DISSERTATION

CHARACTERIZATION AND MASS BALANCE MODELING OF DISSOLVED SOLIDS CONCENTRATIONS AND LOADS IN THE SOUTH PLATTE RIVER SYSTEM, NORTHEASTERN COLORADO

Submitted by

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ABSTRACT

CHARACTERIZATION AND MASS BALANCE MODELING OF DISSOLVED SOLIDS CONCENTRATIONS AND LOADS IN THE SOUTH PLATTE RIVER SYSTEM, NORTHEASTERN COLORADO

Driven by an increasing population in the South Platte River Basin, water which was historically used for agricultural purposes is being diverted to urban areas in order to satisfy increasing municipal and industrial demands. This trend is changing the timing, location, volume, and quality of return flows to the river. The quality of return flows is of particular concern in the lower reaches of the South Platte River Basin where salinization of irrigated soils has emerged as a concern. This study addresses the critical need for a comprehensive understanding of salinity status and provides the basis for understanding the processes involved in the origin, flux, and ultimate destination of salts throughout the basin.

The first phase of this research utilized historical monitoring data in order to characterize dissolved solids status and trends within the basin. Specific objectives of this phase were: (1) the compilation and assessment of available historical streamflow and dissolved solids concentration data, (2) the estimation of daily dissolved solids loads at selected monitoring sites, (3) the characterization of spatial patterns in dissolved solids concentrations and loads, and (4) the determination of temporal trends in dissolved solids concentrations and loads.

The second phase of this research provides a quantification of salt balance and prediction of future streamflow and dissolved solids concentrations resulting from proposed water resource projects. The salt balance of the mainstem of the South Platte River was evaluated through the development of a reach-based water and dissolved solids budget. Components of the budget included upstream inflow, tributary contributions, major point sources, diversions, and downstream outflow. Residuals of the mass balance were used to quantify unmeasured streamflow and salt contributions to the river, the majority of which occur via ground water inflows.

In the final phase of this study, a dynamic streamflow and salt mass simulation model was developed to assess water-quality impacts of water development projects. Based on mass balance concepts, this model allows for the evaluation of changes in streamflow, dissolved-solids loads, and dissolved-solids concentrations along the middle and lower portions of the South Platte River resulting from single or multiple user-configurable upstream water diversion and reuse projects. Details of the model development and operation are presented along with results of simulations of several case studies. Simulation results highlight the utility of a dynamic streamflow and salt mass simulation model in the evaluation of future water-quality conditions and demonstrate the importance of combined evaluation of multiple proposed water development projects.

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Similar to many river basins in the western United States, the South Platte River Basin is undergoing a transformation with regard to land and water use. Driven by an ever-increasing population in the basin, water which was historically used for agricultural purposes is being diverted in greater and greater quantities to growing urban areas in order to satisfy increasing municipal and industrial (M&I) demands. Water rights and water-quantity issues have long been at the forefront of the debate between competing water interests. However, an increasing number of agricultural-urban water exchange agreements, increased water reuse, and an increase in water conservation efforts are forcing additional attention to be given to the water quality impacts resulting from these actions.

Beginning in the latter half of the 19th century, the historical solution to an ever-increasing demand for water in the semi-arid plains of eastern Colorado and Colorado's populous Front Range region was to import additional water from the wetter river basins west of the Continental Divide through a series of transcontinental tunnels and reservoirs. However, due to a combination of water supply limitations, legal challenges, and economic barriers, there is currently limited potential for additional supplementation from basins west of the Continental Divide. This has led to an increasingly competitive environment for water resources in the South Platte River Basin which is already over-appropriated. It has also provided additional incentive for increased water efficiency and water reuse. Because the economic value of water is higher for M&I uses than for agricultural uses, increasingly valuable water rights are being transferred from agricultural areas to municipalities. The commensurate decrease in irrigated acreage in conjunction with increased urban water conservation efforts and new water recycling projects has the potential to change the timing, location, volume, and quality of return flows to the river, especially mid-basin where the bulk of the population growth is occurring.

According to Dennehy *et al.* (1993), return flows often become a source of downstream irrigation water as river water is reused up to an estimated seven times before leaving the basin. These high rates of recycling and return flows in the basin have water-quality implications for the receiving water that have not been properly investigated on a basin-wide scale. The quality of return flow is of particular concern in the lower portions of the South Platte River Basin where salinization of irrigated soil has emerged as a growing concern. The USDA's Natural Resources Conservation Service (West Greeley Soil Conservation District, 1999) estimates that up to 25% of the irrigated land along the South Platte River may be affected by salinity. The process of soil salinization can be greatly accelerated when a proper salt balance of the soil is not achieved through irrigation with sufficient quantities of lower-salinity water and adequate drainage (Tanji, 1996a). A major factor contributing to the increased soil salinity levels in these areas is the deposition of dissolved salts carried by the irrigation water used within the basin (Gomez-Ferrer *et al.*, 1983) .

The severity of soil and irrigation water salinity problems and the salt balance in this region are likely to worsen in the future as recent trends in upstream water use and management continue. Because of this threat to irrigated agriculture, there is a critical need for a comprehensive understanding of current salinity status and recent trends. There is also a need for a system-based, comprehensive understanding of the processes involved in the origin, flux, and ultimate destination of water and salts throughout the basin.

1.2 PURPOSE AND SCOPE

A complete characterization of salinity status and salinity sources in the basin is a necessary first step in quantifying the nature of the problem, as well as identifying effective management and control strategies. Previous salinity characterization efforts by Lord (1997) and the work of Hendricks *et al.* (Gomez-Ferrer *et al.*, 1983; Gomez-Ferrer and Hendricks, 1983; Turner and Hendricks, 1983) provided a fundamental basis for the understanding of historical salinity conditions and the flux of dissolved solids in the basin. This study updates these older characterization efforts and expands the study area to include additional tributary monitoring sites not previously studied and also utilizes state-of-the-art techniques and software applications for trend testing and estimation of daily dissolved solids loads. This work also incorporates the results of the updated salinity characterization effort into a dynamic decision support tool to evaluate future streamflow and dissolved solids conditions resulting from changes in historical water uses, impacts of water recycling efforts, and development of new water resource projects.

This study utilizes historical monitoring data from fixed-site monitoring stations on the mainstem of the South Platte River as well as fixed-site monitoring stations on tributaries of the South Platte River, all of which are located within the state of Colorado. The primary characterization and mass balance efforts were focused on water years 1991 through 2004, however analysis of longer-term trends in dissolved solids concentrations is also included.

1.3 OBJECTIVES

This study was conducted to provide a better understanding of the occurrence, temporal trends and flux of dissolved solids within the South Platte River Basin. The primary goal of this work was to provide not only a snapshot of recent water salinity conditions, but also sufficient information on the processes involved to begin predicting the impacts to irrigated agriculture of future water projects and management changes in the basin.

Specific objectives of this research included:

1) Compilation and assessment of historical streamflow and salinity data for monitoring sites throughout the basin
2) Estimation of dissolved solids loads at selected sites
3) Characterization of spatial patterns in streamflow, dissolved solids concentrations, and dissolved solids loads
4) Determination of temporal trends in streamflow, dissolved solids concentrations, and dissolved solids loads
5) Evaluation of the salt balance between the middle and downstream regions of the basin
6) Development of a reach-by-reach streamflow and salt mass budget for the lower South Platte River
7) Computation of reach-based estimates of river gains and losses of water and salt occurring via ground water
8) Development of a dynamic simulation model for evaluation of future river streamflow and salinity resulting from the combined impacts of multiple new water resource and water management alternatives
9) Identification of information gaps that should be addressed in future monitoring programs

1.4 OVERVIEW OF CONTENTS

The literature review found in Chapter 2 contains an overview of salinity problems, a description of the study area, and a review of past salinity research conducted on the South Platte River Basin. Chapter 3 describes the compilation and processing of historical streamflow and water-quality monitoring data at selected monitoring sites along the South Platte River and its tributaries. These data sets provided the underlying data used in all subsequent analyses.

The next three chapters provide details of a comprehensive characterization of salinity conditions within the basin. Chapter 4 reports on the characterization of streamflow conditions at the selected monitoring sites. Streamflow characterization is a necessary first step in the interpretation of water-quality conditions. Characterization techniques for streamflow include time series plots, summary statistics, analysis of spatial patterns along the stream systems, analysis of seasonal patterns, and analysis of temporal trends in annual streamflow volume. Chapter 5 presents the characterization of dissolved solids concentrations throughout the basin. Characterization techniques include time series plots, summary statistics, analysis of spatial patterns along the stream systems, analysis of seasonal patterns, and temporal trend analysis. Chapter 6 concludes the salinity characterization effort by describing the procedures used to estimate daily dissolved solids loads at selected monitoring sites. The resulting load estimates were analyzed for spatial patterns and temporal trends in order to provide a greater understanding of the origin and movement of dissolved solids throughout the basin.

The final portion of this text describes how the results of the comprehensive salinity characterization work were utilized in the creation of a streamflow and dissolved solids mass balance and then the development of a mass balance simulation model. Chapter 7 describes the use of mass balance techniques to develop a reach-by-reach discharge and dissolved solids budget for the lower South Platte River. Components of the budget include historical upstream inflow to each reach, tributary contributions, major point source inflows, losses to diversions, and downstream outflow from each reach. The mass balance residuals are assumed to be primarily ground water contributions, but will also reflect ungauged inflows and outflows as well as measurement errors.

Utilizing the flow and dissolved solids budget developed in Chapter 7, Chapter 8 details the development and application of a user-friendly, dynamic streamflow and salt flux tracking model for prediction of streamflow, dissolved-solids load, and dissolved-solids concentration along a defined stream network. Based on mass balance concepts, this dynamic modeling system allows for the simulation of possible changes in streamflow, dissolved-solids load, and dissolved-solids concentration along the middle and lower portions of the South Platte River resulting from a combination of user-configurable upstream diversion and reuse projects. Details of the model development and operation are presented along with model-predicted impacts of several simulated upstream water project scenarios.

Chapter 9 provides a synthesis of key findings of this work along with overall conclusions. It also provides some suggestions for future research. Appendices A, C, and D contain additional plots which support the primary results provided in the chapters. Appendix B details results from an additional field monitoring project that was conducted during the low-flow period of fall 2002 through early spring 2003 in an attempt to provide greater spatial resolution of TDS concentration increases along South Platte River tributaries in the middle portion of the basin than could be obtained through use of historical U.S. Geological Survey monitoring data alone.

CHAPTER 2: LITERATURE REVIEW

2.1 THE PROBLEMS OF SOIL AND WATER SALINITY

2.1.1 Introduction

In many parts of the world, elevated salinity levels in soil and irrigation water are a principal cause of soil degradation and can result in large reductions in productivity (Toth *et al.*, 1991). It is estimated that 23% of the cultivated land worldwide is saline, and another 37% is sodic (impacted by high levels of sodium) (Tanji, 1996b). These soils lie primarily in arid and semiarid regions, but salt-affected areas also occur in sub-humid and coastal zones where the climate and mobility of salts produce seasonal problems. In the western U.S., an estimated that up to 5 million hectares of irrigated land are salt-affected (Bohn *et al.*, 1985).

Irrigated agriculture has had to contend with the problem of soil and water salinity for thousands of years. In ancient Mesopotamia around 2500 B.C, it is believed that agriculturalists began to experience problems growing wheat because of increasing soil salinity due to a rising water table resulting from the over-application of irrigation water. Attempts were made to switch to barley and other more salt-tolerant crops, but eventually the soil became too saline even for these crops and the civilization began to gradually decline. In the areas that now comprise modern day Peru and Arizona, the decline of ancient civilizations that practiced flood irrigation is thought to be at least partially attributable to soil salinization (Tanji, 1996b).

2.1.2 Mechanism of Soil Salinization

Man-induced salinization of irrigated land can occur by several mechanisms. When water containing dissolved salts is applied to land for irrigation purposes, a portion of the water is lost to evaporation from the soil surface and transpiration from plants. Because the water is lost in the vapor phase, it leaves the salts behind in the soil. If this happens repeatedly, the concentration of salts in the soil will increase to harmful levels. Normally, the salts are flushed below the root zone during rain or irrigation events. However, if there is an existing shallow water table or if the water table is artificially raised through the continued application of excess irrigation water, salts in the soil cannot be flushed below the root zone and away from the plants. When the ground water table is near the surface, water can be drawn to the surface through capillary action. At the surface, the water evaporates, leaving behind salts that had previously been flushed from the surface or that occur naturally in the ground water (Bohn *et al.*, 1985). This produces the visible salt deposits sometimes seen in low-lying areas. This process of soil salinization can be greatly accelerated when irrigation water is used that is high in dissolved solids. It is because of this problem that irrigation water quality is a major concern in many irrigated areas.

2.1.3 Effects of Soil and Water Salinity on Plants

The most common mechanism through which high soil salinity levels are harmful to plants is through the stress caused by an increase in the osmotic potential of soil water when it contains a large amount of dissolved salts. As a result, plants are unable to extract as much water as they normally would under low-salt conditions. In extreme cases, the plants can appear wilted even though the soil is sufficiently wet for crop growth. In more moderate cases, plant growth is retarded due to the increased expenditure of energy needed to acquire water from the soil matrix. With agronomic crops, this reduction in plant growth usually results in an economic loss to the producer. Extremely high soil salinity levels can result in barren lands incapable of supporting any type of vegetation.

