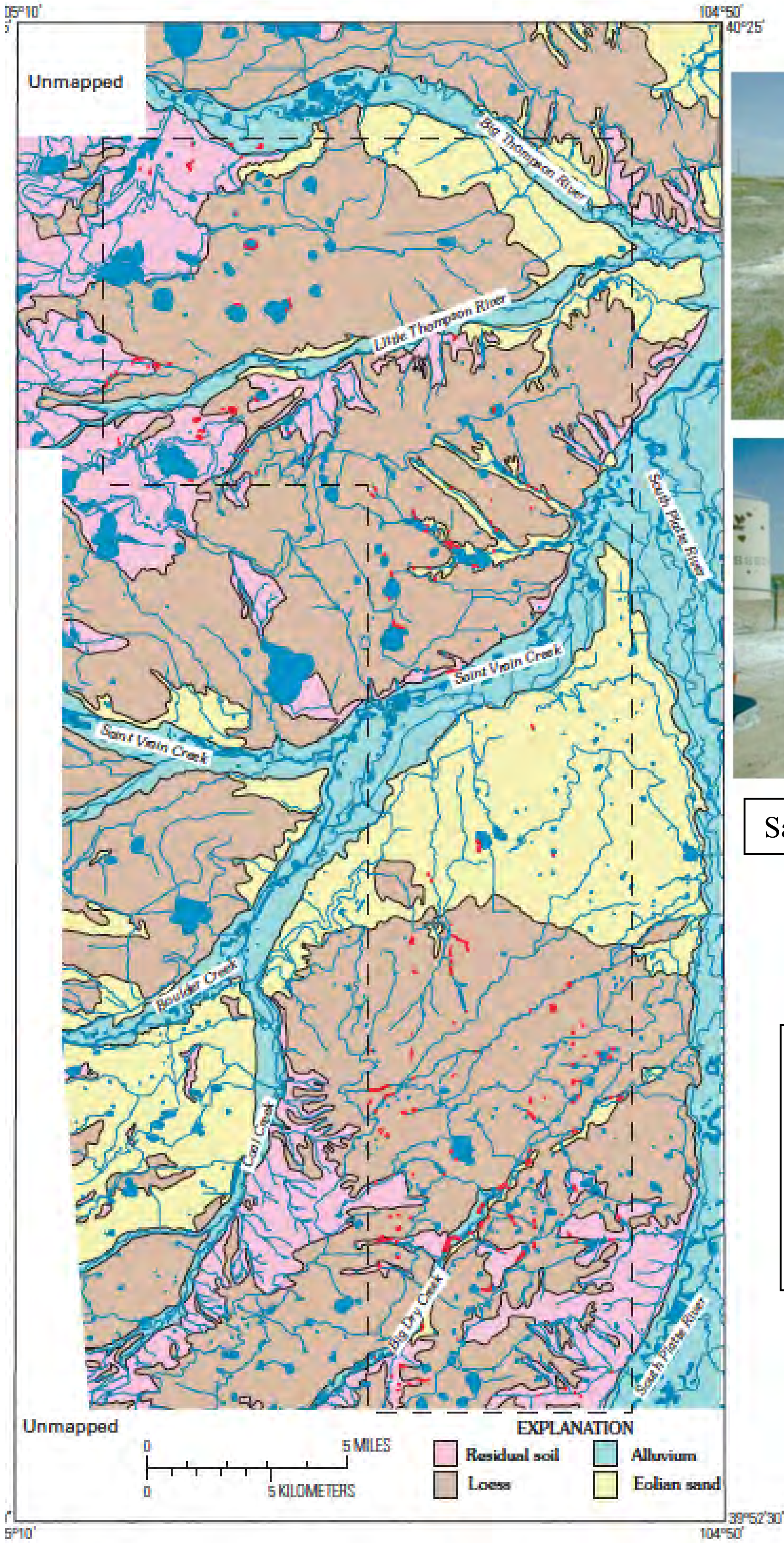
Saline soils are an indicator of underlying saline geologic formations and saline groundwater. Saline soils have been mapped along a belt that extends from Loveland southeastward to the northern Denver suburbs (Figure 7-5; Otton and others, 2005). The northern part of this belt is underlain by the Pierre Shale, which is a thick unit of marine strata deposited in the Western Interior Seaway. The saline soils were mapped throughout much of this area, preferentially in residual soils formed from underlying shale and along minor streams and ephemeral drainages (Figure 7-5; Otton and others, 2005). The saline soils are dominated by sulfate salts that are also present in the underlying groundwater (Flynn, 2002).

The Pierre Shale extends along the Front Range from the southern part of the basin where the South Platte River exits the mountains to near the Colorado-Wyoming state line in the north. It outcrops in a belt as much as 20 miles wide in the northern areas (Scott and Cobban, 1965) and narrows to a thin band in the Denver Metro area. The Cache la Poudre River, Big Thompson River, Saint Vrain Creek, and Big Dry Creek drainages cross wide swaths of the Pierre Shale. Conversely, the more southern drainages like Clear Creek and the South Platte River itself have little contact with the Pierre Shale.

The Pierre Shale, residual saline soils, and underlying groundwater contribute salts to the Cache la Poudre River, Big Thompson River, and Saint Vrain Creek, which are tributary to the South Platte River. The salinity concentrations in these streams immediately upstream of the South Platte River confluences is shown in Figure 7-6. Since 1995, each of these streams has had many months with average salinity concentrations over 800 mg/l. In the late 1990's the Big Thompson River commonly had concentrations of 1,500 to 2,000 mg/l. More recent statistics for 2018 are provided in Table 7-2. Assuming these streams have salinity concentrations of about 200 mg/l as they exit the mountains, the relatively high concentrations of 700 to 1,000 mg/l may be due, in part, to the influence of the Pierre Shale in these drainages. Municipal wastewater effluent and agricultural activity are present in these drainages and they also contribute to stream salinity.

Table 7-2. Total Dissolved Solids Statistics for select tributary streams in 2018

	Saint Vrain Creek	Big Thompson River	Cache la Poudre River
Count	8	36	35,043
Mean	735.5	1,020.9	714.2
Minimum	503.2	638.7	106.9
Maximum	829.6	1,460.0	934.4



Saline soils in the mapped area

Residual soil and loess areas are underlain by the Pierre Shale, which is a primary source of saline soils that contribute salts to the South Platte River tributaries along the Front Range.

Figure 7-5. Surficial geology with mapped saline soils shown in red (Otton et.al, 2005)

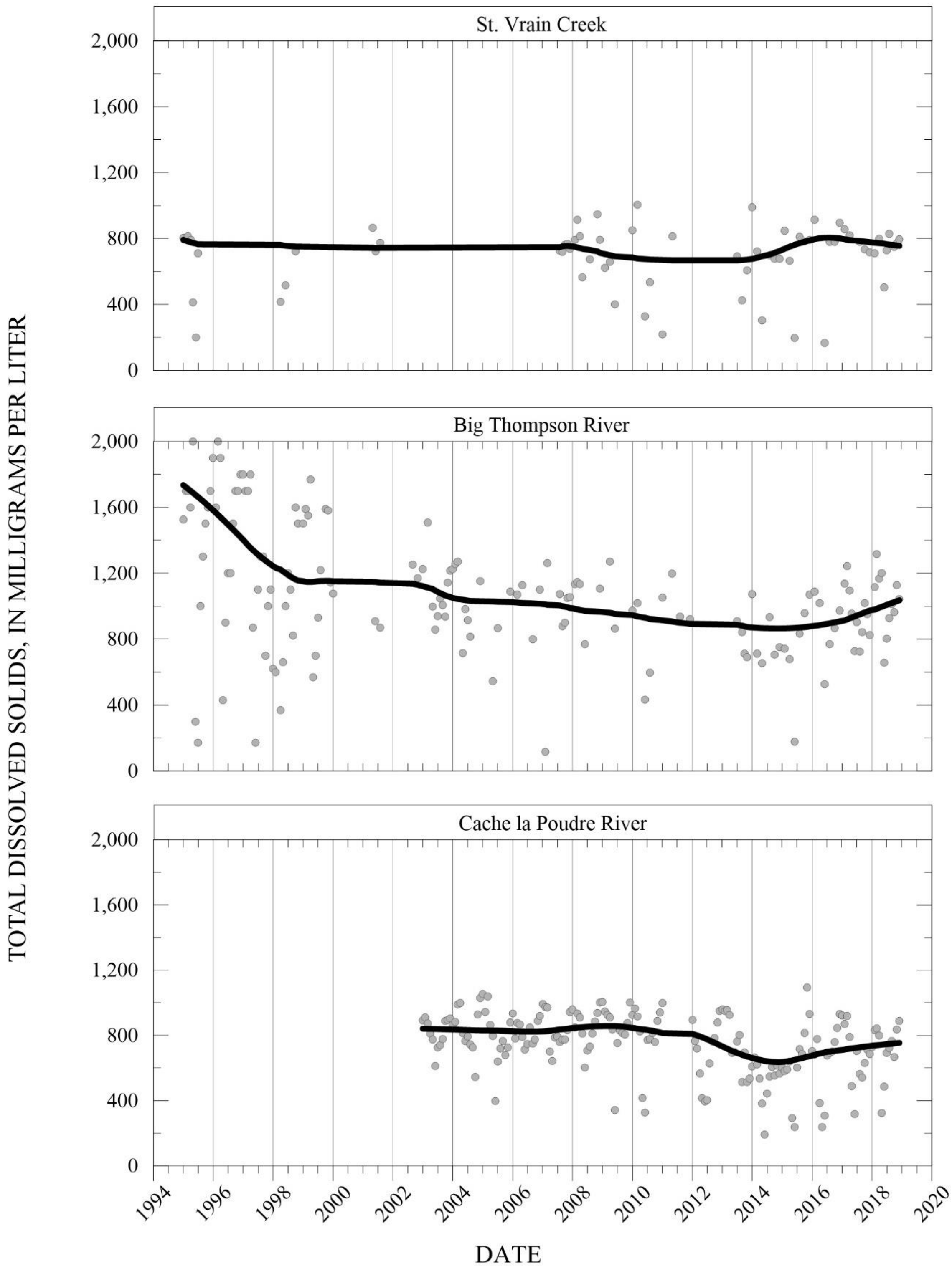


Figure 7-6. Monthly average Total Dissolved Solids in South Platte River tributaries, with LOWESS smoothing curve

7.3 Irrigated Agriculture

Irrigated agriculture is the dominant water user in the South Platte Basin. There are approximately 1.38 million acres of irrigated land in the basin (including the Republican Basin), which is 40-percent of Colorado's irrigated acres (South Platte Basin Implementation Plan, 2015). Most of the agricultural production in the basin requires irrigation to generate economically viable crop yields.