Even when soils do not contain an excessive amount of soluble salts, plants can still suffer salinity damage due to saline irrigation water. The susceptibility of crop plants to salinity in irrigation water varies considerably by species and growth stage. In general, no detrimental effects occur when using irrigation water with a total dissolved solids (TDS) content of 500 milligrams per liter (mg/L) or less. Salt-sensitive crops might experience damage when irrigation water contains 500-1000 mg/L TDS. Waters containing between 1000 and 2000 mg/L TDS may have detrimental effects and will require careful management. Only salt-tolerant crops can be grown using waters higher than 2000 mg/L and even then, permeable soils are required and careful management practices must be observed (Follett and Soltanpour, 1992). One of the management practices necessary to prevent an accumulation of salts is to use enough irrigation water to leach the salts below the root zone. Additionally, the installation of surface or subsurface drains to lower or control the water table in poorly drained soils can help control soil salinity and facilitate increased crop production under these conditions.

Specific ions that are sometimes present in saline soil or water can have direct toxic effects on some plants. The most common toxic elements are boron, chloride, and sodium. Leaf burn can result if water with high levels of these dissolved ions contact the leaf surface through activities such as sprinkler irrigation.

2.1.4 Effects of Salinity on Soil Properties

Generally, high salinity levels reduce the ability of soil to support plant growth, but do not have a dramatic impact on the physical properties of the soil itself. However, 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, which in turn impedes the infiltration and drainage of water. 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.

2.1.5 Economic Effects of Soil and Water Salinity

Although salinization of water resources caused by human activities (often referred to as secondary salinization) can produce highly saline or even salt-saturated waters, it is often the increase in salinity at the lower end of the spectrum that causes the most biological and economic impact. The most significant economic damage is caused when water containing less than 500 mg/L TDS is increased to a salinity of between 500 - 10,000 mg/L (Williams and Noble, 1984).

The yield losses resulting from both saline and sodic soils translate into economic losses for the producer. Because the quality of irrigation water is such an important factor in both of these problems, decreases in the quality of irrigation water results in direct economic effects for the producer through decreases in crop yields as well as increased costs of water and land management (Hem, 1985). In the Colorado River Basin, the large salt load in the river was estimated to be costing users more than $750 million per year in 1985 and was expected to more than double by 2015 if salinity controls were not instituted. Due to remedial actions, the economic costs of salinity problems in the San Joaquin Valley of California decreased by 10 percent or $31.2 million annually during the period 1970 to 1985. The losses were expected to increase to over $320 million by the year 2000 if no remedial action was taken (Ghassemi *et al.*, 1995).

It is not only agriculture that feels the economic effects of saline water. Salinity can affect municipal and industrial water users by clogging plumbing fixtures, causing increased corrosion, and by increasing the costs of water softening (Bauch and Spahr, 1998). In 1987, it was estimated that each additional milligram per liter of salt in the water supply systems of cities using Colorado River water would result in over $300,000 worth of damage per year to water pipes, fixtures, and machinery that came in contact with this water (Ghassemi *et al.*, 1995). Taken together, the costs of increased salinity in domestic, agricultural, and industrial waters has been estimated to be about $5 million per year for every 100 mg/L increase in salinity beyond an initial 300 mg/L (Williams, 1987).

2.1.6 Ecological effects.

Because of the large economic effects associated with increased salinity levels, "off-stream" effects of salinity have received a considerable amount of research. What are often ignored are the "in-stream" or environmental and ecological effects of increased salinity. Because various types of salts play a central role in the many internal physiological functions of all aquatic organisms, it is a logical assumption that the external concentration of salts in these environments could be of critical importance to the health of these organisms. Unfortunately, due to a lack of research, it is not clearly understood to what extent aquatic communities are threatened by the addition of salt. It is also not known how much of an increase in salinity can be assimilated by these environments without damage to the ecological structure. One guideline presented by the

U.S. Environmental Protection Agency recommends that for the protection of wildlife habitat, salinity should not vary by more than 1000 mg/L for water in which the natural salinity is normally between 1000 and 3500 mg/L (Williams, 1987).

Even though much more work is needed in order to more thoroughly understand the impact of increased salinity on aquatic life, salinization of an inland water body has the potential to cause damage to the structure and function of the aquatic communities contained within (Williams, 1987). Disruptions of the aquatic communities can lead to the degradation of many in-stream uses such as fisheries, which depend upon the maintenance of delicately balanced aquatic ecosystems (Williams and Noble, 1984). There is a growing body of anecdotal evidence illustrating the impact that increased solute levels can have on ecosystems. In Australia, unnaturally high salinity levels in the lower Avon River have been suggested as the reason for the replacement of the freshwater mussel by brackish muscle species and for the upstream occurrence of a copepod that is normally considered estuarine (Williams, 1987). Elsewhere in Australia, faunal changes attributed at least in part to salinization include the almost complete disappearance of a crayfish species and the decreased vigor of red-river gums on the floodplain of the Murray River in southeastern Australia (Williams, 1987). In South Africa, river salinization is blamed for the gradual elimination of salt-intolerant diatoms and their replacement by a less diverse but more salt-tolerant collection of diatoms. In North America, changes in salinity levels have been blamed for fish kills in rivers in the northern Great Plains (Ghassemi *et al.*, 1995).

Other ecological effects can occur when saline water such as that collected from drainage networks under irrigated soils is stored in off-stream flood plain areas or wetlands. If these waters are discharged into rivers during periods of high flow, the sudden changes in salinity levels can have detrimental effects on aquatic organisms (Ghassemi *et al.*, 1995). If they are left to evaporate naturally, damage can occur due to the extremely high salinity levels resulting from the concentration of the remaining salts. In addition to damage caused by the general increase in salinity in these evaporation areas, there is a potential for the formation of high concentrations of toxic trace elements. An example of this scenario is the Kesterson Reservoir and Natural Wildlife Refuge in California where drainage waters from the San Joaquin Valley were collected. As the drainage water evaporated, toxic levels of selenium leached from agricultural soils were found to be causing waterfowl death and deformity (Johnston and Hall, 1990).

2.2 CHARACTERISTICS OF SALINITY IN RIVERS

2.2.1 Sources of Salinity in Rivers

All natural waters contain some amount of dissolved solids. Virgin streams in mountain watersheds might only have 50 ppm dissolved solids while the typical concentration in seawater is around 35,000 ppm (Pillsbury, 1981). The two main mechanisms responsible for causing increases in dissolved solids levels are salt concentration and salt pickup. Both of these can be a result of natural causes or human activities (Ghassemi *et al.*, 1995). Salt concentration, also called evaporative salinization, can occur as a result of transpiration and evaporatative processes in which pure water is lost but the dissolved solids contained in it remain, resulting in a higher salt content in the remaining solution. The results of evaporative salinization can be compounded through diversion or consumptive use of low salinity water upstream, resulting in less water being available downstream to offset the concentration processes or for dilution of saline inflows (Bauch and Spahr, 1998).

Salt pickup describes the processes that contribute additional salt mass to the water. Chemical weathering of earth materials such as rocks and soils releases minerals, which are the primary source of salts in waters (Tanji, 1996b). The nature and concentration of dissolved solids are a result of many factors including the composition of the geologic material, the solubility of the mineral forms present, and the relative amount of exposure the water has to the geologic materials. While geologic deposits are normally the major naturally occurring source of dissolved solids, other natural sources can be significant in some situations. In coastal areas, atmospheric deposition of oceanic salts (Mattson and Godfrey, 1994) and seawater intrusion into estuaries or ground water basins can sometimes have an impact on the TDS concentration of freshwaters (Tanji, 1996b).

Salinization of water is a naturally occurring process, but human activities can sometimes have a dramatic impact on both the rate and magnitude of the process (Bruce and McMahon, 1998). It is often hard to separate the magnitude of salinization resulting from man's activities from that which would have occurred naturally. This can present a difficulty in evaluating the effectiveness of water resource management practices designed to minimize salinity increases (Whittemore and Pollock, 1979).

Humans can influence salinization directly through activities such as the land application or discharge to water bodies of materials containing soluble salts. Potential anthropogenic sources of dissolved solids include the application of deicing materials to roadways, the application of fertilizer and other amendments to soils, discharges of industrial and municipal wastewater (Hunter *et al.*, 1979), (Pillsbury, 1981), mine drainage water, and oil and gas field brines (Tanji, 1996b), (Shirinian-Orlando and

Uchrin, 2000), (Knuth *et al.*, 1990). Indirect impacts on salinization can also occur as a result of activities such as irrigation and land disturbance (Ghassemi *et al.*, 1995). These can lead to increased mobilization of soluble salts from natural geologic deposits (Williams and Noble, 1984). Because irrigation results in evaporative salinization as well as leaching of soluble salts as the remaining water moves through the soil profile, it is often listed as the anthropogenic process that has the most significant effect on salinization (Williams and Noble, 1984).

2.2.2 Spatial and Temporal Variations

In much of the western United States and in many other places around the world, rivers are an important source of irrigation water. Rivers that originate in mountainous areas typically contain very little salt. As a river flows downstream, the concentrations and loads of dissolved solids normally increase due to leaching and erosion of geological deposits and soils. Salts from a variety of sources are also transported to the river through tributaries and surface runoff. Ground waters, which typically contain a higher concentration of salts than the overlying surface water, can add a significant amount of salt when they end up in a river via subsurface flow. As the water is used and re-used, it picks up additional salts and is subjected to evaporation. These processes are all potential contributors to the salinity level of a river. In many river basins, these processes can cause downstream salinity levels to be orders of magnitude higher than at the headwaters. This phenomenon is generally referred to as salinization, and as a result of man's activities, it is a growing form of aquatic pollution (Williams, 1987).

In addition to the pattern of increasing downstream salinity levels, dissolved solids concentrations and loads can vary seasonally as well as from year to year. One of the most important factors in the quality of a river or stream is the quantity of streamflow.

Normally, in the case of dissolved solids, the concentration is inversely related to discharge (Wells and Schertz, 1983). Under base flow conditions most water in a stream originates from ground water, which usually contains a significant amount of salts derived from the geologic materials in which it has come in contact. During precipitation or snowmelt events, the resulting runoff will usually have a much lower dissolved solids concentration than the base flow in the river. Therefore, as runoff increases and causes an increase in streamflow, the concentration of dissolved solids in the base flow is diluted.

The highest dissolved solids loads generally occur in conjunction with the highest streamflows, but because of the dilution effect runoff has on dissolved solids concentrations in streams, there is not a 1:1 or even a linear relationship between dissolved-solids loads and stream discharge (Butler, 1996). Dissolved solids loads normally increase along with stream discharge, but to a lesser degree. The relationship between dissolved solids loads and streamflow can also be influenced by anthropogenic processes such as water importation and discharges of water with a much higher or lower concentration of dissolved solids than the receiving water.

In addition to streamflow, there are a number of other factors that can influence dissolved solids concentrations and loads in rivers. These can include channel evolution and hydrologic variation in the basin, changes in the quality or quantity of ground water discharges, changes in precipitation patterns, and changes in land use and irrigation practices (Bauch and Spahr, 1998).

2.2.3 National Trends

In a comprehensive analysis of water-quality trends in major U.S. rivers during the period 1974-1981, Smith *et al.* (1987a; 1987b) studied trends in 24 measures of water quality at 380 monitoring sites located throughout the United States. With respect to salinity, they found a high frequency of increasing trends versus the number of decreasing trends in the flow-adjusted concentrations of several dissolved substances that contribute to salinity in natural waters such as chloride, sulfate, and sodium. An analysis of the magnitude of these trends showed that the average increase was 30 percent. Because of the frequency, magnitude, and wide distribution of these trends they concluded that there was a significant increase in the salinity of the nation's rivers during the 1974 to 1981 period. Although not discussed in detail in the reports, a table summarizing the results of the trend analysis indicates that there were over three times as many decreasing trends in dissolved calcium concentrations as there were increasing trends. It also shows that the number of significant increasing trends for dissolved magnesium was approximately equal to the number of decreasing trends (48 increasing versus 41 decreasing out of a total of 289 sites).

Both increasing and decreasing trends in the major cations had a wide geographic distribution, but increases were especially common in the Missouri Basin and decreases were frequent in the Lower Colorado Basin. Sodium trends had a geographic distribution pattern that closely resembled that of chloride trends, therefore indicating the potential for a common origin of both. Chloride increases were found in almost all drainage systems, but they were especially frequent in the Missouri, Mississippi, Ohio, and Atlantic Coastal Basins. The only places where decreases in chloride trends were frequently found were in the Great Lakes and Lower Colorado Basins.

Using a variety of ancillary data sources describing various basin characteristics, the authors attempted to find possible explanations for some of the trends they observed.

In the case of chloride trends, they found a moderately positive correlation with basin population changes from 1970 to 1980. This is not surprising given the fact that previous reports have shown that human wastes are a major source of chloride in many populated basins (Biesecker and Leifeste, 1975). Another potential cause of increasing trends in sodium and chloride concentrations is the increased use of road salt, which during the time of the study generally consisted of sodium chloride. Between 1950 and 1980, the use of salt on highways increased nationally by factor of more than 12. Smith *et al.* found that increased sodium and chloride concentrations in some basins were significantly associated with high rates of highway salt use in those basins and with large increases in its use from 1975-1980. The strongest associations between road salt use and increased chloride concentrations occurred in the Ohio, Tennessee, Lower Missouri, and Arkansas-Red Basins.

Irrigated agriculture is commonly listed as the major cause of river salinization, however in the study by Smith *et al.*, the authors did not find any significant correlation between chloride trends and the amount of irrigated acreage or to changes in the amount of irrigated acreage during the 1974-1982 period. Decreases in chloride concentrations in the Colorado drainage were observed. These have been partially attributed to the effects of reservoir filling during the early 1970’s.

Monitoring sites that had significant increasing trends in sulfate concentration outnumbered those with decreasing trends by nearly a 2:1 margin. Many increases were seen in the Southeast and in the Missouri and Pacific Northwest basins. Common sources of sulfate in rivers include atmospheric deposition and weathering of sulfur-bearing minerals. Sulfate trends in headwater streams previously have been shown to be related to trends in atmospheric sulfur emissions. Although the authors detected similarity between stream-sulfate trends and the geographic pattern of trends in sulfur emissions, they concluded that terrestrial sources of sulfur greatly exceed atmospheric deposition in many of the study basins. The movement of terrestrial sources of sulfur into river systems can be greatly increased in pyrite-rich basins due to land disturbances such as surface mining. Surface coal production and changes in surface coal production from 1974 to 1981 were found to be highly associated with sulfate trends.

2.3 DESCRIPTION OF THE SOUTH PLATTE RIVER BASIN

2.3.1 Overview and Geographic Setting

The South Platte River Basin (Figure 2-1) is located primarily in the north-central and north-eastern regions of Colorado. It originates in the mountains southwest of Denver along the Continental Divide at an altitude of more than 14,000 feet and flows in a northerly direction until it reaches Greeley, Colorado where it begins to flow in an easterly to northeasterly direction across the plains.

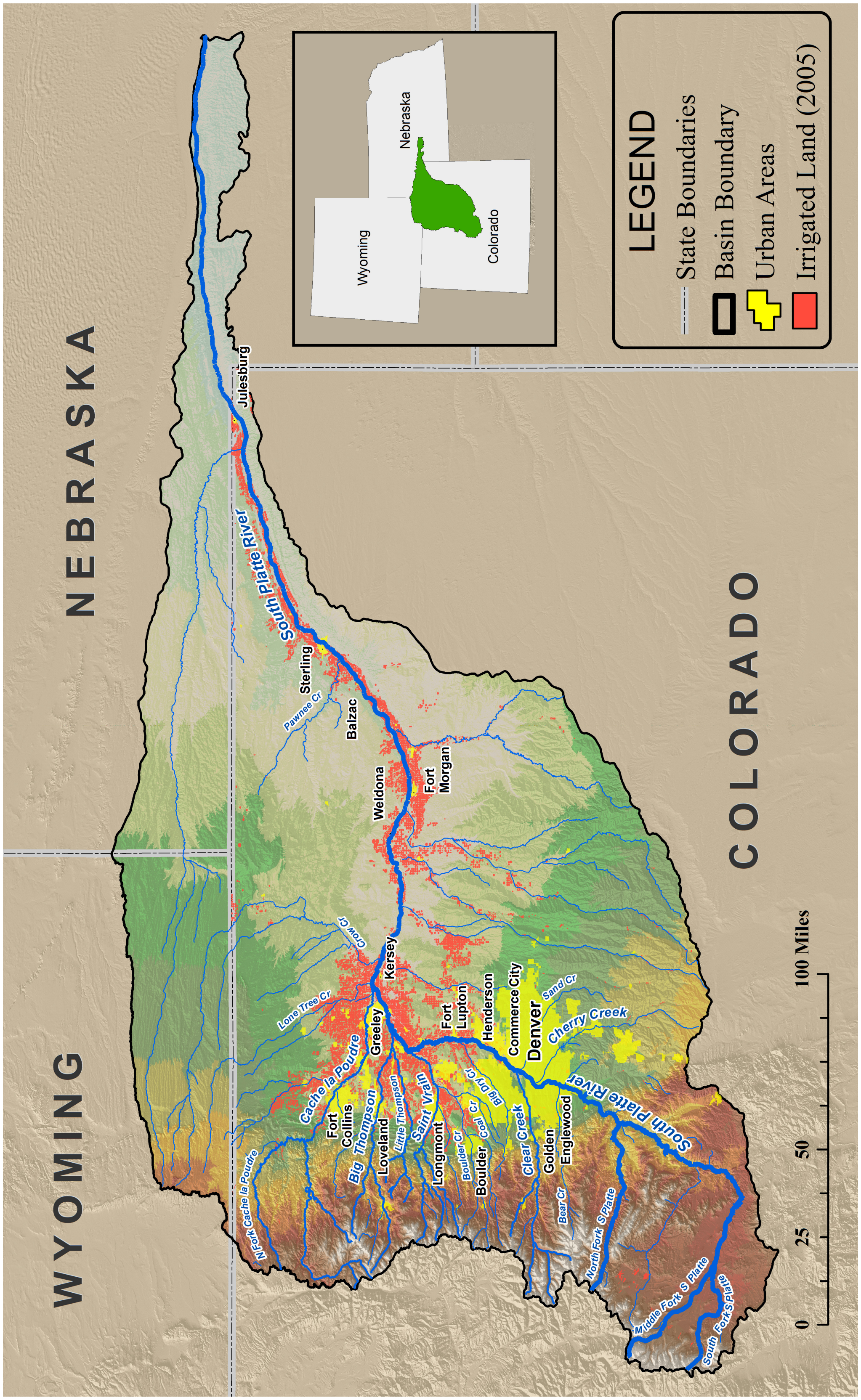


Figure 2-1. The South Platte River Basin.

Along the plains, the topography of the basin slopes gently toward its confluence with the North Platte River at North Platte, Nebraska. The primary focus of this study is the middle and lower portions of the South Platte River Basin, which consists of the section between Denver and Julesburg, Colorado. The elevation at the mouth of the river is around 2,800 feet, thus resulting in a net altitude change of around 11,000 feet (Litke and Kimbrough, 1998), (Dennehy *et al.*, 1998). The South Platte River drains a basin comprised of approximately 62,940 km^2 within the states of Nebraska, Wyoming and Colorado (Gomez-Ferrer *et al.*, 1983). Colorado accounts for the majority of both the land area (79 percent) and human population (95 percent) of the basin (Dennehy *et al.*, 1998). The basin experiences large temperature fluctuations and irregular seasonal and annual precipitation. Mean temperatures typically increase from the mountainous west to the eastern plains. The plains typically receive anywhere from 7 to 15 inches of precipitation annually, mostly in the form of rain falling between April and September. The mountainous areas, especially along the Continental Divide, have an average annual precipitation of 30 inches or more; the majority of which is in the form of snow (Dennehy *et al.*, 1995). In 1991, the U.S. Geological Survey (USGS) received funding to begin the National Water-Quality Assessment (NAWQA) Program, which was designed to provide a comprehensive assessment of the water-quality conditions of more than 50 of the Nation's largest river basins and aquifers. As a preliminary part of the USGS South Platte NAWQA program, a comprehensive description of the South Platte River Basin was published by Dennehy *et al.* (1993). For the rest of this site description, all information about the basin will be derived from this study unless otherwise noted.

2.3.2 Population

There is a large amount of variation in the population density of the South Platte River Basin. The mountainous areas in the headwaters region and the rural agricultural areas in the eastern plains are sparsely populated, while the Denver metropolitan area in the south-central part of the basin has a high population density. According to the 1990 census, the population of the South Platte River Basin was 2,361,000. Approximately 90 percent of the population can be found in only 10 percent of the basin area (Litke and Kimbrough, 1998). This area, commonly referred to as the Front Range, is located in a narrow band stretching from Denver to Fort Collins along the transition zone between the mountains and the plains. This area has experienced strong growth in the past 15 years. As a whole, the basin has been growing at about 3 percent per year, which is approximately twice the national average. This growth is expected to continue in the urban areas and mountain communities while remaining constant or decreasing in the basin's agricultural communities (Dennehy *et al.*, 1993).

2.3.3 Land Use

Predominant land utilization in the basin includes rangeland (41%), agricultural (37%), forest (16%), urban or built-up (3%), and other (3%) (Dennehy *et al.*, 1998). Of the 5.7 million acres of land categorized as agricultural, 1.1 million are irrigated and 1.6 million are used for dry land farming. The irrigated land is used to grow a variety of crops such as corn, barley, alfalfa, wheat, dry beans, and a large assortment of high-value vegetable crops. Within the watershed, the majority of Colorado's corn, winter wheat, and dry beans are grown (Gates *et al.*, 1993). The remaining acreage is either fallow or non-irrigated pasture. Most of the irrigated land can be found between the cities of

Boulder, Fort Collins, and Greeley as well as the region along the mainstem of the South Platte River in the eastern plains of Colorado.

2.3.4 Water Use

In 1990, the estimated total off-stream water use in the South Platte River Basin was almost 3.9 billion gallons per day. Surface water provided 70 percent of all water use, with ground water providing the remaining 30 percent. The largest areas of water use are along the South Platte River downstream from Denver and along the lower stretches of the major tributaries. Accounting for over 70 percent of the off-stream water use, irrigation is by far the single largest water use in the basin. Other major uses include cooling for thermoelectric power plants (15 percent) and domestic use (8 percent). The thermoelectric power plants withdraw the water for cooling and then return it to the streams. This typically results in a consumptive use of about three percent of the intake water due to evaporation.

As would be expected due to the population distribution in the basin, most of the domestic water use occurs along the Front Range corridor. Ninety percent of the 460 million gallons withdrawn per day for public water supplies is surface water collected in the mountains along the Continental Divide. Lawn watering accounts for 40 percent of the domestic water use.

Not all of the water withdrawn for domestic use is consumed. On average, only about 44 percent of withdrawals are lost via processes such as evaporation, transpiration, or incorporation into products. The remaining 66 percent of the withdrawn water is returned to the hydrologic system and in some parts of the basin can comprise a significant portion of the total river flow.

2.3.5 Surface Water Hydrology

The South Platte River and its major tributaries originate in the Rocky Mountains where the majority of the perennial flow is generated by snowmelt runoff. Upstream from Denver, the South Platte River is regulated by water-supply reservoirs and most of the water is diverted via pipelines to water-treatment plants. Just upstream from Denver, the river flows to Chatfield reservoir. Because it is used primarily for flood control purposes, the inflows usually mirror the outflows.

Between Chatfield Reservoir and Henderson, the river flows through downtown Denver and is joined by several tributaries including Bear Creek, Cherry Creek, and Clear Creek. Flow is also increased through the addition of treated wastewater from 8 plants, which contribute a combined average flow of around 275 cubic feet per second (cfs). On average, approximately 100 cfs are diverted for irrigation use by the Burlington Ditch and other irrigation ditches (Dennehy *et al.*, 1995). From Denver, the river flows north and is joined by three major tributaries by the time it reaches Kersey: the Saint Vrain, Big Thompson, and Cache la Poudre rivers. Even though the sum of the inputs within this reach nearly equals the flow at Kersey, several hundred cubic feet per second are diverted for irrigation within this reach and a significant amount of flow is gained primarily through ground-water return flows. Because of the large volumes of water diverted below this point, the maximum average annual flow in the South Platte River is reached at Kersey.

As the river flows across the plains of eastern Colorado, it passes through a large agricultural region for 250 km before reaching Julesburg. Along this stretch, it is joined by several small streams including Kiowa Creek, Beaver Creek, Lone Tree Creek, and Lodgepole Creek. These streams tend to be ephemeral and contribute little water to the

South Platte during most years except during large storm events. From Kersey to North Platte, Nebraska, the primary alterations to flow are removal of water via irrigation diversions and addition of ground water. At several locations, almost the entire flow can be diverted during the high-demand irrigation season. Below these diversions, the flow in the river gradually increases due to ground water and occasional surface inflows. Much of the ground water inflow is due to irrigation return flows, which add an estimated 1.2 billion gallons per day to the river. Additional inflows come from ground water storage and recharge projects that are being installed to help maintain legal and ecological minimum flow requirements (Dennehy *et al.*, 1995).

Water development has caused substantial changes to the natural hydrology of the South Platte River. There are 15 inter-basin transfer projects that import water from the Colorado, Arkansas, and North Platte River Basins (Dennehy *et al.*, 1995). Starting in the late 1800s, these projects were built to provide a reliable water supply for agricultural production in the arid eastern plains of Colorado. Today, they transport an average of 400,000 acre-feet per year to the South Platte River Basin for use both by agriculture and to help satisfy the demand of the growing population centers. The largest of these projects, the Colorado-Big Thompson Project, transports approximately 285,000 acre-feet per year of Colorado River water through a 13-mile tunnel under the Continental Divide.

Imported and native water is fed into a complex network of ditches, pipelines, and reservoirs spread throughout the basin. This has resulted in an extremely complex operational and legal infrastructure as water is used and reused multiple times for a variety of uses as it moves downstream. Due to the complexity of the water control system, the South Platte River is considered one of the most regulated rivers in the United States (Dennehy *et al.*, 1995).

The increasing urbanization along many of the rivers in the basin has also had an impact on the hydrology of the river. Municipal discharges can sometimes make up a substantial portion of the total streamflow downstream from the discharge point. The Littleton/Englewood treatment plant contributes an annual average of 21 percent of the total river flow at Englewood, Colorado. The Denver Metropolitan Wastewater Reclamation District, which is the largest point-source discharger to the South Platte River, contributes almost 70 percent of the total flow downstream from the discharge point on an annual basis, and at times can contribute as much as 100 percent (Dennehy *et al.*, 1995). This causes the river segment from Denver to the confluence with the Big Thompson River to be dominated by Denver sewage effluent for eight months of the year (Dennehy *et al.*, 1993). Within the entire basin, there are over 100 municipal wastewater treatment plants that discharge anywhere from 0.01 to 150 million gallons per day as point sources (Pocernich and Litke, 1997) and cumulatively return over one million cubic meters of water to the river daily (Litke and Kimbrough, 1998).