Statewide, 89-percent of water is used for irrigated agriculture, 7-percent is used by municipalities, and about 4-percent is used by large industries. Within the South Platte Basin, irrigated agriculture accounts for 85-percent of total water diversions (Colorado Water Plan, 2016). However, while irrigated agriculture withdraws the most water, the water that isn't consumed by crops and doesn't evaporate flows back to the river as surface flow or groundwater flow and is called irrigation return flows. Agricultural crops consume 20 to 85-percent of the irrigation water applied. The amount of consumptive use depends on soil type, crop, irrigation management, location, and irrigation method. Municipal consumptive use varies from 5-percent during the winter to 50-percent during the summer landscape irrigation season (Water Education Colorado, 2015).

The diversion and distribution of South Platte River water for agricultural use relies on a complex network of head gates and ditches (Figure 5-2, Figure 5-3, and Figure 5-4). There are 500 ditch service areas in the basin and the largest, Farmers Reservoir and Irrigation Company (FRICO/Barr Lake) Ditch, serves an area of over 100,000 acres (Basin Water Entities, 2019). Service areas are not typically fully irrigated because there are fallow fields, areas unsuitable for farming, and the land has been urbanized.

Agricultural fields can be a source of salinity due to natural soil chemical composition, soil amendments, and saline irrigation water. Irrigation return flows transport salts that are leached from the soils and from the applied irrigation water, back to river. This water can seep back into ditches, be discharged directly into the river, or it can return as groundwater flow in reaches where the river gains water from the alluvial aquifer.

Irrigation return flow is well known and the significance related to salinity can be seen most clearly in the lower basin reaches. The river gains water from the alluvial aquifer in these lower reaches (Litke, 1996; Litke, 1998; Hurr and others, 1975; Ruddy, 1984; Wind, 1994). There are several ditches downstream of Kersey that divert river water for irrigation and some of this water returns to the river. Although streamflow decreases between Kersey and Julesburg, the river salinity increases. Agricultural return flow and municipal wastewater are likely salinity sources in the lower reaches.

7.4 Industrial Sources

Industrial discharging activities, like municipal wastewater, are regulated by the Colorado Department of Public Health and Environment (CDPHE), which administers state programs that implement the federal Clean Water Act. The Clean Water Act protects the quality of Colorado's rivers, streams, lakes, reservoirs and groundwater (CDPHE, 2018). Colorado's water quality management process has several major steps including water quality monitoring, assessment and reporting; water quality classifications, standards and designations; total maximum daily load limits; source controls; and compliance.

Industrial discharges were not explicitly analyzed in this study. Obtaining discharge reports, monitoring data, and the wide range of potential water-quality impacts were beyond the scope of this project. However, the salinity concentrations and trends measured in the South Platte River and its tributaries are influenced by industrial sources and their wastewater effluents.

7.5 Other Sources

Stormwater runoff, road deicing solutions, oil and gas operations, and livestock waste are examples of other salinity sources in the South Platte Basin. The net affect of all salinity sources were reflected in the data analyzed for this study.

Identifying and quantifying specific salinity sources typically requires specialized monitoring. It is unknown whether the CDPHE or other entities have monitored salinity in stormwater runoff and other periodic, short-term discharges that would likely not be detected by routine, general monitoring. Publicly available data collected by CDPHE's routine and special water-quality monitoring networks have been incorporated into this study.

The process for contributing salts to the South Platte River differ depending on the source. Animal feeding operations (AFO), for example, cannot have direct discharges to surface water, unless it is during a 25-year, 24-hour precipitation event, and approved by the CDPHE. These releases are allowed because the high flows will dilute the release, so there is no harm to aquatic species. During normal operation, livestock waste must be contained in lined ponds and/or land applied according to permit conditions (CDPHE, 2013). There is the potential for land applied livestock waste to infiltrate into groundwater and flow to the South Platte River and its tributaries.

Oil and gas wells often extract groundwater that is called "produced water." This water can have very high salinity concentrations. Most produced water is re-injected into deep formations using injection wells. In areas with little or no shallow groundwater, produced water may be stored in surface pits and allowed to evaporate. About 20-percent of produced water is discharged to surface streams under an approved state discharge permit. There is a risk that produced water can be accidentally spilled or released and adversely affect surface or groundwater quality.

High-frequency, continuous monitoring is needed to detect the effect of random discharge events. The Northern Colorado Water Conservancy District (Northern) collected 15-minute electrical-conductivity data from 2002-2017. This analysis included three (3) South Platte River sites (Kersey, Masters, and Weldona) and the Cache la Poudre River at the South Platte confluence.

The Northern Water continuous data were evaluated for correlations between electrical conductivity increases and winter stormwater runoff. Although there were several dramatic electrical conductivity increases during winter months, they did not appear to correlate with winter snow precipitation and road deicing. The electrical conductivity increases could be instrument error or unidentified, short-term high-salinity discharge releases. The monitoring locations were also many miles downstream of the Denver Metro area, mountain highways, and cities where deicing agent use would be highest. Mixing and dilution over these distances would tend to decrease salinity increases.

8. SALINITY TRENDS

Water quality in the South Platte River depends on many factors. The river receives water from many sources, both natural and engineered. These sources are influenced by water management policies, population increases, climate changes, seasonal changes, and practices in the industrial, agricultural, and governmental sectors. These processes are continuously changing and the prevailing salinity is a blend of sources from across the basin.

Statistical-trend analyses can provide methods for predicting future conditions based on past conditions. These analyses assume that the cause and effect relationships can be largely explained by statistical models. These predictions are useful if conditions are constant or the changes are consistent and predictable.

This study does not attempt to make predictions of future water-quality conditions. The objective is to identify general water-quality trends that have occurred since 1995. Have water-quality concentrations remained constant and are insensitive to the many factors that influence the river? Is water quality improving or degrading over time? Can changes in water quality be correlated to changes in water-management practices?

Water-quality measurements tend to vary due to the many influences. This variability and the extremes can be important to water users that may be negatively impacted if their water's quality exceeds an acceptable range. Statistical measures are provided to describe this variability in numerical terms. Boxplots provide a visual method for evaluating the statistical characteristics in each reach by year. The boxplots show five percentiles of the data distribution. The box edges are the 25th and 75th percentiles[3]. The center line is the 50th percentile (median) and the whiskers represent the 10th and 90th percentiles. The maximum and minimum values were not used for the whiskers because these extreme values can be due to measurement errors that are not representative.

Individually, boxplots can indicate the properties of the distribution, such as spread and skewness. For example, if the median line is not centered in the box and the upper whisker is long, the distribution is skewed to higher concentrations. Side-by-side boxplots allow visual comparison of the water-quality in different reaches. Salinity boxplots for each reach are provided in Appendix B.

General trends, that remove most of the variability, are provided to give a visual sense of whether concentrations are increasing or decreasing. Statistics and visual trends, however, can strongly influenced by the flow conditions that change from year to year. The water-quality data were analyzed to remove flow effects that can mask changing chemical loads (Section 8.5, Flow-Adjusted Trends).

[3] A percentile is the value where a certain percentage of all the values is less than that number. For example, if the 25th percentile is 378 mg/l, 25-percent of the concentrations are less than 378 mg/l.

8.1 Streamflow Influence

Higher salinity concentrations occur when there is less freshwater from snowmelt runoff or precipitation runoff in the hydrologic system. Understanding how salinity varies with streamflow can help water users manage the resource. The WRTDS (Weighted Regressions on Time, Discharge, and Season) analysis provides concentration versus discharge relationships (Hirsch and others, 2010). This analysis characterizes how salinity concentrations have changed over time and under different streamflow conditions.

Salinity at three river discharges and in each decade since 1995 were analyzed. The selected streamflow discharge for analysis were based on the flows in each reach. The "low" flow discharge was approximately the median flow for dry years. The "moderate" discharge was approximately the median for "normal" flow years and the "high" discharge was in the 75 to 90 percentile range for normal flow years. The flows used for each reach are provided in Table 8-1. Streamflow boxplots for each reach are provided in Appendix A. Conditions in July during 1998, 2008, and 2018 were selected to evaluate changes over these decades. If there were no data available on those dates the years were modified to a period with data. This analysis is complementary to the results provided in Section 8.5 Flow-Adjusted Trends.

Table 8-1. Stream discharge for each reach used in WRTDS analysis (in cubic feet per second)

Reach*	Low	Moderate	High
1	100	200	300
2	150	300	400
3	250	400	500
4	300	400	500
5-6	--	--	--
7	500	750	1,000
8	100	500	1,000
9	100	500	1,000
Saint Vrain Creek	125	200	250
Big Thompson River	50	100	150
Cache la Poudre River	50	150	200

* See Figure 5-1 for reach locations
-- = no discharge data available and not enough salinity data for analysis

In the upper reaches, salinity concentrations are highest at low streamflow and decrease as streamflow increases. Over time, the salinity at each streamflow has been increasing. Reach 1, for example, at a streamflow of 100 cfs salinity was about 360 mg/l in 1995 and in 2018 it was about 470 mg/l (Figure 8-1). Reach 2 (Figure 8-2), 3 (Figure 8-3), and 4 (Appendix C) have generally linear salinity increases over time. Reach 1 salinity, however, was decreasing from 1995 to about 2005 and it has been increasing since 2005. This trend occurs at low (100 cfs), moderate (200 cfs), and high (300 cfs) flows (Figure 8-1A).

Reach 1 includes the mountains, Chatfield Reservoir, and upstream part of the Denver Metro area (Figure 5-2). This analysis indicates that salinity inputs to Reach 1 have increased noticeably since 2005.