2.3.6 Ground Water Hydrology

There are three primary aquifers in the South Platte River Basin (Figure 2-2): the unconsolidated alluvial aquifer, the unconsolidated High Plains aquifer, and the consolidated sedimentary bedrock of the Denver Basin aquifer system (Dennehy *et al.*, 1993). The unconsolidated alluvial aquifer is the most productive aquifer in the basin and is found in both current and historic riverbed channels along the South Platte River and its tributaries. It encompasses an area of about 4,000 square miles and consists mostly of gravel, sands, silt, and clay. Underlying bedrock formations form a relatively impermeable lower boundary to the aquifer. Almost the entire thickness of the alluvium is saturated near the South Platte River where the water table is near the land surface (Robson and Banta, 1995).

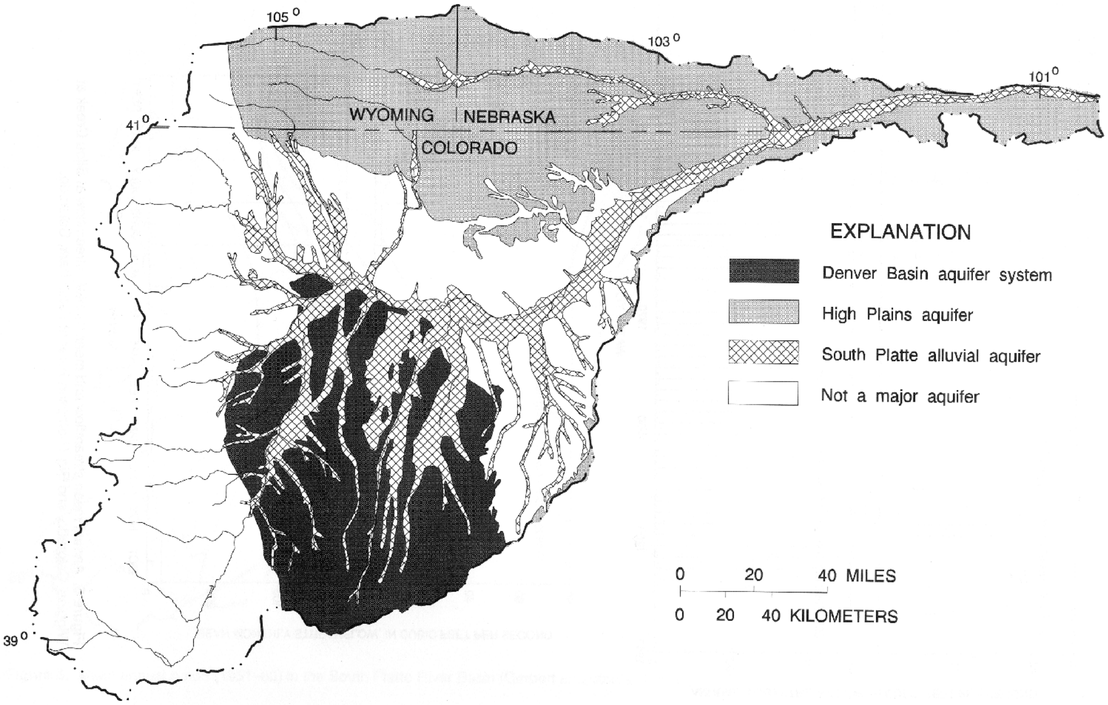


Figure 2-2. Major aquifers of the South Platte River Basin (from Dennehy *et al.* (1993))

The alluvial aquifer is in direct hydraulic connection with the South Platte River and its major tributaries and is recharged through precipitation, percolation of applied irrigation water, and leakage from streams, reservoirs, and ditches (Dennehy *et al.*, 1995). Ground waters in this aquifer generally flow toward the river from the recharge areas resulting in increased streamflow. Intensive pumping during the irrigation season can cause water level fluctuations, however water level declines have not been a significant problem within this aquifer system (Dennehy *et al.*, 1993). The majority of the water pumped from it is used for irrigation of agricultural crops, however due to the decline of some deeper drinking-water aquifers, this aquifer may become an important drinking-water supply in the future (Bruce and McMahon, 1998).

The High Plains aquifer system found along the northern edge of the basin is generally unconfined, but is subject to local confinement due to silt and clay lenses. Although this aquifer has a high water-yielding capacity in other regions, the portions underlying the South Platte River Basin comprise the western edge of the High Plains aquifer and are generally not a significant source of water. In isolated areas, however the aquifer does supply enough water for domestic use along with some limited public supply and irrigation usage.

The Denver Basin aquifer system is found within a 6,700 square mile area in East-Central Colorado. The northern boundary is near Greeley and its southern boundary extents almost to Colorado Springs, Colorado. The Colorado Front Range forms the western boundary and the aquifer system extends east nearly to Limon, Colorado. The Denver Basin aquifer system is composed of four major bedrock aquifers: Dawson, Denver, Arapahoe, and Laramie-Fox Hills. These aquifers are an important source of drinking water for towns in the Denver metropolitan area and in rural communities and farms. Recharge occurs primarily through rainfall, snowmelt, and streamflow. Overuse of the aquifer system has resulted in water-level declines during the past 15 years. These range from 10 to 20 feet in some rural areas to more than 200 feet in the Arapahoe Basin in southeastern Denver. Continuing population growth and resultant increased water demand will likely lead to further water-level declines in the Denver Basin aquifer system (Dennehy *et al.*, 1993).

Due to the large-scale water development in the basin such as water storage projects, conveyance of water to traditionally drier areas, and the importation of large amounts of water to the basin, changes in the spatial and temporal flow patterns have occurred. Before the construction of water conveyance and storage projects, the lower reaches of the South Platte River were ephemeral and would run dry when the supply of snowmelt from the mountains was exhausted. With the development of irrigation in these areas starting around 1860, the alluvial aquifers started to be replenished during spring and summer due to seepage from ditches and fields. Because the South Platte alluvial aquifer system is hydraulically connected to the South Platte River along its entire length, the aquifer slowly drains into the South Platte River in the fall and winter months, insuring at least a small amount of base-flow throughout the entire year (Robson, 1989).

Ground water inflows are also responsible for keeping the river flowing in reaches downstream from several diversion points that sometimes remove almost all the water from the river. A study by Litke (1996), found that the South Platte River is essentially a recycled river. Much of the water diverted for irrigation use infiltrates into the aquifers and is eventually returned to the river via ground-water inflows. Litke's water balance on a site downstream from Kersey using data from April 1994 found that although an average of 1,485 ft^3/s was diverted from the river, this was essentially offset by the average gain of 1,430 ft^3/s of discharge from ground water inflows.

Several other studies have attempted to quantify the amount of ground water inflow to the river. Two independent studies on a 26-mile reach near Fort Morgan in the late 1970's and early 1980's found that ground water inflow along this reach adds approximately 150 ft^3/s (5.77 ft^3/s/mile) of streamflow to the river (Dennehy *et al.*, 1993). A study published by the U.S. Geological Survey in 1995 (McMahon *et al.*, 1995) investigated ground water recharge along a stretch of the South Platte River from 64th Street in Denver to Fort Lupton. Using both mass balance techniques and direct measurements of the instantaneous ground-water discharge across the sediment/water interface in the river channel, they determined that the ground-water discharge rate into the river was 4.6 ft^3/s/mile and that 13 percent of the total river discharge in this reach was due to ground water inflow. All of the studies seem to show that although the ground-water discharge to the stream was variable from one location to another, there is a measurable, consistent discharge to the river and that the discharge rate appears to be related to the saturated thickness of the alluvial aquifers.

To illustrate the amount of water flux and recycling between the aquifer and the river, Dennehy (1993) presented the following estimate: on a basin-wide scale, recharge from irrigation water via both ground water and surface water are estimated to be about 50 percent of what is applied. Therefore, in the South Platte River Basin, this would be approximately 1,200,000 acre-feet per year. Natural recharge to the alluvial aquifer due to precipitation is estimated to be about 372,000 acre-feet per year, and leakage from canals and reservoirs throughout the basin contribute about 200,000 acre-feet per year for a total of approximately 1.7 million acre-feet per year. Assuming that the an estimated 4.5 ft^3/s of ground water inflow per mile of river is valid along the entire length of the South Platte River and its major tributaries, 1.5 million acre-feet of water are added to the South Platte River through ground water inflow every year. These high rates of recycling and return flows have water-quality implications for the receiving water that, according to Dennehy in 1993, had not been properly investigated on a basin-wide scale.

2.3.7 Surface and Ground Water Quality

2.3.7.1 Geologic Impacts

Water quality in the South Platte River Basin is a result of both natural conditions and human factors. Because of the diverse nature of these factors, water quality in the basin tends to be highly variable. Natural conditions that can impact water quality include topography, climate, geology, and the properties of the soils in the basin. Both streams and ground water can be affected by the various geologic formations in which they come in contact. Different geologic formations can contribute a variety of soluble salts, minerals, and trace elements to the water depending on the mineral content of the materials. Other factors influencing the impact of geologic materials on water chemistry include the amount surface area exposed to the water, the length of time water is in contact with the material, and the chemical and physical properties of the water itself.

The South Platte River Basin consists of a variety of lithologies through which surface and ground waters pass. As water contacts these materials it water dissolves certain constituents, resulting in changes in the chemical composition of the water and an increase in the concentration of dissolved solids. The Pierre Shale is one particular geologic formation found in the basin that has a high potential for causing changes to the chemical composition and dissolved solids concentrations of water passing through it. Because it is a marine deposit, the Pierre Shale is rich in soluble salts such as calcium, sodium, and magnesium. Pierre Shale is found along the Foothills Belt, which each major tributary to the South Platte flows through on the way to the South Platte River.

The main stem of the South Platte River is also exposed to Pierre Shale in certain areas of the Eastern Plains.

2.3.7.2 Anthropogenic Impacts

The South Platte River system is subjected to a large number of anthropogenic factors such as water use, population, land-use, and water management practices that can have a pronounced impact on water quality. In fact, water quality in the South Platte River Basin has been affected by human activity more than any other river basin in Colorado (Colorado Department of Health, 1988), (Gates *et al.*, 1993). Not all anthropogenic factors are necessarily detrimental to water quality in the basin. On a local scale, transfers of high-quality water into the basin have the effect of diluting constituents in the receiving water. This narrow view, however, ignores the possible negative impacts of such transfers on the contributing basin. The primary activities with the potential for impacting water quality in the basin are mining, urbanization, and agriculture.

The impact of mining occurs predominately in the mountain headwaters of the South Platte River and several of its tributaries including Clear Creek and the North Fork of the South Platte River. These rivers drain one of the primary metal mining regions in Colorado. The large number of active and abandoned mines in this region has impacted streams through point-source mining discharge and through non-point surface and subsurface runoff from mined areas. As a result, concentrations of copper, zinc, manganese, iron, cadmium, mercury, and lead are elevated in some reaches of the streams. Little is known about the transport of these heavy metals into the middle and lower portions of the basin. Both in the foothills area and along the main stem of the South Platte River downstream from Denver, there is a large amount of gravel mining that has had an effect on the local hydrology and has the potential to impact water quality. Uranium concentrations in the South Platte River Basin are among the highest in the nation. Although uranium mining was once active along the Front Range, is not known whether these activities had any water-quality effects on the river. There has been substantial oil and gas development within the basin, especially in southwestern Weld County. While these activities are known to have significant local effects on surface and ground water quality, little is known about potential larger scale effects.

Although urbanized areas comprise only a small portion of the total basin area, they have a disproportionate effect of the water quality of the river. Urbanization effects occur mostly along the Front Range where the majority of the population is clustered. These effects come from both point-sources such as municipal and industrial discharges, and non-point sources such as storm runoff and subsurface return flows. In the Denver metropolitan area, urbanization of watersheds has resulted in accelerated eutrophication of area reservoirs. In examining sources and loads of nutrients in the South Platte River, Litke (1996) found that wastewater treatment plant discharges were almost entirely responsible for the total nitrogen load at Henderson, which is directly downstream from the Denver metropolitan area and its wastewater treatment plants. Even 60 miles downstream from Denver, the proportion of the nitrogen load attributable to wastewater treatment plants was nearly 50 percent. Urban storm runoff has been shown to be a significant contributor of ammonia, copper, iron, lead, and zinc to downstream waters. Urban snowmelt runoff during the winter and spring months was historically a significant contributor of sodium and chloride to downstream waters (Ellis and Alley, 1979). Before the NAWQA study, most studies had focused on changes in quantity and quality of runoff from small basins after urbanization. Relatively few have examined the cumulative effect urban runoff has on the South Platte River (Dennehy *et al.*, 1993). Urban impacts on salinity in the South Platte River Basin will need to be addressed when assessing the both the causes of the salinity problem and potential management strategies.