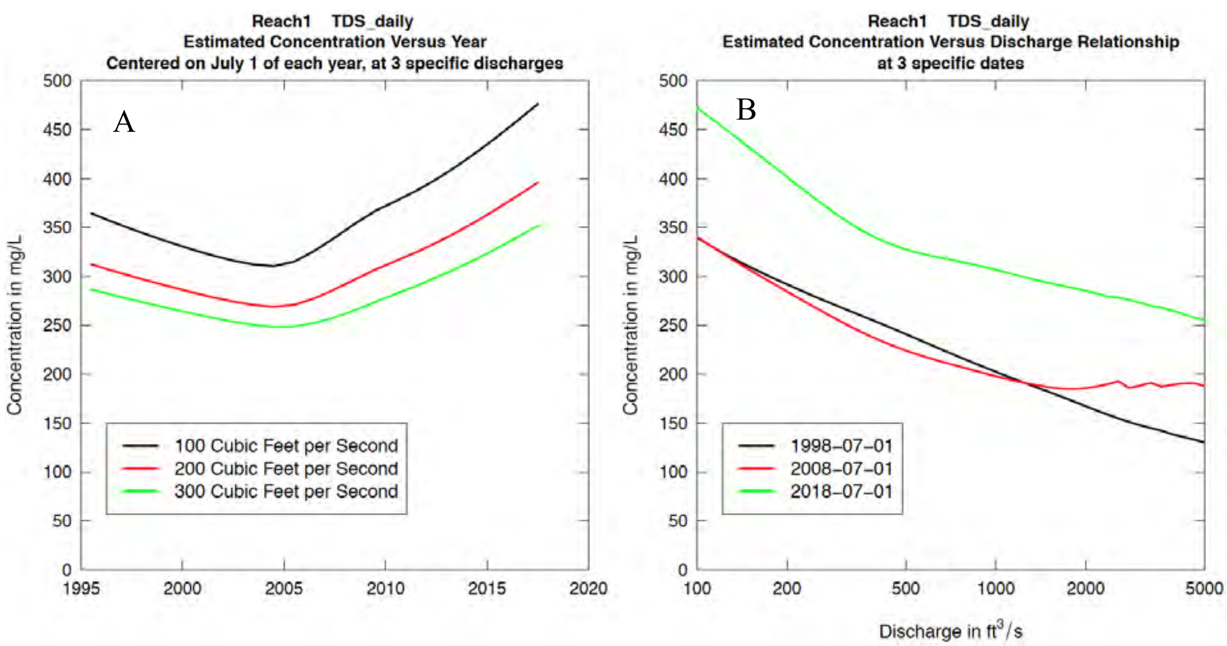


Figure 8-1. Estimated Total Dissolved Solids concentrations by year (A) and streamflow (B) for Reach 1

Reach 2, which receives effluent from the Littleton-Englewood WWTF and Cherry Creek (Figure 5-2) has had consistently rising salinity concentrations since 1995 (Figure 8-2). By 2018 the low flow (100 cfs) concentrations had reached about 650 mg/l, which is an increase of about 450 mg/l relative to the flow discharging at Waterton Canyon.

Reach 3, which receives the Metro wastewater facility effluent (Figure 5-2), has shown the least change over time of the upper basin reaches (Figure 8-3). This is at least partially due to Metro effluent concentrations being in the 500-600 mg/l range under normal flow conditions since 1995 (Figure 7-2). Since the Metro effluent has had consistent salinity concentrations the salinity increases over time are likely due to other sources.

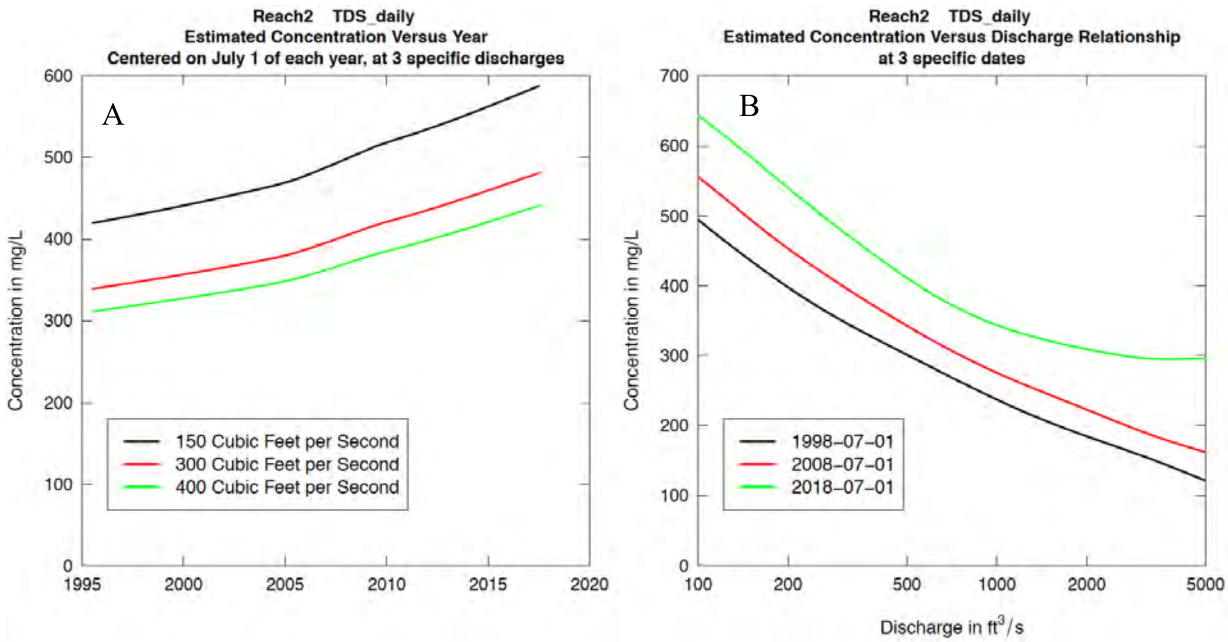


Figure 8-2. Estimated Total Dissolved Solids concentrations by year (A) and streamflow (B) for Reach 2

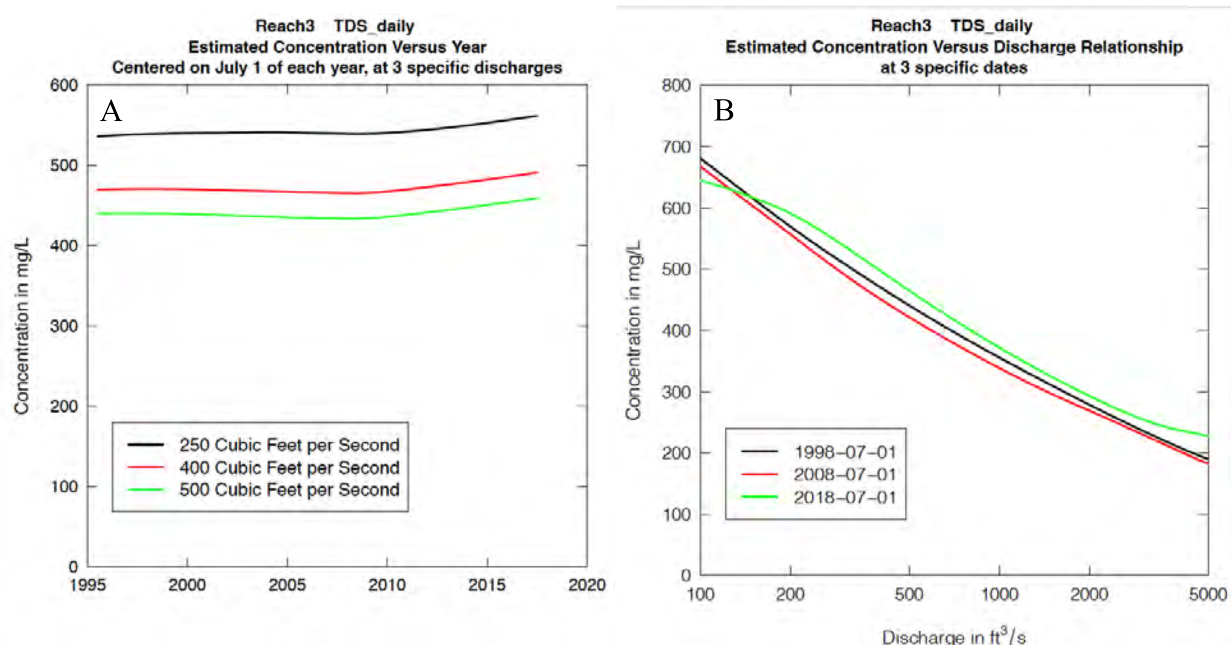


Figure 8-3. Estimated Total Dissolved Solids concentrations by year (A) and streamflow (B) for Reach 3

The upper basin reaches (1-4) have low-flow salinity concentrations of about 500 to 700 mg/l (Table 8-2). Lower basin Reach 7 has low-flow concentrations of about 650 mg/l (Table 8-2, Appendix C). Reach 8 has low-flow concentrations approaching 1,000 mg/l and Reach 9 is approaching 1,200 mg/l. These salinity levels will reduce crop yields for nearly all crops and will require treatment for most uses.

The lower reaches and tributaries have salinity-discharge relationships that are similar to the upper reaches, with higher salinity at lower streamflow. Salinity trends in Reach 7, the Big Thompson River, and the Cache la Poudre River have generally been declining over time (Appendix C). A declining salinity trend in Reach 8 has flattened in recent years. Reach 9 has an increasing trend over time at the lowest streamflow but decreasing salinity at higher flows. However, these trends are poorly defined and uncertain due to the lack of data.

During hot and dry conditions, the demand for water increases, streamflow decreases, and salinity increases. This analysis illustrates that the salinity hazard for irrigated agriculture is at its highest during periods of low streamflow Water users that can be negatively affected by salinity may need to take mitigating measures to reduce impacts when these conditions occur. A summary of the 2018 salinity concentrations during low-flow periods is provided in Table 8-2. The salinity-discharge relationship changes over time and at different streamflow, for all reaches and tributaries are provided in Appendix C.