Agricultural impacts on water quality can occur along the Front Range region where there is a significant proportion of agricultural land, as well as in the vast agricultural regions of the eastern plains. Water quality can be impacted directly through the application of agricultural chemicals and animal wastes to soils, which sometimes reach rivers and reservoirs through return flows. Agriculture can also have secondary impacts on water quality by increasing the potential for erosion, which can cause an increase in suspended sediments. Consumptive use of water and the dissolution of geologic salts in the soil can contribute to increased salinity levels. Changes in the flow and temperature regimes of the river can increase or decrease the amount of water available to dilute contaminants and can have an impact on biological communities within the river. Agricultural pesticides can sometimes be found in surface water downstream from agricultural production areas. The South Platte NAWQA study (Dennehy *et al.*, 1998) detected low concentrations of several of the most commonly used pesticides throughout the agricultural areas of the basin during the growing season. An estimated 200,000 tons of nitrogen and 40,000 tons of phosphorus in the form of chemical fertilizer or manure are applied in the basin each year (Litke, 1996). Although nutrient concentrations were generally highest immediately downstream from wastewater treatment plants, alluvial ground waters below isolated pockets of agricultural lands receiving applications of agricultural fertilizers and manure were found to have elevated nitrate concentrations (Dennehy *et al.*, 1998).

2.3.7.3 Overview of Water Quality in the Basin

Due to the varied geology of the South Platte River Basin, each of the principal aquifer systems has different water-quality characteristics. Because of local geologic variability and occasional anthropogenic effects, these characteristics can also vary greatly within the individual aquifers. For example, the alluvial aquifer has a median dissolved-solids concentration of 1000 mg/L, but the range is between 100-500 mg/L in the upper part of the aquifer to more than 2500 mg/L in the lower region. Water in this aquifer is generally either a calcium bicarbonate or calcium sulfate type and ranges from hard to very hard (Dennehy *et al.*, 1993). While shallow ground water aquifers such as this generally tend to have fewer dissolved constituents than deeper water supplies in buried aquifers, they are particularly vulnerable to water-quality degradation due to surface activities (Bruce and McMahon, 1998).

With the exception of an increase in the dissolved solids concentrations in some deeper portions of the aquifer, the consolidated bedrock aquifers within the Denver Basin aquifer system are generally considered to have excellent water quality. Dissolved-solids concentrations typically increase with the distance from recharge outcrops. Dissolved-solids concentrations in the Dawson aquifer are generally less than 200 mg/L, while those of the Denver, Arapahoe, and Laramie-Fox Hills aquifer are generally less than 700, 1000, and 1200 mg/L respectively. Waters are mostly calcium and sodium bicarbonate or sodium sulfate types. Additional discussion of ground water quality in the basin is presented in Section 2.4.3 with the summary of the USGS publication by Bruce and McMahon (1998).

Both the main stem and major tributaries of the South Platte River show an increase in dissolved solids concentrations in a downstream direction. The average TDS concentration ranges from 95 mg/L above Denver to 1,550 mg/L about 200 miles downstream at Julesburg. Calcium and sodium are the principal cations in surface water, and bicarbonate and sulfate are the principal anions in surface water in almost all streams within the South Platte River Basin.

Even with all the prior water-quality studies that have been done on the basin, at the onset of the South Platte NAWQA program, Dennehy et. al. (1993) concluded that the relative effects of mining, urbanization, and agriculture on water-quality constituents in the basin were not well understood. They also saw the need to address the interrelation of the surface water and ground water systems and the chemical and biological processes that affect the transport of various constituents. The completion of Phase I of the South Platte NAWQA program furthered the level of understanding on these issues, but there is still plenty of work that needs to be done before this complex system can be fully understood. This is especially true in regard to understanding the past, present, and future status of salinity in the basin.

2.4 SALINITY IN THE SOUTH PLATTE RIVER BASIN

2.4.1 The Salinity Problem

As with many irrigated lands in the western United States and many parts of the world, soil salinization is believed to be increasing in the irrigated fields of northeastern Colorado. The USDA’s Natural Resources Conservation Service estimates that up to 25% of the irrigated land along the South Platte in eastern Colorado is now affected by salinity. High soil salinity levels have begun to limit the species of crops that can be successfully grown in these areas and have even reduced the yield of more tolerant species (West Greeley Soil Conservation District, 1999).

In conversations with state Cooperative Extension Specialists and agricultural professionals in northeastern Colorado, Lord (1997) reported that everyone interviewed expressed concerns over what they perceived to be an increasing soil salinity problem and the current and future impacts of elevated salinity levels on agricultural production and processing in this part of the state. One of the most impacted groups so far has been the dry bean producers because this crop tends to be more salt sensitive than many other common row crops. Because of the problems growing dry beans, the processing plant in Sedgwick County had to shut down (Lancaster, 2000). In Logan County, cases were cited of farmers along the South Platte River who were no longer able to grow beans and had switched to growing corn but were now having salinity-related yield reductions with the corn as well. Near Cook, Colorado, extremely saline fields have had to be abandoned because the producers could not get a more-salt tolerant crop such as alfalfa to grow (Lord, 1997).

2.4.2 Potential Causes

To date, no comprehensive studies have been done to document both the causes and extent of the salinity problem in northeastern Colorado. It is commonly believed that a major factor contributing to the increased soil salinity is elevated water table levels (sometimes less than a foot from the surface) commonly caused by the application of excess irrigation water, seepage from canals and reservoirs, and insufficient drainage. Water from the elevated water tables is continuously drawn to the surface and evaporates, leaving its load of salt behind. The other major factor believed to be contributing to soil salinity problems in the basin is the amount of dissolved salts contained in the irrigation water that is often derived from the South Platte River. In addition to having direct detrimental effects on plants, the application of water with significant amounts of dissolved solids to lands with elevated water tables can increase the mass of salts that will be left behind in the soil when the water evaporates.

The concentrations of dissolved solids in the middle and lower portions of the South Platte River and even in the lower portions of some tributaries are often high enough to have the potential to reduce the yields of some crops. As with most significant river salinity increases, a combination of salt concentration and salt pickup are believed to be responsible for increasing these levels. Salt concentration is likely to be a significant factor behind the increased salinity levels because of the large amount of irrigated agriculture in the basin, the high amount of evapotranspiration losses when used as irrigation water, and the interconnectedness of the surface and ground water systems (Dennehy *et al.*, 1993). Every time river water is diverted and used for irrigation, a significant portion of it is lost to evapotranspiration, resulting in increased dissolved solids concentrations in the water that remains. This water then percolates through the soil and into the ground water system-picking up minerals along the way before it eventually finds its way back to the river where it is likely to be used for irrigation several more times before it exits the basin.

With such a large and varied basin such as the South Platte, there are many potential contributors to salt-pickup by the river. One contributor likely to be very significant is the geology of the basin. Among the various geological formations, the one believed to have the most potential for contributing dissolved solids to water which comes in contact with it is the Pierre shale formation. Underlying almost the entire basin, Pierre Shale is rich in sodium and is a large contributor of other dissolved solids. Seepage water from Pierre Shale has been found to have TDS concentrations ranging from 4,000 to 6,000 mg/L (Deweese *et al.*, 1993). Although aquifers within the Pierre Shale are not high-yielding and therefore are generally not used as a water source, there is the potential for seepage of water with high concentrations of TDS from the shale aquifers to surrounding higher-yield aquifers and adjacent water bodies. In some parts of the basin in Morgan and Logan counties, the Pierre Shale is exposed to the surface (Bjorklund and Brown, 1957) where it can contribute dissolved solids to the rivers via surface runoff and channel erosion of rivers and canals that run through it.

Many other common sources of dissolved solids can be found in the basin. Due to the high population density along the rivers, urban contributions, including sources such as wastewater treatment plants and highway deicers, have the potential to be a significant source of dissolved solids. To date, however, these sources of dissolved solids have been among the least studied. Some areas of the basin, especially parts of Weld County, are important petroleum-producing areas. Formation waters associated with oil production can contain high levels of dissolved solids (Lord, 1997). According to Bjorklund and Brown (1957), these formation waters can have concentrations of sodium ranging from 950 to 4480 mg/L. TDS concentrations above 5000 mg/L in formation waters are common, with some areas reaching as high as 12,400 mg/L. The use of unlined formation water holding ponds in the past was shown to be responsible for the salt-water contamination of freshwater wells near the ponds (Lord, 1997), however it is not known if these prior practices continue to have an impact on water quality.

2.4.3 Previous Studies

Gomez-Ferrer and Hendricks (1983) performed a comprehensive evaluation of dissolved-solids concentrations and loads within the lower South Platte River Basin in the early 1980s. Utilizing USGS records of daily and monthly salinity and flow data for the

15-year period from 1965 to 1979, they performed a materials balance analysis for water and salt for a 343 km stretch of the river between Henderson and Julesburg. Within this stretch, they examined records from 5 mainstem monitoring sites and 3 tributary sites. They attempted to incorporate all major inputs and outputs of water and salt to and from each reach; including return flows, diversions, tributary flows, and point source discharges. Interestingly, even though point source discharges from canals were considered, wastewater discharges from municipalities and industries within the basin were assumed to not have significant affects on river salinity because they were said to comprise only seven percent of the total diversions.

Load calculations were performed by first converting EC data to TDS using a linear TDS-EC regression relationship determined independently for each site. A linear log salt mass flow-log water flow regression relationship was fitted to the data for each of the monitoring sites by season. This allowed the daily salt mass flow to be computed using daily flow values and the corresponding regression relationship. For the water balance, return flows were computed as the residual of all inflows and outflows to the reach. For point sources discharges and diversion flows in which the TDS concentration levels were not known, values were assumed using averages of the nearest available values. The flow weighted mean annual TDS concentrations for the Saint Vrain River, Big Thompson River, and Cache la Poudre River were found to be 867, 1,393, and 1,018 mg/L, respectively.

At Julesburg, the mean annual flow during the 15-year study period ranged from 2.8 to 43 cubic meters per second and the mean salt mass flow ranged from 400,000 to 3,700,000 metric tons per day. The flow weighted annual mean salt concentration was somewhat less variable, ranging from 1,000 mg/L TDS at the highest flow to 1,600 mg/L TDS at the lowest flow. Plots of the flow profile from Henderson to Kersey showed that the average annual flow doubled between the sites due to the large tributary inflows within this segment. Downstream from Kersey, the flow declined sharply as a result of irrigation diversions. This flow decline continued as the river passed Weldona, than stabilized in the stretch from Balzac to Julesburg.

Salt concentrations were found to sharply increase from Henderson to Weldona. Gomez-Ferrer and Hendricks attributed this to the tributary inflows along this stretch, which they say are comprised largely of irrigation return flows. An exception to this phenomenon occurs during the spring when snowmelt comprises a large portion of the tributary inflow. The TDS concentration change between the upstream and downstream sites was found to range from 450 mg/L to 950 mg/L during years with high flows and from 600 mg/L to 1,400 mg/L during low flow years such as 1977. Plots of salt mass showed that salt load was being gained from Henderson to Kersey and lost between Kersey and Balzac. Gomez-Ferrer and Hendricks attributed the salt-mass accumulation between Henderson and Kersey to the salt content of irrigation return flows from the three tributary streams carrying salt leached from the lands they drain. During the study period, an average of 1,700 metric tons per day of salts from land along the Front Range was reaching the South Platte River. The loss of salt mass from downstream portions of the river was attributed to irrigation diversions, which remove both water and the associated dissolved solids load it carries. Although there is a slight gain in salt mass from Balzac to Julesburg, the net loss between Kersey and Julesburg was found to be approximately 380 metric tons per day. Over half of the mass of salt lost in this stretch was found to be diverted from the river in the fall and winter when salt concentrations are highest and in-stream flows are low. The authors calculated that if this amount of salt mass was distributed evenly over the 330,000 acres of irrigated land between Kersey and Julesburg, each acre would receive approximately 0.42 metric tons of salt per year.

In order to create a salt balance for the basin so that agricultural production would be sustainable, Gomez-Ferrer and Hendricks provided several management recommendations. The first was to improve drainage in the lower part of the basin to allow return flows to carry the salts back to the river. A second recommendation was to change the current operation of the reservoirs, which normally refill the reservoirs by diverting flow between Kersey and Balzac during the fall and winter. Since the highest salinity occurs during the fall and winter, it was suggested that flow during this period be allowed to continue downstream in order to transport salts from the basin. The Narrows Reservoir, which was under consideration at the time but never constructed, was suggested as a possible source of replacement water. The final management recommendation was to reduce the amount of salt leaching from the upper lands through the use of more efficient irrigation practices. It was the author's hope that continued routine analysis of water and salinity data in the river basin would provide policy guidance for improved salinity management during future water resources development and operation.

A similar study was completed in 1997 at Colorado State University by Sara Lord (1997) as part of her Masters degree research. Using data primarily from the USGS, she examined salinity in the South Platte River Basin during the period 1963 through 1994. The study area was the same as that examined by Gomez-Ferrer and Hendricks (1983) and used data from the monitoring sites at Henderson, Kersey, Masters, Weldona, Balzac, and Julesburg as well as sites at the mouths of the Saint Vrain, Big Thompson, and Cache la Poudre rivers. The goals of the project were (1) to perform a salt balance analysis within this section of the river in order to identify stretches that are the largest contributors of salt, (2) to examine changes in salt concentration over time at the major monitoring stations, and (3) to determine how salt load increases and decreases along the length of the river. Methods for calculating salt load and for performing the water and salt mass balance were similar to those used by Gomez-Ferrer and Hendricks.

Results from the water balance highlighted some discrepancies in the available data, especially for the river segment between Balzac and Julesburg. The author concluded that a more detailed study of this section would need to be performed to better understand the movement of water into and out of this segment. A comparison of the spatial variability of the salt loads at the mainstem monitoring stations highlighted the large gain in salt loads between Henderson and Kersey. Again, this was attributed to several factors with the most important being the flow of the three major tributaries within this section. Mean annual salt loads contributed by the Saint Vrain River, the Big Thompson River, and the Cache la Poudre River were calculated to be 176,000, 9,150,000, and 138,000 metric tons respectively. The techniques used to deal with gaps in the data record when performing the load calculations might have introduced significant error into these results. The application of data reconstruction methods using data from adjacent monitoring sites followed by revised load calculations would provide more insight into the load contributions from these three tributaries.