Table 8-2. Low streamflow salinity (TDS) concentrations in 2018 for each reach (in milligrams per liter)

Reach	Low Streamflow (cfs)	Low-flow Total Dissolved Solids (mg/l)
1	100	475
2	150	680
3	250	570
4	300	560
5-6	--	--
7	500	650
8	100	980
9	100	1,180
Saint Vrain Creek	125	810
Big Thompson River	50	800
Cache la Poudre River	50	580

-- = no discharge data available and/or not enough salinity data for the WRTDS analysis

8.2 Seasonal Trends

Seasonal trends were evaluated by compiling average monthly salinity concentrations. High streamflow during spring runoff has lower salinity concentrations. Late summer, winter, and spring months have lower flow and higher concentrations. Storms that generate substantial runoff can also lower salinity concentrations. The influence of these storms on the average monthly salinity depends on the duration and magnitude of the runoff. Streamflow graphs, statistical summary tables, and boxplots that aid interpretation of salinity variations are provided in Appendix A.

When evaluating salinity data keep in mind that concentrations of 500 to 1,000 mg/l will reduce yields of sensitive crops and concentrations over 1,000 mg/l reduce yields of most crops (Table 3-2). Drinking water taste degradation and scale starts to occur at 500 mg/l and treatment is required at concentrations over 1,000 mg/l (Table 3-1).

Seasonal salinity trends during 2015-18 for each reach are shown on Figure 8-4, Figure 8-5, and Figure 8-6. This recent period was selected as an example, previous years have similar seasonal trends. These graphs have the individual salinity measurements and the calculated average monthly salinity. These graphs also illustrate the data available for analysis. Upper basin reaches have much more data than the lower reaches and tributaries. The seasonal trends are better defined when more data are available. Reach 5 did not have enough data to calculate representative monthly averages (Figure 8-5) and Reach 6 has virtually no data and it was omitted.

During spring runoff salinity in the upper basin reaches 1-4 can approach 200 mg/l, which is about the concentration as the river exits the mountains (Figure 8-8). This illustrates the dilution effect that snowmelt runoff has on the river. Conversely, during low-flow periods salinity concentrations much higher than the monthly average can occur. These spikes are presumably due to short-term, high-salinity discharges from wastewater treatment facilities or other large salinity sources. These high-salinity pulses may be important if these flows are being diverted and stored for future use or groundwater recharge.

The lower basin reaches and tributaries tend to have much less data than the upper reaches, so the seasonal trends are not as well defined (Figure 8-5, and Figure 8-6). The exception is the Cache la Poudre River, which has abundant data collected by Northern Water. Lower salinity during spring runoff and higher salinity during low-flow periods is evident.

All reaches (Figure 8-8, Figure 8-5, and Figure 8-6) indicate an upward overall salinity trend from 2015-18. This is likely due to the decreasing streamflow trend during this period (Appendix A). Longer-term trends are discussed in the following sections.

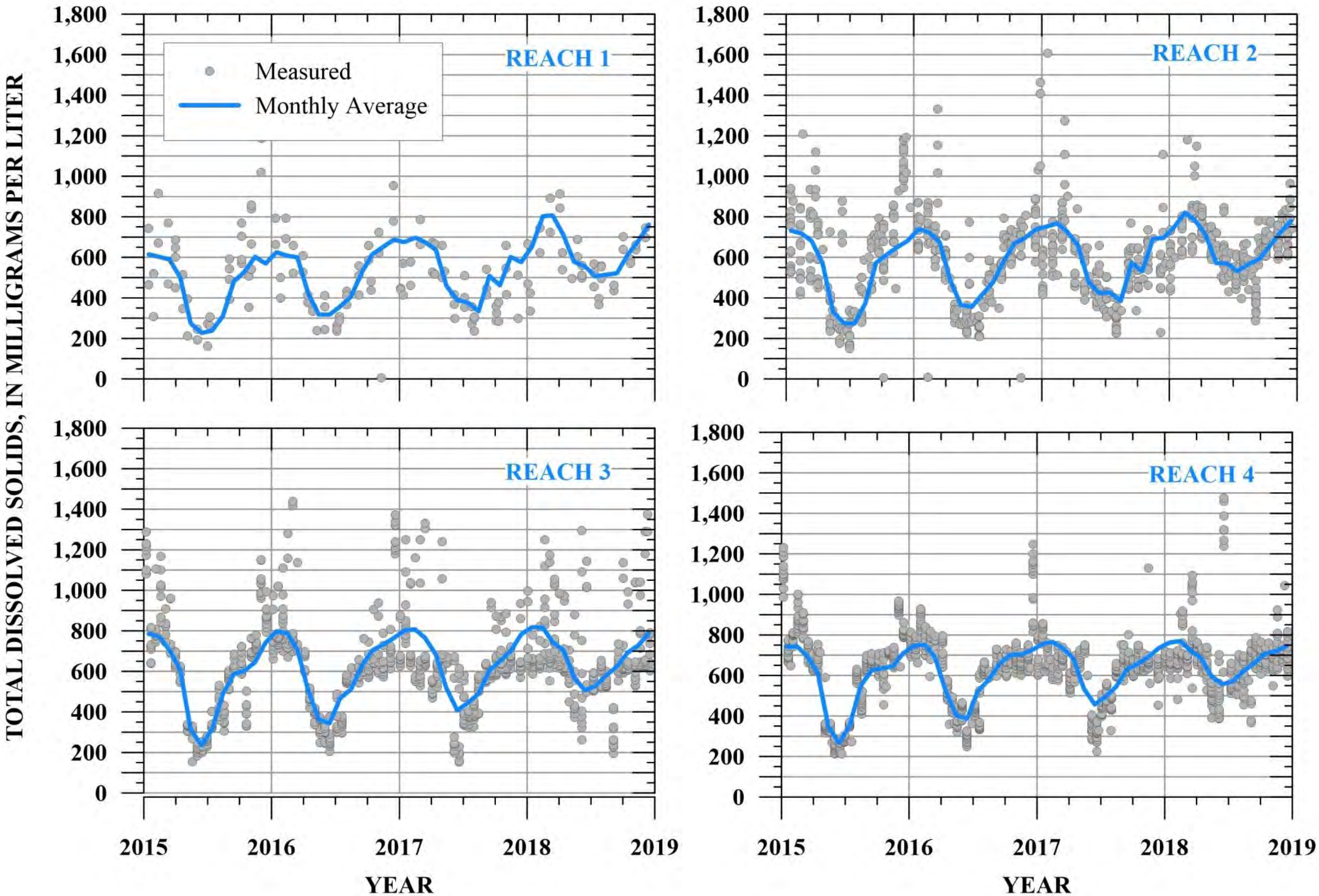


Figure 8-4. Seasonal salinity trends in South Platte River reaches 1 through 4

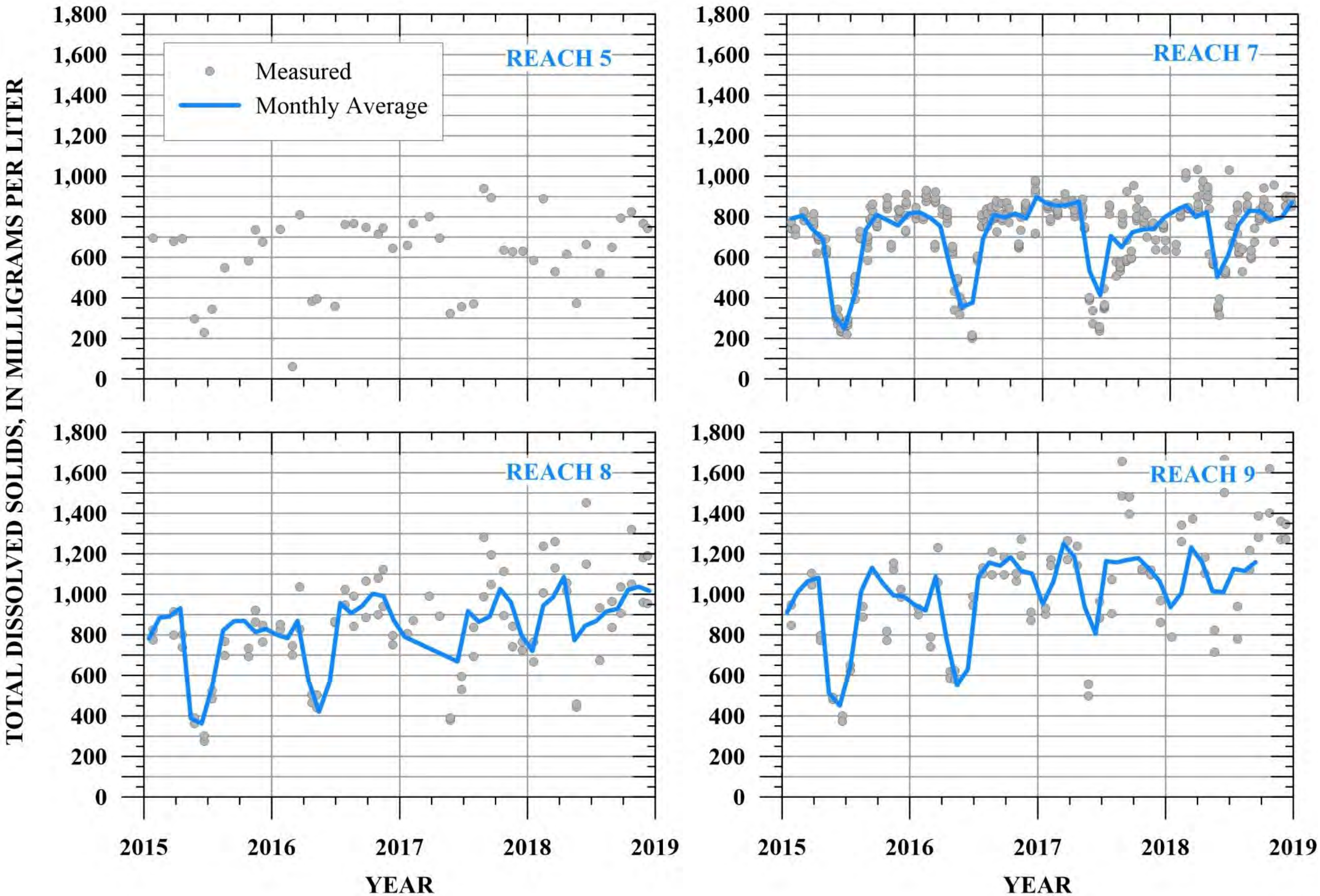


Figure 8-5. Seasonal salinity trends in South Platte River reaches 5, 7, 8, and 9