In the middle stretch of the study section, the salt loads were found to decrease, especially between Kersey and Masters. This was attributed to the large amount of water diverted into the 15 canals between Kersey and Balzac. Depending on the year, they divert between 1.0×10^9 to 1.0×10^{10} cubic meters of river water and associated dissolved solids contained in it to the irrigated lands in this region. The unused portion of this water finds its way back to the river primarily via subsurface flows. The water and salt balance indicated that ground water inflows contributed to both the flow and salt loads of the river in this section. Although the salt loads in the river is higher at Julesburg than it was at Balzac, Lord states that this section of river was actually gaining salts because much of the water used for irrigating this region is diverted upstream from the site at Balzac. This conclusion was supported with accounts from county agents and others in the region that feel the soil salinity problem is more severe along this stretch than in other parts of the basin and that it is continuing to get worse.

Trend analysis was performed on the flow-adjusted TDS concentrations for each of the major monitoring sites along the mainstem of the South Platte River that were included in this study. Using the seasonal Kendall test, the author found evidence of significant increasing trends in concentration at Henderson (2.1 mg/L/yr) and Julesburg (3.1 mg/L/yr) and significant decreasing trends at Masters (-11.4 mg/L/yr) and Weldona (-5.9 mg/L/yr) during the 32-year period examined in the study. No attempt was made to provide possible explanations for why these trends might be occurring. The monitoring sites at Henderson, Kersey, and Weldona had significant gaps of up to 10 years or more in the data record which might have impacted the results of the trend analysis at these sites. Further analysis of the data including trend analysis of both flow-adjusted and non-flow-adjusted concentrations along with an examination of changes in the management of the river system might result in a greater degree of confidence in the results and should provide some insight into the mechanisms behind the observed trends.

A cursory examination of changes in the major ion composition at sites along the lower South Platte was performed using pie charts which displayed individual ion concentrations (mg/L) as a fraction of the total dissolved solids. This was done using both the average values of each site for the entire 32 years and in ten-year block averages to look for changes in the composition of the dissolved solids over time. Sulfate was found to be the dominant ion while phosphorus, potassium, and magnesium comprised only a small portion of the total dissolved solids. Large changes in the average composition of the dissolved solids were observed between monitoring sites, but a consistent composition was observed at each site for each 10-year average. This showed that the composition of dissolved solids in the river changes spatially along the river, but the composition has not changed much over the 32-year period of this study. This suggests that the sources of dissolved solids in the river have not changed drastically during this period.

Sodium Adsorption Ratio (SAR) values were examined to determine the potential impacts on soil structure and water infiltration that could occur when irrigation water contains an unfavorable balance in the concentration of sodium versus the concentration of calcium and magnesium. Of the 1,215 records that contained a value for SAR, the author did not find any that could be considered potentially dangerous for use in irrigation. Similarly, an examination of 345 surface water-quality records containing an analysis of boron concentration revealed only two with a value that exceeded the maximum recommended value of 500 μg/L which can be toxic to sensitive plants. The report does not state whether any boron concentrations from ground water samples were examined, but it does state that the Morgan County Cooperative Extension Agronomy Specialist had observed increased levels of boron in some ground water analyses from wells in the county. This highlights the need to incorporate boron analysis in future ground water-monitoring programs.

Like the earlier study by Gomez-Ferrier and Hendricks (1983), the results of Lord's study show that the majority of the salt load in the South Platte enters the river between Henderson and Kersey. Additionally, it shows that salt mass is being lost between Kersey and Julesburg where it is most likely deposited in the soils and ground water as a result of irrigation. The author recommends that future work be performed to identify the sources along the Front Range that are contributing significant amounts of salt to the South Platte River so that appropriate management plans might be developed.

As part of the U.S. Geological Survey's NAWQA program, twelve fixed sites in the South Platte River Basin were sampled monthly from March 1993 to September 1995 (Litke and Kimbrough, 1998). Samples were subjected to field measurements for temperature, pH, specific conductance, and dissolved oxygen. Laboratory analysis was used to determine the concentrations of major constituents, organic carbon, nutrients, and suspended sediment. After conducting summary statistics on these data, the authors summarized the water-quality concentration data, investigated the effects of land use on constituent concentrations, and developed estimates of stream loads for selected constituents. Additionally, historical USGS data were used to look for evidence of historical trends in concentrations at selected sites.

As would be expected given the diverse nature of the basin, median specific conductance varied substantially among the fixed sites. The lowest median specific conductance value was 29 µS/cm, which was observed at the Big Thompson River below Moraine Park, near Estes Park, Colorado. The largest value observed was 1,940 µS/cm at Lone Tree Creek near Greeley, Colorado. Median specific conductance increased in a downstream direction from Denver to Henderson to Kersey to Balzac, Colorado, and then decreased between Balzac and North Platte, Nebraska. Although there are no state stream standards for dissolved solids, the U.S. Environmental Protection Agency has a recommended limit of 500 mg/L for drinking water. In this study, two sites that are classified for water-supply use had median dissolved-solids concentrations greater than this limit. Cherry Creek at Denver, Colorado and the South Platte River at Henderson, Colorado had a median dissolved-solids concentration of 642 mg/L and 557 mg/L, respectively. One site classified for agricultural use had a median dissolved solids concentration greater than the commonly recognized level of 1,500 mg/L which, if used as irrigation water has the potential to cause crop damage. Lone Tree Creek near Greeley, Colorado is a small ephemeral plains stream that had a median dissolved-solids concentration of 1,540 mg/L.

Chloride was not a predominant ion at any of the sites and did not exceed the chronic standard of 250 mg/L for use as a water supply. The range in median sulfate concentrations mirrored that of median specific conductance with the lowest value of 1.6 mg/L occurring at the Big Thompson River below Moraine Park, near Estes Park and the highest value of 760 mg/L occurring at Lone Tree Creek near Greeley.

Sulfate was often a predominant anion at many of the sites, but among the sites classified for use as a water source, only the site located on Cherry Creek at Denver (median dissolved sulfate concentration: 270 mg/L) exceeded the chronic standard of 250 mg/L. The largest concentrations of dissolved sulfate were found at agricultural and mixed urban/agricultural sites. The authors speculated that the concentrations might be due to application of sulfur and sulfate in fertilizers applied to agricultural lands, which were then being transported to surface water through irrigation return flows.

A closer examination of the author's assumptions regarding the cause of elevated sulfate concentrations tends to cast doubt on their unsubstantiated speculation. Sulfate is regarded as a micronutrient required by plants in only small quantities. As a result, it is typically applied as a fertilizer in very small quantities. Because of the small amounts applied, fertilization of agricultural lands is unlikely to have any significant impact on the elevated sulfate levels typically observed in the lower South Platte River Basin even if all of the applied mass eventually reached the river. Additionally, this assumption ignores the large amount of sulfates naturally present in the geology of this region which are much more likely to be the primary source of dissolved sulfate. Before accepting this kind of conclusion, more work should be done to investigate the total mass of sulfate added to the basin via fertilization and the potential impact it would have on sulfate concentrations in downstream surface waters.

Piper plots were used to illustrate the median ionic composition of water from the various sites. Calcium and sulfate were found to be predominant in water from agricultural sites. The water type at these sites was found to be similar to the type in alluvial water from agricultural wells along the South Platte River. Water from the sites representing urban land-use appeared as a distinct group on the Piper diagram. Samples from these sites were found to have more sodium and/or potassium and more chloride than water from agricultural sites. The ionic composition of water from sites having a mixture of urban and agricultural land use appeared on the Piper plots between samples from purely agricultural sites and purely urban sites. Most of the forested and rangeland sites plotted as a group on the Piper plots and were classified as calcium bicarbonate-dominated waters. Samples from Clear Creek at Golden, Colorado were found to be an exception to the rest of the forest sites. These samples had a composition more similar to the urban/agricultural sites. The authors concluded that other factors besides the predominant land use are controlling the water quality at this site.

The seasonal Kendall test was applied to data obtained from the USGS and U.S. EPA for the period 1963-1996 to examine the possibility of trends in constituent concentrations and streamflow. Significant upward trends in streamflow and significant downward trends in salinity were observed at sites along the river. The results of trend testing were the same for flow-adjusted data and non-flow-adjusted data, except that the magnitude of change was larger for the non-flow-adjusted data. Upstream sites at Denver, Henderson, and Kersey indicated a significant downward trend in specific conductance while downstream sites had mixed results. No trend was observed at Balzac and an upward trend was indicated at North Platte, Nebraska. Hardness, chloride, and sulfate also had downward trends except for an upward trend in chloride near Balzac. The authors concluded that since the downward trends occurred even in the flow-adjusted data, the sources of these constituents may have declined during this period except in the lower part of the river where salinity problems might be increasing.

Load calculations were performed for eleven of the twelve fixed sites by multiplying daily mean streamflow by constituent concentrations estimated for each day. Daily constituent concentrations were estimated through a linear time-based interpolation between concentrations on sample dates. These estimates were modified by discharge-based interpolation during storms. Daily load estimates were summed by month and water year to provide mean monthly and yearly load estimates for the period of study. The mean annual dissolved solids load increased from Denver to Kersey and was the largest (810,000 tons) observed. This monitoring site also had the largest mean streamflow observed in the study. Between Kersey and North Platte, Nebraska, the mean dissolved-solids load was found to decrease by a factor of about 1.4. The spring runoff season that normally occurs between May and June was found to be the most significant two-month period for transport of dissolved solids. During this period, the river transports an average of 40 percent of the entire annual dissolved solids load.

A principal hypothesis of the USGS NAWQA study design is that differences in water quality are a result of different land uses (Litke and Kimbrough, 1998). A major focus of Litke & Kimbrough's report was to test this hypothesis by looking for significant differences in the water quality of samples derived from each of the major land uses. While this approach might provide some scientific value as an indicator of possible water-quality degradation due to land use, it does not always provide a reliable method for determining the actual reasons for the observed differences, especially when examining naturally occurring water-quality constituents such as major ions. To assume that land-use is the controlling factor in the water quality at any given point is not always valid, especially for ground water-dominated rivers such as the South Platte. In many cases, the geology of the runoff area and aquifers can have a much larger impact. As an example, consider the differences observed in median specific conductance between the forested site on the Big Thompson River near Estes Park and the agricultural site on Lone Tree Creek. The difference in water quality between these two sites is clearly not simply due to the fact that one is covered with trees and the other is farmed. The mountain site near Estes Park has a crystalline bedrock aquifer and the agricultural site has an alluvial aquifer in which the water is often in contact with sandstone and shale which can contribute large amounts of dissolved solids. If the land uses were reversed and the Eastern Plains were covered in forest while the mountains were farmed, the approach used in this study would have found that the agricultural land-use had the lowest concentrations of dissolved solids.

The U.S. Geological Survey in conjunction with the Northern Colorado Water Conservancy District and the U.S. Bureau of Reclamation completed a retrospective study in 1990 which examined historical data from monitoring sites which were associated with the Colorado-Big Thompson Project (CBT) (Mueller, 1990). The purposes of the project were to gain an understanding of the water quality at each site including significant trends in specific water-quality constituents and to evaluate the current monitoring system with respect to the number of sites monitored, frequency of sampling, and the constituents examined. A total of 10 sites were examined: four of which were on natural streams, three were on the CBT Project carriage facilities, and three were on CBT Project reservoirs. The four sites on natural streams were located on Boulder Creek and its mouth near Longmont, the South Platte River at Masters, the South Platte River near Weldona, and the Colorado River near Radium. The site on the

Colorado River was chosen to evaluate the potential impacts water diversions by the CBT project might be having on the Colorado River. All data used in this study were retrieved from the U.S. Geological Survey Water Data Storage and Retrieval System (WATSTORE).

The study found that mean values of specific conductance were 50-60 μS/cm at headwater sites and increased to about 1600 μS/cm downstream. Trend analysis using the seasonal Kendall test was performed on original and flow-adjusted data from the early 1970s through 1987. Flow-adjusted concentrations were defined as the residuals (actual minus estimated value) of a linear regression between the logarithm of streamflow and the logarithms of each constituent examined. Results indicated significant reductions in specific conductance, dissolved-solids concentrations, and concentrations of major dissolved constituents at many sites in the basin. The magnitude of decreases in dissolved solids concentrations ranged from 0.3-27 mg/L per year. The site in the upper Colorado River Basin was found to have an increasing trend in dissolved-solids from 1981 through 1987 at a rate of 4.4 mg/L per year. This is possibly a result of upstream diversions via the CBT, which remove water with a low concentration of dissolved-solids. This leaves less freshwater available for dilution of more saline inflows downstream.

This report did not provide any possible explanations for the observed decreasing trends in specific conductance at sites associated with the Colorado River Basin headwaters (Lake Granby near Granby, Granby Pump Canal near Grand Lake, and Alva B. Adams Tunnel at east portal near Estes Park). Decreases in specific conductance at these sites were thought to have influenced specific conductance in downstream sites including the Olympus tunnel, Carter Lake, and the South Platte River near Weldona. Sites at the Olympus Tunnel and the South Platte River near Weldona also had decreasing trends in many of the major ionic constituents. The site on the South Platte River near Weldona had an average change in mean dissolved-solids concentration of -27 mg/L per year, which amounts to a 31 percent decrease during the 16 years of record. The magnitude and significance of the decrease at the site are much larger than those observed in CBT project delivery water, indicating that changes in CBT project water quality are not the sole cause of trends observed downstream. Dissolved sulfate concentrations represent the largest component of the decrease in dissolved-solids concentrations observed at the Weldona site. The authors speculated that since sulfate is commonly associated with agricultural return flows, the trends at this site could be due to changes in irrigation practices in the South Platte River Valley.