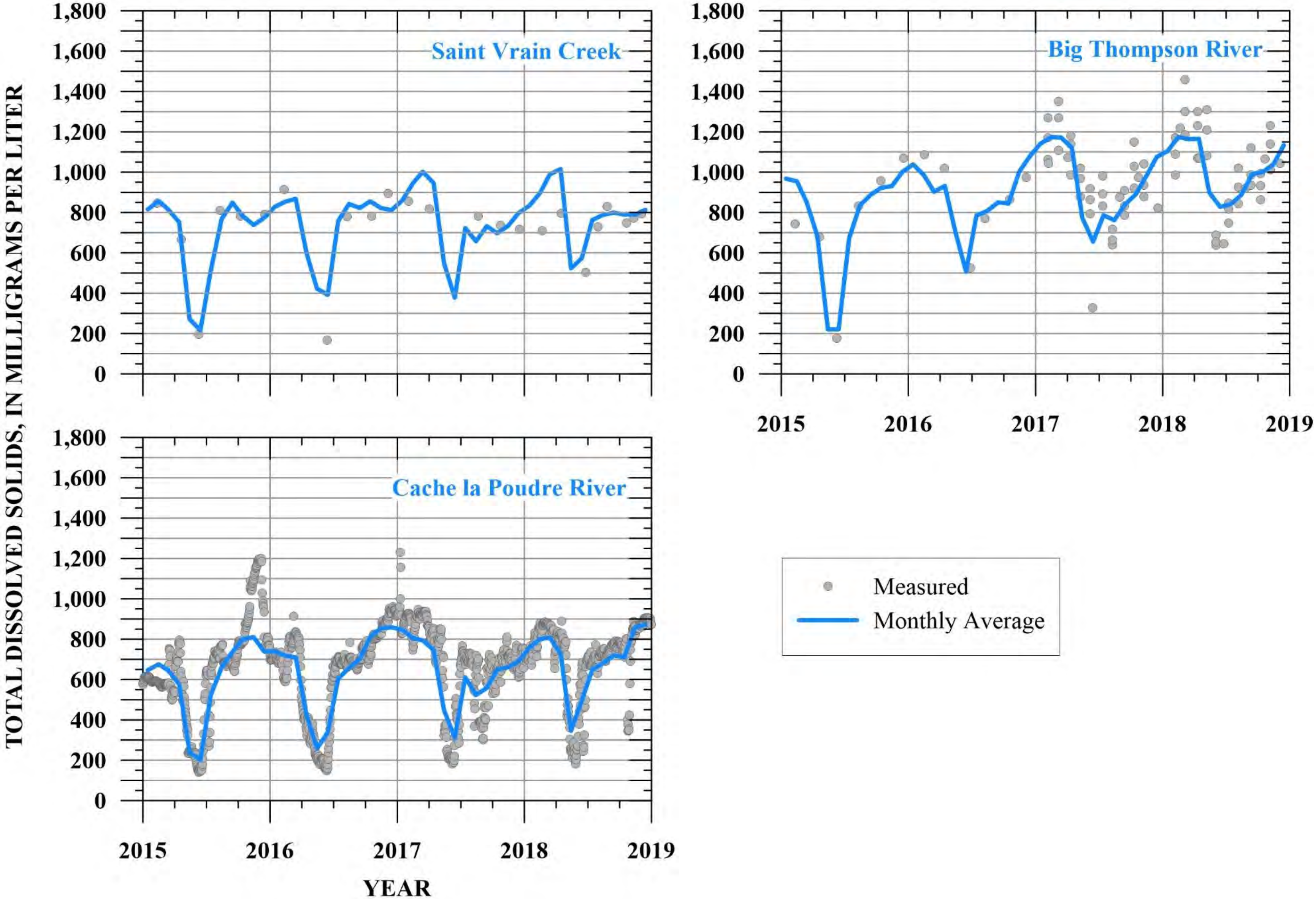


Figure 8-6. Seasonal salinity trends in select South Platte River tributaries

8.3 Seasonal Variability

The statistical analyses tend to minimize the extreme salinity concentrations in favor of more likely, average conditions. However, the South Platte River salinity variability can result in delivery of water with 500 mg/l on one day and 1,500 mg/l on another day at the same location. This variability may result in some water users being adversely affected if they obtain water on a day with extreme salinity concentrations.

The salinity variability for each month, from 1995 through 2018, for each South Platte River reach is summarized in boxplots. The boxes are defined by the concentrations at the 25^{th}, 50^{th}, and 75^{th} percentiles. The 75^{th} percentile, for example, means 75-percent of the values are less than the value and 25-percent are higher. The boxplot 'whiskers' presented in this section, extend to the maximum concentration or 1.5 times the interquartile range (e.g. 1.5 x (75^{th} concentration – 50^{th} concentration), whichever is less. Extreme salinity concentrations, outside of the whiskers, are also shown. Additionally, the width of the boxes shows the relatively number of samples available for each month. Thin boxes have few data available, wider boxes have more data.

Seasonality was considered by analyzing the data on a monthly basis. The range of salinity that has been measured in each reach from 1995 to 2018 is summarized in the Figure 8-7 boxplots. These boxplots show that salinity concentrations are typically lowest during May and June when snowmelt runoff is at its peak. Late runoff and summer rainstorms can contribute to lower July concentrations. Late summer, fall, and winter tend to have higher salinity concentrations. While the boxes show the concentrations where most samples have occurred, the whiskers show the extreme concentrations. For example, in Reach 1 the June median (50^{th} percentile) concentration is about 300 mg/l and shows the influence of snowmelt runoff. However, concentrations of 500 to 800 mg/l have also been measured in June (Figure 8-7).

The median salinity concentrations in Reach 3 are less than 800 mg/l in every month. However, there have been numerous measurements in the 1,000 to 1,400 mg/l range. An irrigator, recharge project, augmentation project, or water-storage project that receives water diverted from the South Platte River during these high-salinity conditions may find the water-quality unacceptable for use or requiring treatment.

In Reach 7 the median concentrations are consistently 800 to 900 mg/l, except during May and June. However, in every month, including May and June, there have been concentrations of 1,000 to 1,200 mg/l. Concentrations of 1,200 to 1,600 mg/l occur throughout the year in Reaches 8 and 9.

The Big Thompson River had the largest number of high salinity concentrations among the tributaries. These results are influenced by the large number of samples from the 1990's that had concentrations of 1,500 to 2,000 mg/l. More recently concentrations have been less than 1,400 mg/l with a median of less than 1,000 mg/l. Saint Vrain Creek and the Cache la Poudre River have had relatively few salinity concentrations that exceeded 1,000 mg/l.

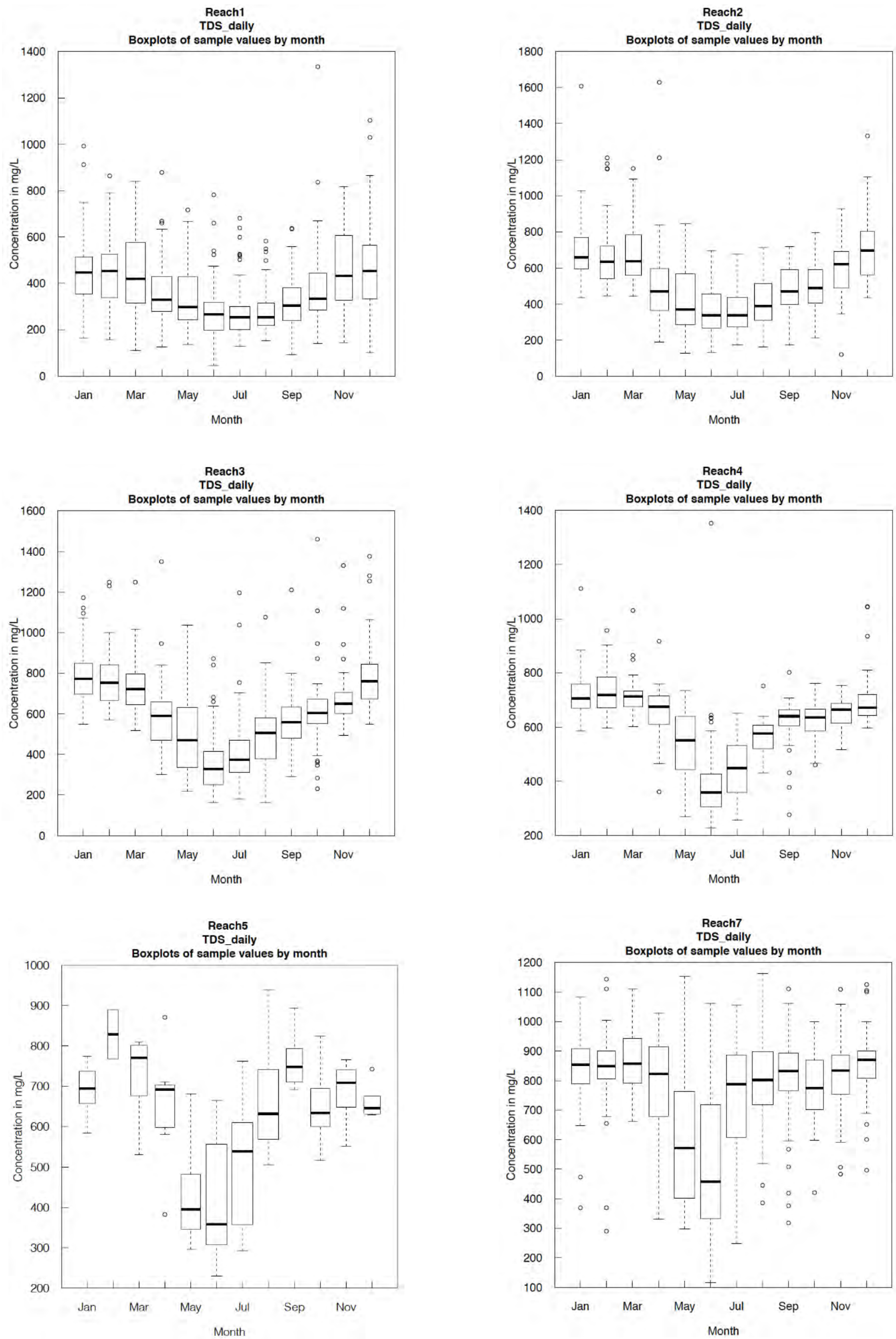


Figure 8-7. Boxplots of monthly Total Dissolved Solids concentrations for 1995-2018