As part of the USGS South Platte NAWQA study (Bruce and McMahon, 1998), fifty-seven wells representing several combinations of land-use and aquifer settings were sampled once each between 1993 and 1995 and analyzed for approximately 170 constituents. Major-ion concentrations were relatively low in upstream wells representing urban land-use and a crystalline bedrock aquifer, while wells in the downstream study area representing agricultural land-use and alluvium aquifers had much higher concentrations of dissolved solids. The increase in dissolved solids concentrations was correlated with a change from bicarbonate to sulfate as the dominant anion and by increasing concentrations of calcium, sodium, and sulfate. Samples from wells representing urban land-use and alluvium aquifers exhibited water-quality characteristics somewhere between the other two study areas. A median dissolved-solids concentration of 833 mg/L was found in the urban alluvium and 1,510 mg/L in the agricultural alluvium. Median sulfate concentrations in the agricultural alluvium study area were 695 mg/L. Although the authors concluded that natural rock/water interactions and anthropogenic land-use activities affect the quality of shallow ground water in the region, the design of their study did not allow for the impacts from land-use and aquifer type to be examined independently.

Even with the results of these studies, there are still many questions that need to be addressed to fully understand the salinity problem in the South Platte River Basin. These previous studies did a good job in documenting changes in dissolved solids concentrations and loads occurring along the middle and lower portions of the South Platte River, however some of the major questions that still need to be addressed are:

1. What are the primary sources of these dissolved solids?
2. Where are these dissolved solids entering the river?
3. What processes or mechanisms are causing the salts from these sources to migrate into the river system?

Most of the previous work has concentrated on the middle or lower portions of the South Platte River, but found that the majority of the salt load is entering these stretches via the major tributaries. A more detailed examination of the tributaries is needed in order to determine where this loading is occurring and identify the major sources. Identification of the major sources and quantification of their relative contribution to the total salt mass in the river will provide a much clearer picture of the causes of the salinity problem in the basin. More examination of historical data for seasonal, spatial, or long-term changes in the composition of the dissolved solids will provide a better understanding of the problem. Carefully conducted trend analysis of historical data in conjunction with an examination of management and other salinity-impacting changes in the basin might reveal explanations for some of the discrepancies observed among several of the previous studies.

Once these questions have been addressed as part of a complete characterization of the salinity problem in the basin, management and engineering recommendations can be developed to provide guidance in managing and possibly even reducing the salinity problems in the South Platte River Basin.

CHAPTER 3: DATA COMPILATION AND PROCESSING

3.1 INTRODUCTION

Streamflow and salinity measurements were required for the calculations of salt loads and other parameters found later in this study. This chapter describes how the historical streamflow and water-quality monitoring data for the South Platte River Basin, including major tributaries, were compiled and processed. As described below, water quality has been monitored at 763 sites in the basin, the vast majority of which are inconsequential to this study. The 43 sites included in this analysis represent those deemed significant for two reasons: (1) geographic, e.g., those along the South Platte and its major tributaries, and (2) adequacy of historical record. The resulting streamflow and water-quality databases provide the underlying data required for salinity characterization, dissolved solids load analysis, and mass balance modeling work described in the remaining chapters of this text.

3.2 HISTORICAL WATER-QUALITY DATA

3.2.1 Data Sources

All available historic water-quality data for all USGS surface-water monitoring sites within the South Platte River Basin were obtained in electronic format from the United States Geological Survey’s (USGS) National Water Information System (NWIS) online database (U.S. Geological Survey, 2006). The U.S. Environmental Protection Agency's (EPA) STORET water-quality database (U.S. Environmental Protection Agency, 2007b) was evaluated as an additional source of data, however it was determined that it would not provide any additional benefit beyond the use of NWIS by itself. When the data retrieval from NWIS was performed in late 2005, records were only available to the public through September, 2004 due to the time lag associated with quality assurance checks performed by the USGS. The initial data retrieval from NWIS resulted in data for 763 sites and included water-quality measurements from March, 1900 through September, 2004. The period of record for each site varied widely with many sites having limited data.

3.2.2 Site Selection

Of the 763 water-quality monitoring sites in the South Platte River Basin, 43 were selected as integral to this study. Geographic location played the largest role in selecting sites. Completeness of historical records played a secondary role. The resulting database contained data for 43 sites. Due to the lack of regular monitoring at any of the 43 selected sites before October, 1949 (water year 1950), records prior to water year 1950 were excluded from additional analysis. The database was further screened to remove multiple, same-day observations and to remove non-routine sampling events (as noted in the "Hydrologic Event" field of the USGS database), such as events occurring during floods. The 43 sites selected from this screening are listed in Table 3-1 along with the respective USGS site name and USGS identification number. Also listed are the site code and abbreviated site name used throughout this study. The location of each of the sites within the basin is shown in Figure 3-1.

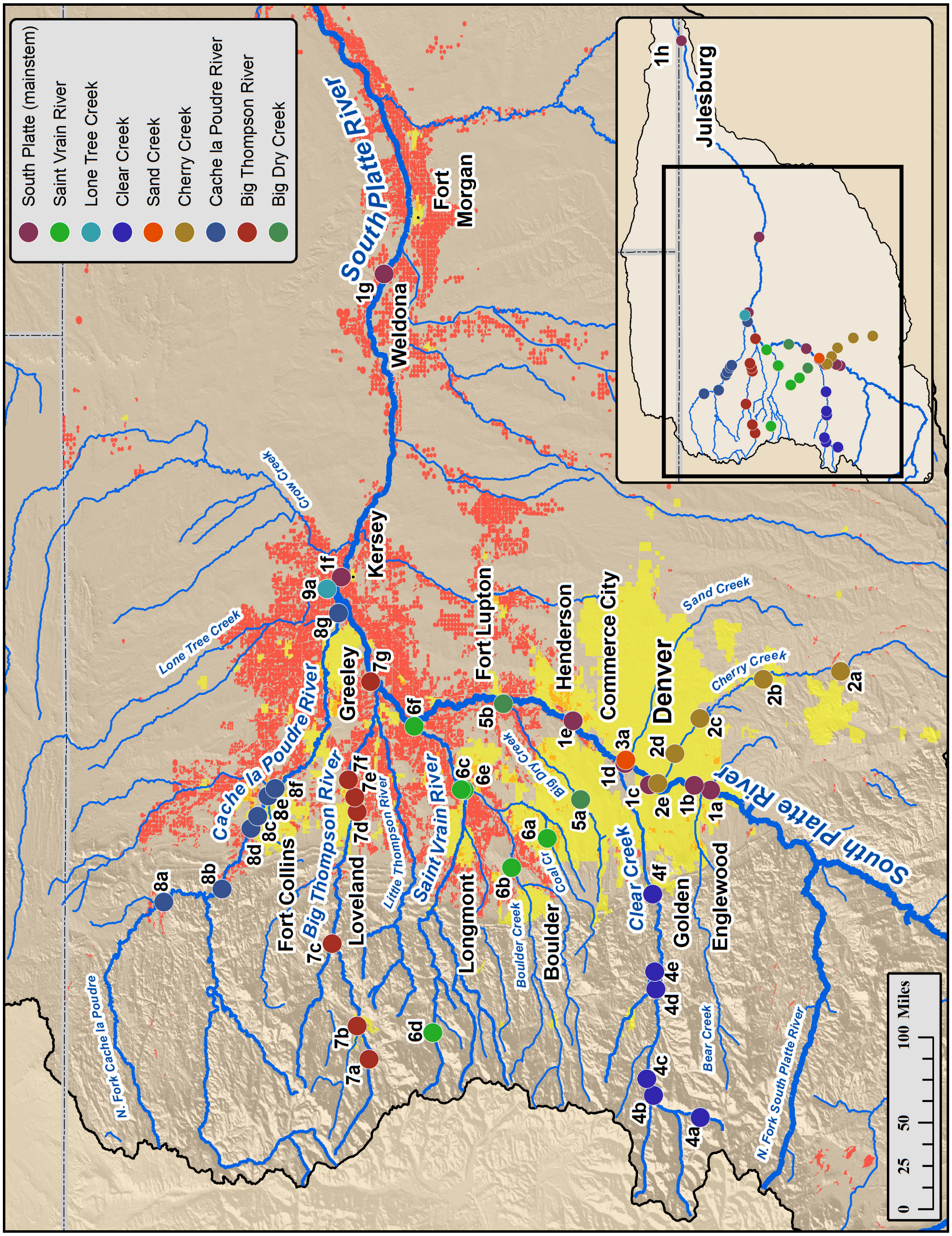


Figure 3-1. Location of selected water-quality monitoring sites, South Platte River Basin.

Table 3-1. Selected water-quality monitoring sites in the South Platte River Basin

USGS site name	USGS identification number	Site number used in this study	Site name used in this study	Latitude	Longitude
South Platte River					
SOUTH PLATTE RIVER AT UNION AVE AT ENGLEWOOD, CO	6710245	1a	SPR nr Englewood	39.63109873	-105.01442744
SOUTH PLATTE RIVER AT ENGLEWOOD, CO.	6711565	1b	SPR at Englewood	39.66498738	-105.00414909
SOUTH PLATTE RIVER AT DENVER, CO.	6714000	1c	SPR at Denver	39.75970893	-105.00331507
SOUTH PLATTE R AT 64TH AVE. COMMERCE CITY, CO.	6714215	1d	SPR at Comm. City	39.81220846	-104.95831293
SOUTH PLATTE RIVER AT HENDERSON, CO.	6720500	1e	SPR at Henderson	39.92192935	-104.86830850
SOUTH PLATTE RIVER NEAR KERSEY, CO.	6754000	1f	SPR nr Kersey	40.41220312	-104.56329219
SOUTH PLATTE RIVER NEAR WELDONA, CO.	6758500	1g	SPR nr Weldona	40.32192660	-103.92189508
SOUTH PLATTE RIVER AT JULESBURG, CO.	6764000	1h	SPR at Julesburg	40.97943713	-102.25462954
Cherry Creek					
CHERRY CREEK NEAR FRANKTOWN, CO.	6712000	2a	Cherry Cr nr Franktown	39.35582342	-104.76330920
CHERRY CREEK NEAR PARKER, CO	393109104464500	2b	Cherry Cr nr Parker	39.51915571	-104.77969748
CHERRY CREEK BELOW CHERRY CREEK LAKE, CO.	6713000	2c	Cherry Cr bl CC Res.	39.65359899	-104.86303258
CHERRY CREEK AT GLENDALE, CO	6713300	2d	Cherry Cr at Glendale	39.70609840	-104.93747950
CHERRY CREEK AT DENVER, CO.	6713500	2e	Cherry Cr at Denver	39.74248685	-104.99998174
Sand Creek					
SAND CREEK AT MOUTH NR COMMERCE CITY,CO	394839104570300	3a	Sand Cr nr Comm City	39.80998628	-104.95053485
Clear Creek					
SOUTH CLEAR CREEK ABV LOWER CABIN CREEK RESERVOIR	6714400	4a	S Clear Cr ab LCCR	39.65248728	-105.70750485
CLEAR CREEK ABV WEST FORK CLEAR CREEK NR EMPIRE CO	6715000	4b	Clear Cr nr Empire	39.75193193	-105.66194696
CLEAR CREEK NEAR LAWSON, CO.	6716500	4c	Clear Cr nr Lawson	39.76582091	-105.62611234
CLEAR CREEK ABV JOHNSON GULCH NR IDAHO SPRINGS, CO	6718300	4d	Clear Cr nr Idaho Spgs	39.74637684	-105.43610579
NORTH CLEAR CREEK ABOVE MOUTH NR BLACK HAWK, CO	6718550	4e	N Clear Cr nr Blk Hwk	39.74887674	-105.39971585
CLEAR CREEK AT GOLDEN, CO.	6719505	4f	Clear Cr at Golden	39.75304299	-105.23526675
Big Dry Creek					
BIG DRY CREEK AT WESTMINSTER, COLO	6720820	5a	BD Cr at Westminster	39.90554095	-105.03498196
BIG DRY CREEK AT MOUTH NEAR FORT LUPTON, CO.	6720990	5b	BD Cr nr Fort Lupton	40.06915015	-104.83163944
St. Vrain Creek					
COAL CREEK NEAR LOUISVILLE CO	6730400	6a	Coal Cr nr Louisville	39.97609623	-105.11720683
BOULDER CR AT NORTH 75TH ST NR BOULDER	6730200	6b	Boulder Cr nr Boulder	40.05165184	-105.17887544
BOULDER CREEK AT MOUTH, NEAR LONGMONT, CO.	6730500	6c	Boulder Cr nr Longmont	40.15220650	-105.01497987
NORTH ST. VRAIN CREEK NEAR ALLENS PARK, CO.	6721500	6d	N SVR nr Allens Park	40.21887370	-105.52833292
ST. VRAIN CREEK BELOW LONGMONT, CO.	6725450	6e	SVR bl Longmont	40.15831760	-105.01386868
ST. VRAIN CREEK AT MOUTH, NEAR PLATTEVILLE, CO.	6731000	6f	SVR nr Platteville	40.25803869	-104.87969601
Big Thompson River					
BIG THOMPSON BL MORAINE PARK NR ESTES PARK, CO.	402114105350101	7a	BTR nr Estes Park	40.35387292	-105.58416787
BIG THOMPSON RIVER AT ESTES PARK, CO.	6733000	7b	BTR at Estes Park	40.37831704	-105.51388702
BIG THOMPSON R ABV NF BIG THOMPSON AT DRAKE, CO	402554105202100	7c	BTR at Drake	40.43165024	-105.33971243
BIG THOMPSON RIVER AT LOVELAND, CO.	6741510	7d	BTR at Loveland	40.37859462	-105.06109091
BIG THOMPSON RIVER BELOW LOVELAND, CO.	6741520	7e	BTR bl Loveland	40.38331670	-105.02970080
BIG THOMPSON RIVER AT I-25, NEAR LOVELAND, CO.	6741530	7f	BTR at I-25	40.39748311	-104.99275482
BIG THOMPSON RIVER AT MOUTH, NEAR LA SALLE, CO.	6744000	7g	BTR at La Salle	40.34998172	-104.78496932
Cache la Poudre River					
NORTH FORK CACHE LA POUDRE R. AT LIVERMORE, CO	6751490	8a	NF CLPR at Livermore	40.78748150	-105.25220471
CACHE LA POUDRE R A MO OF CN, NR FT COLLINS, CO.	6752000	8b	CLPR nr Fort Collins	40.66442621	-105.22442713
CACHE LA POUDRE R A SHIELDS ST A FT COLLINS, CO.	6752258	8c	CLPR at Shields-FTC	40.60303790	-105.09581207
CACHE LA POUDRE RIVER AT FORT COLLINS, CO.	6752260	8d	CLPR at Fort Collins	40.58914908	-105.06970016
CACHE LA POUDRE RIVER BELOW FORT COLLINS, CO.	6752270	8e	CLPR bl Fort Collins	40.56692691	-105.02719884
CACHE LA POUDRE R AB BOXELDER C, NR TIMNATH, CO.	6752280	8f	CLPR nr Timnath	40.55192692	-105.01136508
CACHE LA POUDRE RIVER NEAR GREELEY, CO.	6752500	8g	CLPR nr Greeley	40.41775868	-104.63996239
Lone Tree Creek					
LONE TREE CREEK NEAR GREELEY, CO.	6753990	9a	LT Cr nr Greeley	40.44248081	-104.58884871