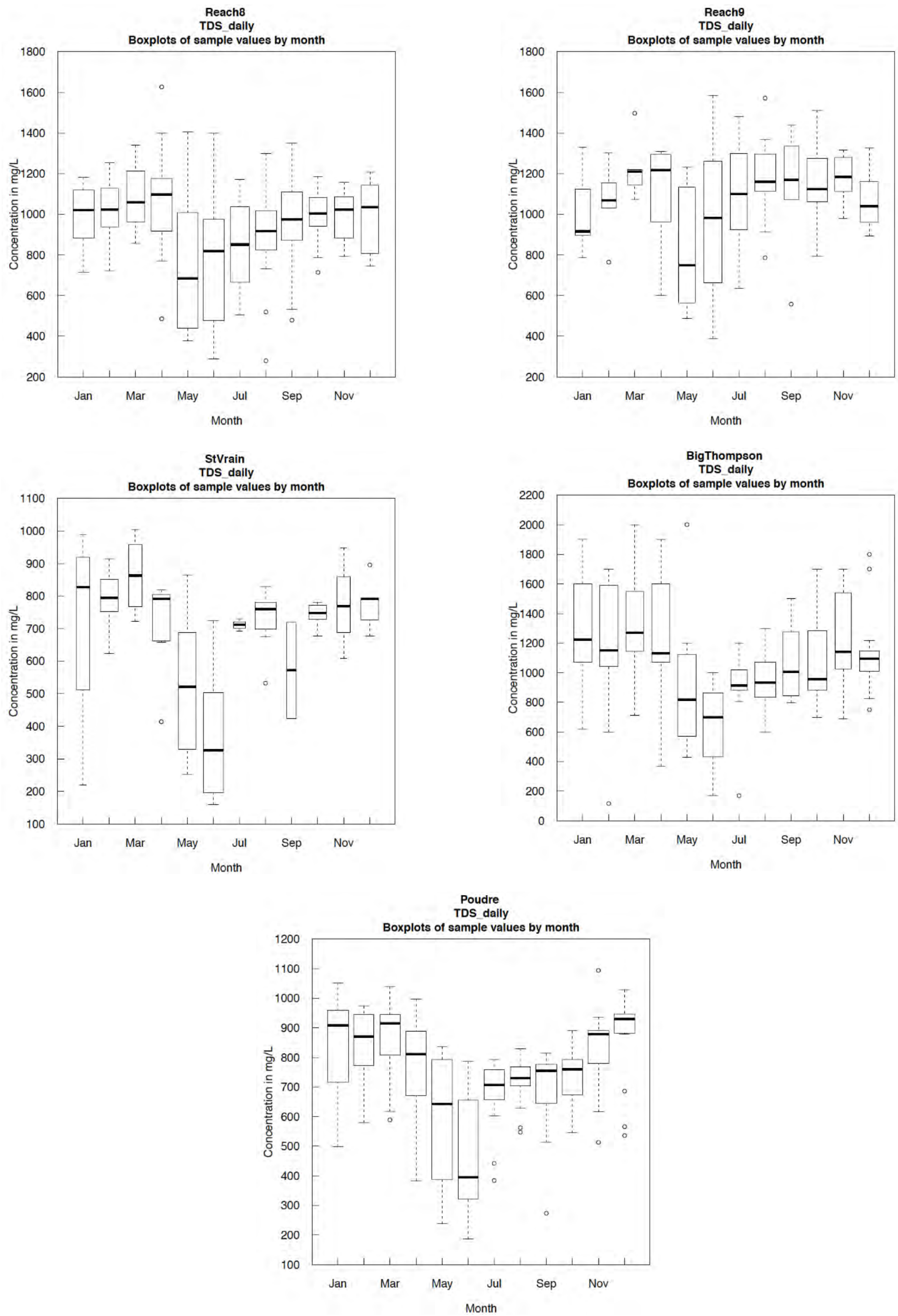


Figure 8-25. Boxplots of monthly Total Dissolved Solids concentrations for 1995-2018 – Continued

This analysis was limited by the available data. These data were generally collected at random times under random conditions. Salinity concentrations are constantly varying due to changing flows and changing inputs. Periodic salinity sampling may underestimate the variability and occurrence of high salinity concentrations. More frequent monitoring may indicate that even higher salinity concentrations occur.

Northern Water operated 15-minute electrical conductivity monitoring stations on the Cache la Poudre and South Platte River from 2003 to 2017. Select continuous monitoring data were reviewed and salinity concentration variations of 500 mg/l or more were measured over a few days. Salinity spikes approaching 2,000 mg/l were also recorded. These data have not been published by Northern and are, therefore, not provided here. When quality-control procedures are completed and these datasets are released, they may provide additional insights into salinity variability in these watersheds.

The cause of large salinity variations is currently unknown, but all types of wastewater treatment facilities, livestock operations, oil and gas facilities, etc. can have upset conditions that result in short-term release of higher salinity effluent than under normal operating conditions. These releases could result in periods of higher river salinity that would be exacerbated under low river flow conditions. Releases during high flow conditions would be diluted by the higher flow and result in smaller salinity increases.

8.4 Long-term Trends

Two methods were employed to evaluate long-term trends. The first was fitting a LOWESS trend line to the measured concentrations. The LOWESS trend line aids in visualizing the general pattern but may not represent the data mean because outliers have less influence. The second method accounts for year-to-year streamflow variations and is discussed in Section 8.5 Flow-Adjusted Trends. The salinity concentrations presented in this section are also provided in tabular form by year and by reach in Appendix B.

Salinity trends from 1995-2018 for each reach are shown on Figure 8-8. Salinity concentrations have increased with downstream distance, regardless of the year. The lowest concentrations are in Reach 1, they consistently increase downstream, with the highest concentrations in Reach 8 and 9 where it can exceed 1,400 mg/l.

The upper reaches, 1-4, have had generally consistent increasing average monthly concentrations. These reaches had salinity increases of about 250 mg/l from 1995 to 2018. Reach 5 and 6, which are between the Saint Vrain and Cache la Poudre confluences, do not have adequate data to evaluate trends.

Overall trends in Reach 7, below the Cache la Poudre confluence, were slightly decreasing from about 800 to 760 mg/l (Figure 8-8). Reach 8 was highly variable from 1995 to 2010 with monthly average concentrations from 200 to 1,600 mg/l. Decreasing concentrations from 2010 to 2015 was followed by an increasing trend from 2015 to 2018 and both may be due to streamflow trends.

Reach 9 had concentration trends like Reach 8 with a decrease from 2010 to 2015, followed by an increasing trend from 2015 to 2018 (Figure 8-8). There were several months in 2017-18 with monthly average concentrations of 1,400 to 1,500 mg/l. In 2018, the average salinity at Kersey (Reach 7) was 759 mg/l, Fort Morgan/Balzac (Reach 8) was 985 mg/l, and at Julesburg (Reach 9) it was 1,233 mg/l.

The apparent declining salinity trends in the lower reaches was unexpected since the upper reaches have been increasing. The salinity concentration variability and trends are influenced by streamflow and the many different salinity sources in the basin. A discussion of these trends, including contributing factors and possible causes, is provided in Section 12 DISCUSSION.

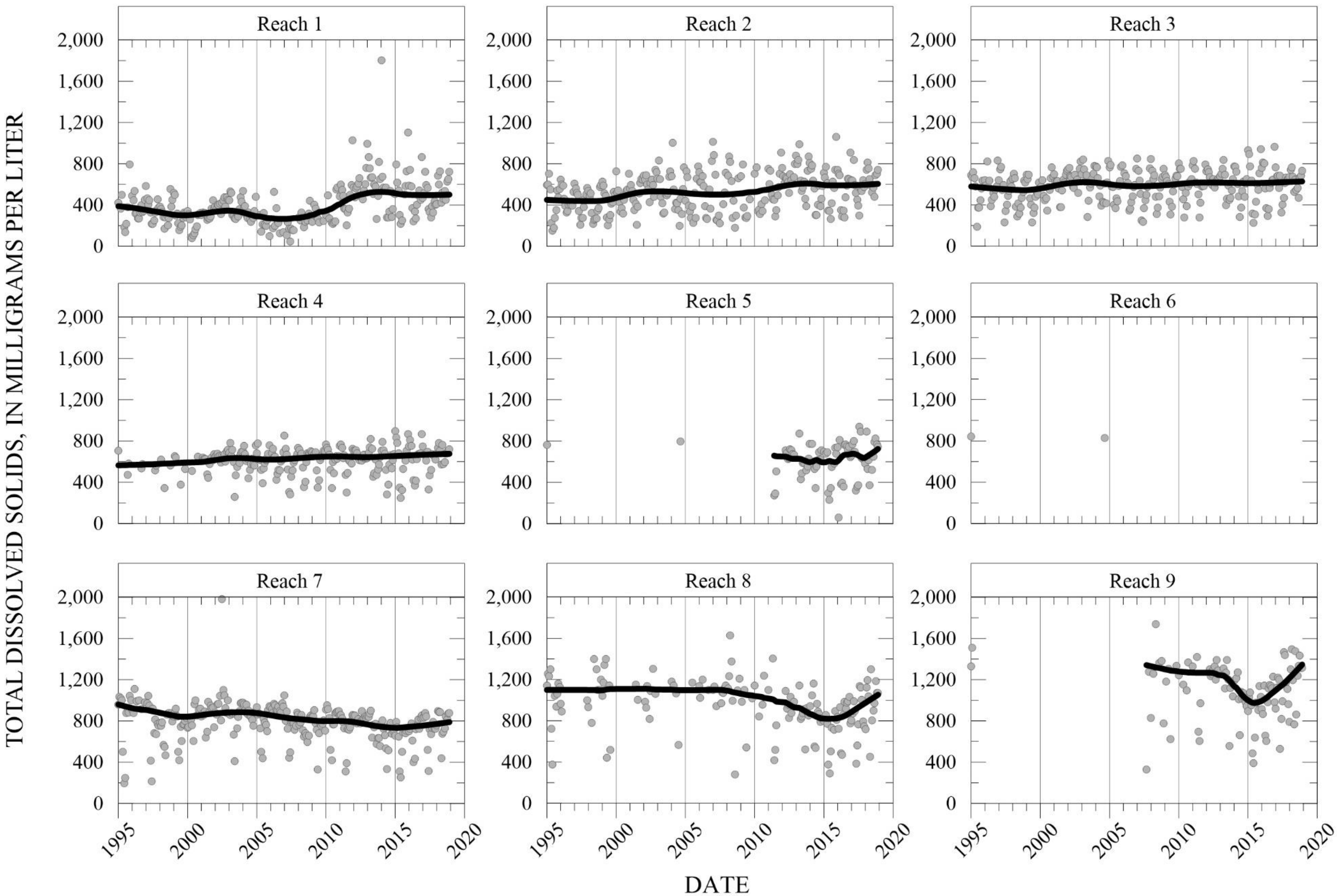


Figure 8-8. Average monthly Total Dissolved Solids with LOWESS trend line for South Platte River reaches

Table 8-3. Total Dissolved Solids Statistics

	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Reach 6	Reach 7	Reach 8	Reach 9
Count	1341	2582	3252	3421	80	5	1144	247	163
Mean	378.4	519.7	595.8	618.3	619.2	832.4	755.3	901.3	1079.5
Minimum	5.6	5.3	4.9	6.1	60.8	787.2	5.1	275.2	328.3
Maximum	5414.4	2099.2	2600.0	1477.1	939.5	896.0	1290.0	1625.6	1739.5
Std Dev	231.0	220.7	237.3	151.7	175.4	41.1	205.6	275.0	282.0
10th Percentile	196.0	245.1	310.0	390.0	355.8	797.4	417.2	472.3	642.7
25th Percentile	240.0	345.0	452.5	552.3	531.4	812.8	665.5	757.4	921.6
50th Percentile	321.3	523.0	596.7	640.0	653.8	821.0	800.0	933.1	1113.6
75th Percentile	481.9	658.4	682.2	702.7	743.0	844.8	882.3	1100.0	1270.7
90th Percentile	635.0	780.0	844.0	759.0	802.0	875.5	972.9	1218.6	1385.7

Table 8-4. Total Dissolved Solids Statistics for Tributary Rivers

	St. Vrain Creek	Big Thompson River	Cache la Poudre River
Count	111	235	525210
Mean	681.1	1053.0	747.0
Minimum	148.0	117.1	0.6
Maximum	3419.1	2000.0	1427.2
Std Dev	341.7	337.9	204.5
10th Percentile	252.9	683.0	438.4
25th Percentile	529.6	865.0	650.9
50th Percentile	746.2	1030.4	784.0
75th Percentile	798.4	1205.0	897.9
90th Percentile	855.9	1586.0	966.4

Salinity trends for the Saint Vrain, Big Thompson, and Cache la Poudre tributaries are shown on Figure 8-9. Saint Vrain Creek has sporadic and variable data with no consistent trends. Concentrations have been about 800 mg/l from 1995-2018. The Big Thompson River has seen the largest changes in salinity since 1995. There were concentrations of 2,000 mg/l in 1995 that declined to about 800 mg/l by 2015 (Figure 8-9). During the 2015-18 period, concentrations began to rise, reaching an average of 1,020 mg/l in 2018.

The Cache la Poudre River had salinity concentrations of about 800 mg/l from 2003, when monitoring become available, to 2011. Concentrations decreased from 2012 to 2014 and then began an increasing trend since 2015. Maximum monthly salinity concentrations in 2015 and 2017 exceeded 1,200 mg/l. Average monthly concentrations in 2018 were about 710 mg/l, which is about the same as the Saint Vrain and about 300 mg/l lower than the Big Thompson.

These tributaries receive wastewater effluent contributions from front range cities like Boulder, Longmont, Loveland, Fort Collins, and Greeley. Salinity increases due to municipal wastewater are probably similar for these cities and those in the Denver Metro area. It would be expected that these tributaries would have similar salinity to the South Platte River. However, these tributaries have historically had higher salinity than the South Platte River.

One unique difference is that these tributary watersheds have geologic salinity sources that may contribute to the elevated concentrations. Geologic units that formed in marine environments, like the Pierre Shale, outcrop and underlay alluvial deposits along the foothills from the Denver area to north of Fort Collins (see Section 7.2). Although the direct exposure of the tributaries to these shale units is limited, groundwater that flows slowly over and through these units eventually discharges to the alluvial channels and flows downstream to the South Platte River.

These tributaries have relatively low streamflow. The Saint Vrain and Cache la Poudre rivers typically range from 100 to 300 cfs, with the Big Thompson typically ranging from 50 to 100 cfs. Water quality is more sensitive to changes in chemical loading with lower streamflow, which contributes to the highly variable conditions. The Big Thompson and Cache la Poudre rivers frequently have maximum salinity concentrations in the 1,000 to 1,200 mg/l range. Conversely, spring runoff and stormwater runoff can dramatically reduce concentrations. Each of these tributaries has monthly salinity concentrations of 200 mg/l or less when there are high flow events.

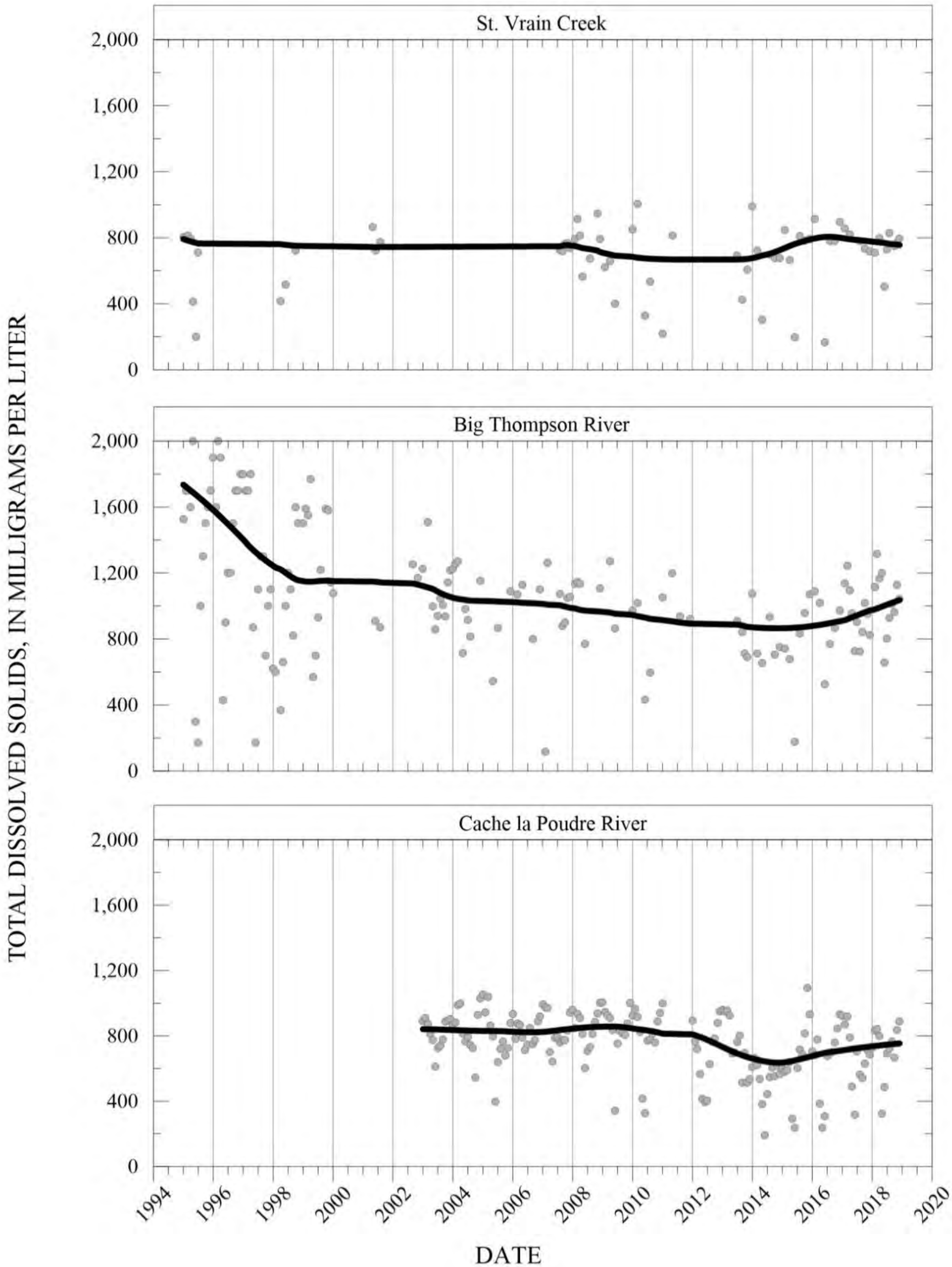


Figure 8-9. Average monthly Total Dissolved Solids with LOWESS trend line for tributaries

8.5 Flow-Adjusted Trends

Salinity concentrations measured in rivers are sensitive to streamflow. Concentrations increase during low-flow periods when point sources, like wastewater effluent, and non-point sources, like groundwater return flow, are the dominate water sources. Concentrations decrease during high-flow periods when more freshwater is in the system. The highly variable streamflow conditions result in highly variable salinity concentrations. This natural variability makes it difficult to observe the underlying salinity loading that results in persistent trends.

The WRTDS (Weighted Regressions on Time, Discharge, and Season) analysis was used to characterize the salinity concentration and flux trends (Hirsch and others, 2010). Flow-adjusted salinity concentrations were calculated to remove the year-to-year streamflow variability and to provide annual concentrations that would reflect changes in salinity loading.

The WRTDS analysis, described in Section 5.3, pairs the measured salinity concentrations with the daily flow for each reach. A statistical relationship between concentration and flow is developed that allows concentration predictions for every day based on the daily streamflow. Even though there may only be a few salinity measurements during a month, this analysis will predict salinity concentrations every day based on the measured streamflow. These predicted daily values are then used to calculate monthly average concentrations. The predicted daily and monthly concentrations are still influenced by the streamflow conditions. The final step is to calculate an annual average concentration that reduces the influence of streamflow and its year-to-year variability.

Long-term trends that reflect large watershed-scale changes in chemical loading, water management practices, and other underlying changes can be seen in the flow-adjusted salinity concentrations. The individual salinity measurements are highly variable, and the predicted monthly average concentrations illustrate the seasonal changes with higher concentrations in the low-streamflow fall and winter months and lower concentrations in the higher flow spring and summer months.

The long-term trends presented in Section 8.3 show upper basin reaches have increasing salinity trends since 1995, but the trend is influenced by streamflow changes. The flow-adjusted, average annual salinity for Reach 1 is provided on Figure 8-10 with the monthly streamflow in the lower panel. Monthly salinity reflects the seasonal streamflow variations, whereas the flow-adjusted annual concentrations remove most of this variability so that salt loading changes are more apparent.

Reach 1 salinity was 300-400 mg/l from 1995 to 2005 and then it starts increasing, reaching an average of about 550 mg/l by 2018 (Figure 8-10). The influence of streamflow on the monthly salinity concentrations (blue line, upper panel) can be seen on Figure 8-10 by comparing the streamflow in the lower panel with the concentrations in the upper panel. Low streamflow in 2002 and 2012 have the highest monthly salinity concentrations, but the annual average (red line) is less affected. This suggests that the high salinity in 2002 and 2012 were largely the result of streamflow rather than a change in salt loading.

The overall annual average salinity trend indicates that there has been increasing salt loading to Reach 1 since 2005. The individual salinity measurements illustrate the salinity variability, monthly averages show seasonal changes, and annual average concentrations show changes in salt loading (Figure 8-11).

Although the annual average salinity in Reach 1 since 2010 is less than 600 mg/l, concentrations of 800-1,200 mg/l have been measured. The magnitude and frequency of these high concentrations has increased since 2005.

The flow-adjusted, average annual salinity for Reaches 1-4 are shown on the following pages. There were not enough salinity data to determine a reliable concentration-flow relationship in Reaches 5 and 6. The salinity values on Figure 8-11 through Figure 8-22 include all of the instantaneous measurements available for analysis. These figures illustrate the salinity variability, whereas the salinity values on the LOWESS trend graphs on Figure 8-8 and Figure 8-9, are monthly averages.

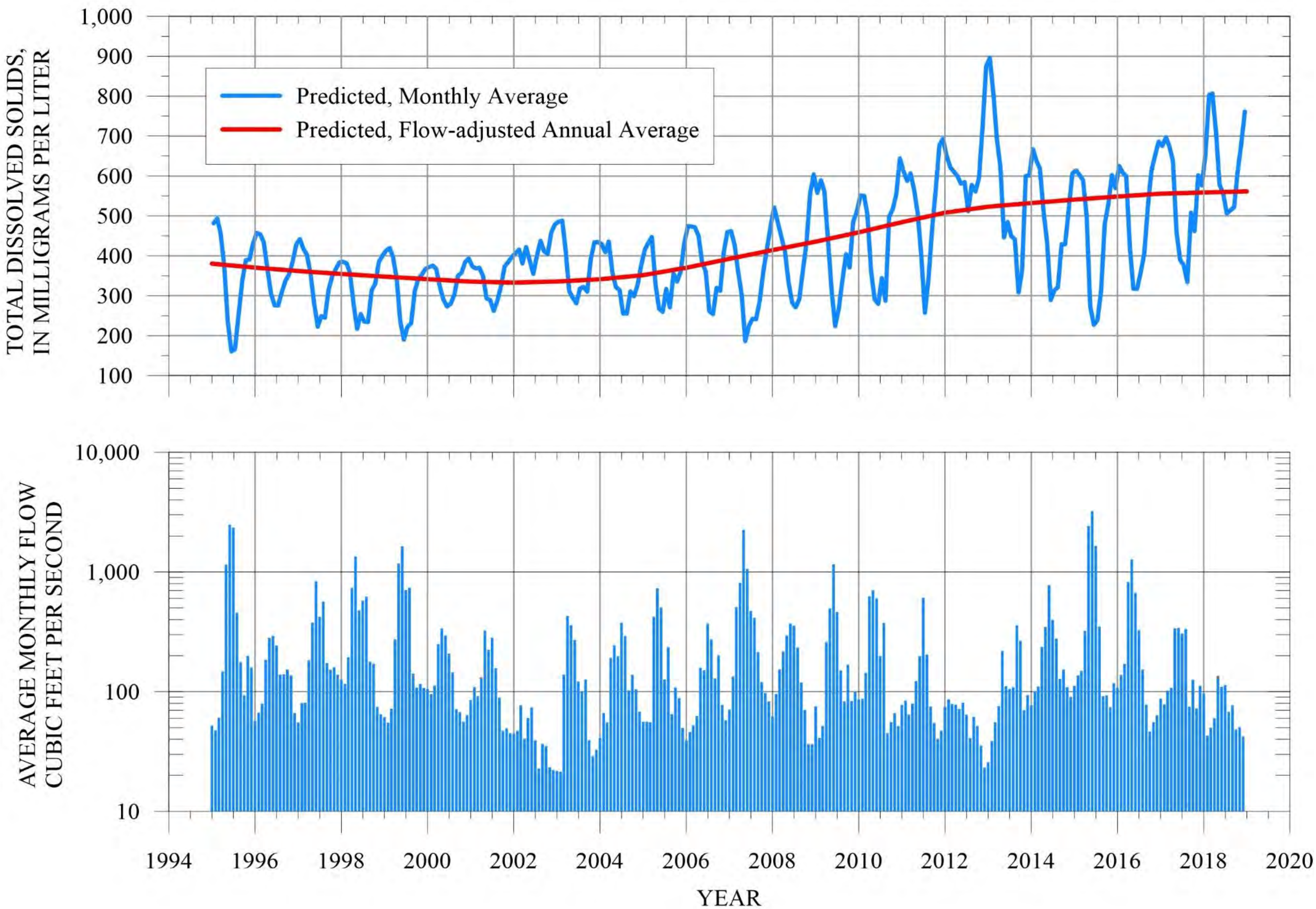


Figure 8-10. Flow-adjusted Total Dissolved Solids concentrations and streamflow in Reach 1

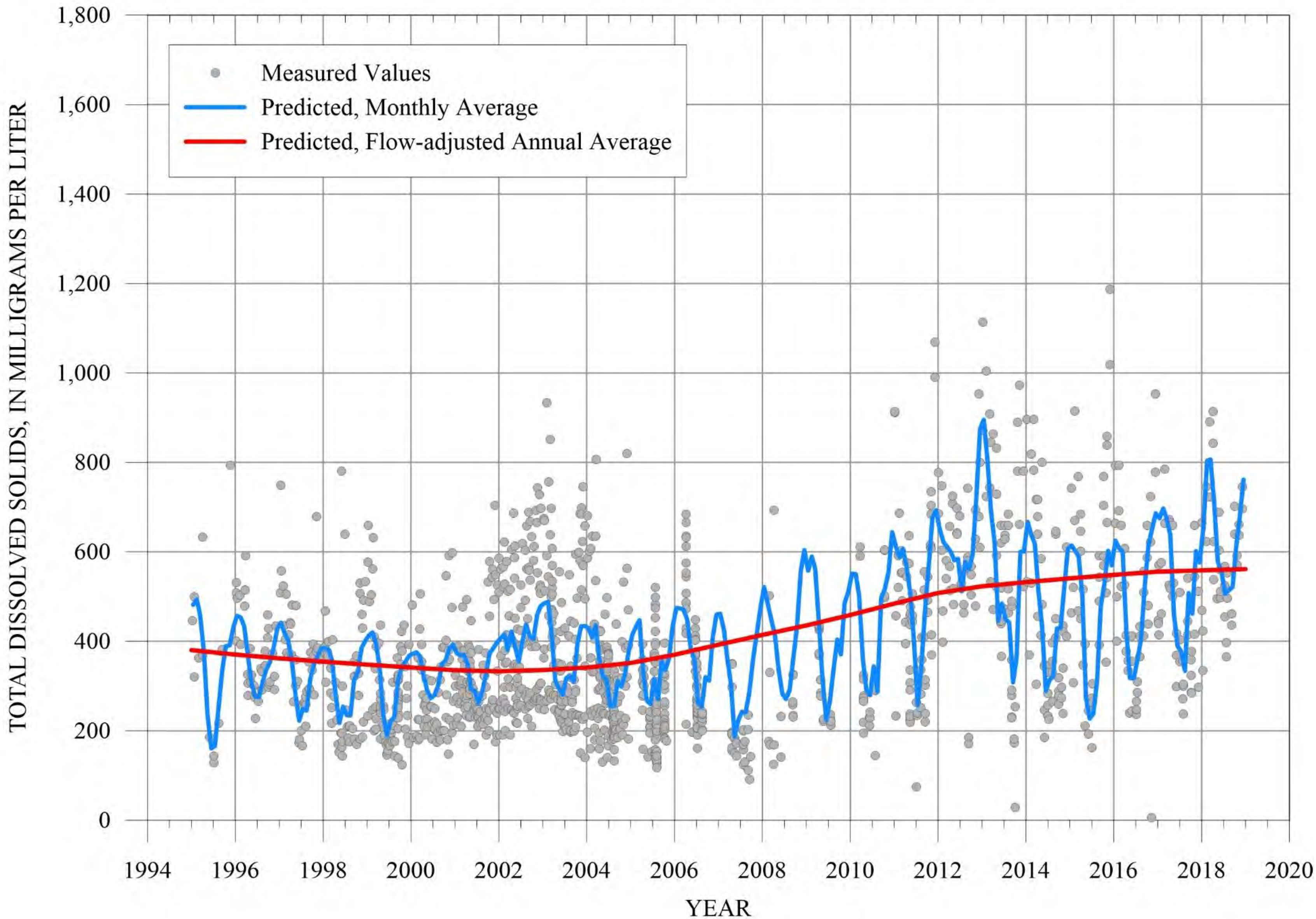


Figure 8-11. Flow-adjusted, average annual Total Dissolved Solids concentrations for Reach 1