3.2.3 Measures of Salinity

The USGS has used both specific conductance (SC) and total dissolved solids (TDS) to measure salinity in the South Platte River Basin. Specific conductance measurements have been calculated using two methods: in the field (Parameter Code 00094) and in the laboratory (Parameter Code 90095). In some cases the measurement technique was not recorded (Parameter Code 00095). In other cases multiple parameter codes were listed per sampling event. In cases where this occurred, the mean value of the multiple measurements was used to represent the sampling event in this study.

Total dissolved solids (TDS) were measured and reported using three direct analytical methods: as residue on evaporation (Parameter Code 00525), residue on evaporation dried at 105 degrees Celsius (Parameter Code 00515), and residue on evaporation dried at 180 degrees Celsius (Parameter Code 70300). A fourth, indirect method was also used in the USGS database: Parameter Code 70301 which reports TDS as the sum of the analytically-determined concentrations of major ions. Most of the selected data were reported as Parameter Code 70300 (residue on evaporation dried at 180 degrees Celsius). In cases where multiple parameter codes for TDS were recorded per sampling event, Parameter Code 70300 (residue on evaporation dried at 180 degrees Celsius) was selected for use in this study. When a measured TDS value was not available, the calculated TDS value (Parameter Code 70301) was used. When both a measured and calculated value were available, the mean of the two values was used.

As the concentration of dissolved ions in a solution increases, the electrical conductance of the solution increases (Hem, 1985). Therefore, measurement of electrical conductance (EC), also referred to as specific conductance (SC), provides an indication of ion concentration. The exact relationship between SC and TDS varies depending on the types of ions present in the sample, but generally remains relatively constant over a range of SC values for a given monitoring site. Due to changes in the dissolved constituents, the relationship between SC and TDS might vary across monitoring sites. As a result, the relationship between SC and TDS should be determined independently for each monitoring site. Measurement of SC is less time and labor intensive than measurement of TDS, therefore the USGS measures SC of water samples more often than it measures TDS.

Because the calculation of dissolved solids loads requires units with mass, SC measurements were converted to TDS values using site-specific regression equations developed for each monitoring location using paired SC – TDS values. Although the relationship between SC and TDS is generally linear, the slope of the regression is sometimes steeper for lower conductance values. The degree of change in slope at lower conductivities varies with the types of salts present in the solution (Hem, 1985). This behavior was observed for some South Platte River Basin monitoring sites in plots of SC versus TDS. To improve the accuracy of the conversion for these sites, separate regression coefficients were developed for observations with SC values below 300 - 500 microsiemens per centimeter (μS/cm). The cutoff value for the low-SC value regression coefficients was determined based on the location of the inflection point in the SC – TDS plots developed for each site. The resulting regression coefficients for both high and low SC values for each location are presented in Table 3-2 along with the SC cutoff criteria for use of the low-SC regression coefficients. Available measured TDS values were plotted against the converted TDS values for each site to confirm the adequacy of the conversion equations.

Table 3-2. Regression coefficients used for relation of total dissolved solids to specific conductance.

[SC, specific conductance; μS/cm, microsiemens per centimeter at 25 degrees Celsius]

Site	Site name	Higher SC values		Lower SC values		Threshold for low SC regression terms (μS/cm)	Comments
		Slope m *	Constant b *	Slope m *	Constant b *		
1a	SPR nr Englewood	0.650	-15.0	0.650	0.0	300	Estimated **
1b	SPR at Englewood	0.655	-17.1	0.655	0.0	300	
1c	SPR at Denver	0.636	-9.4	0.636	-9.4	300	
1d	SPR at Comm. City	0.630	-8.0	0.630	-8.0	300	Estimated **
1e	SPR at Henderson	0.630	-6.6	0.630	-6.6	300	
1f	SPR nr Kersey	0.813	-115.4	0.631	0.0	500	
1g	SPR nr Weldona	0.833	-173.3	0.700	0.0	500	
1h	SPR at Julesburg	0.811	-80.8	0.811	-80.8	300	
2a	Cherry Cr nr Franktown	0.630	5.0	0.630	0.0	300	Estimated **
2b	Cherry Cr nr Parker	0.630	5.0	0.630	5.0	300	Estimated **
2c	Cherry Cr bl CC Res.	0.630	5.0	0.630	0.0	300	Estimated **
2d	Cherry Cr at Glendale	0.630	5.0	0.630	0.0	300	Estimated **
2e	Cherry Cr at Denver	0.636	4.6	0.636	0.0	300	
3a	Sand Cr nr Comm City	0.650	0.0	0.650	0.0	300	Estimated **
4a	S Clear Cr ab LCCR	0.674	0.0	0.674	0.0	300	
4b	Clear Cr nr Empire	0.550	8.0	0.600	0.0	300	Estimated **
4c	Clear Cr nr Lawson	0.550	8.0	0.600	0.0	300	Estimated **
4d	Clear Cr nr Idaho Spgs	0.550	8.0	0.600	0.0	300	Estimated **
4e	N Clear Cr nr Blk Hwk	0.550	8.0	0.600	0.0	300	Estimated **
4f	Clear Cr at Golden	0.603	1.2	0.603	1.2	300	
5a	BD Cr at Westminster	0.650	-5.0	0.650	0.0	300	Estimated **
5b	BD Cr nr Fort Lupton	0.650	-5.0	0.650	0.0	300	Estimated **
6a	Coal Cr nr Louisville	0.700	-20.0	0.700	0.0	300	Estimated **
6b	Boulder Cr nr Boulder	0.700	-20.0	0.700	0.0	300	Estimated **
6c	Boulder Cr nr Longmont	0.725	-50.0	0.580	0.0	300	
6d	N SVR nr Allens Park	0.550	5.0	0.550	0.0	300	Estimated **
6e	SVR bl Longmont	0.768	-62.1	0.580	0.0	300	
6f	SVR nr Platteville	0.792	-105.0	0.658	-19.2	500	
7a	BTR nr Estes Park	0.667	6.8	0.667	6.8	300	
7b	BTR at Estes Park	0.650	6.3	0.800	0.0	300	
7c	BTR at Drake	0.533	12.0	0.533	12.0	300	
7d	BTR at Loveland	0.803	-56.4	0.618	2.3	300	
7e	BTR bl Loveland	0.727	-26.9	0.750	0.0	300	
7f	BTR at I-25	0.796	-61.4	0.796	-61.4	300	
7g	BTR at La Salle	0.857	-156.8	0.531	17.4	500	
8a	NF CLPR at Livermore	0.511	25.0	0.511	25.0	300	
8b	CLPR nr Fort Collins	0.503	11.7	0.499	11.7	300	
8c	CLPR at Shields-FTC	0.598	0.2	0.598	0.2	300	
8d	CLPR at Fort Collins	0.612	-2.1	0.520	7.5	300	
8e	CLPR bl Fort Collins	0.657	-16.1	0.617	-1.6	300	
8f	CLPR nr Timnath	0.846	-94.3	0.647	-9.2	500	
8g	CLPR nr Greeley	0.818	-124.1	0.750	-48.0	500	
9a	LT Cr nr Greeley	0.909	-222.1	0.800	0.0	500	

*** TDS = m(SC) + b**

**** Insufficent availability of measured TDS values. Regression coefficients estimated from neighboring monitoring sites**

3.2.4 Historical Salinity Monitoring Patterns

Many of the monitoring sites within the basin have sporadic or incomplete monitoring records. This may have resulted from budgetary limitations, changes in monitoring priority, and the occurrence of short-term water-quality monitoring studies.

Figure 3-2 displays the historical monitoring pattern for each of the 43 selected water-quality monitoring sites for water years 1950–2004 (October, 1949–September, 2004). As evident from the figure, some important monitoring sites are missing data for large time periods or have been discontinued entirely. Figure 3-2 also shows differences among sites with regard to the number of samples taken per year.

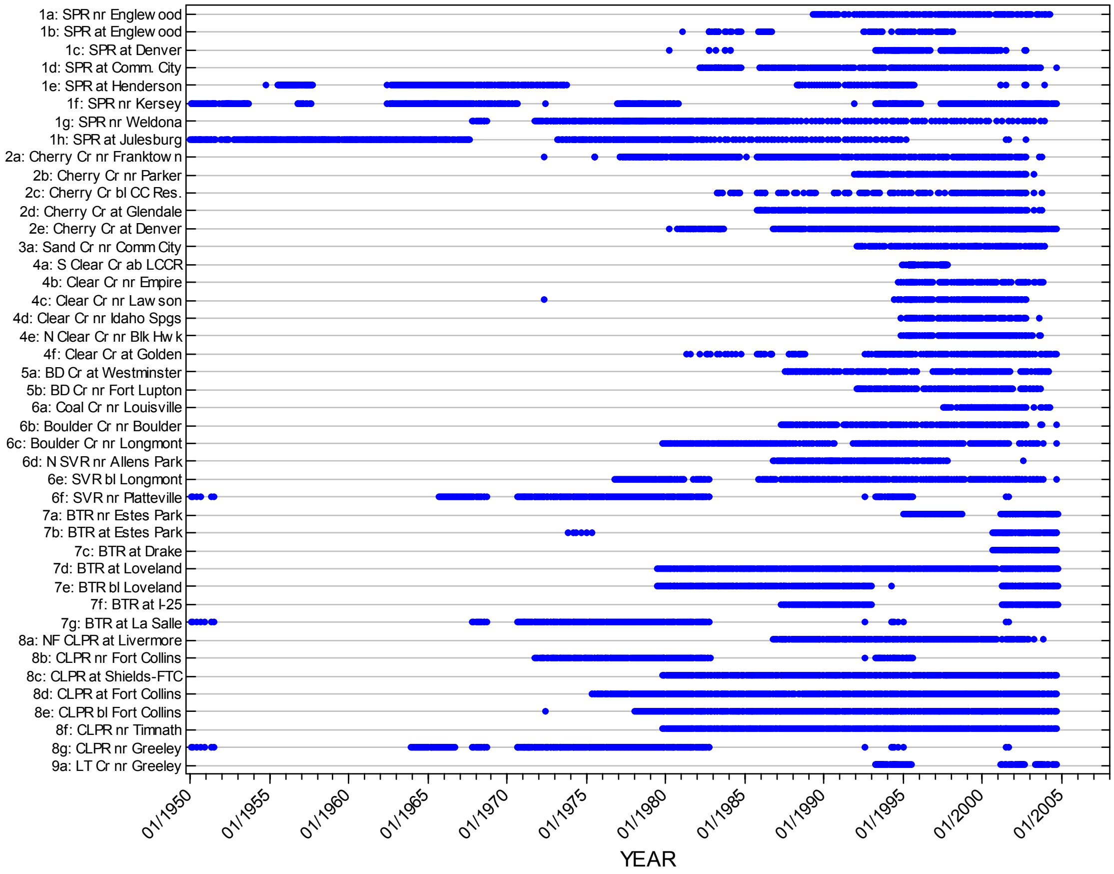


Figure 3-2. Available records of specific conductance measurements at selected South Platte River Basin water-quality monitoring sites, water years 1950–2004.

Based on the availability of salinity data at key sites, it was decided that the period of water years 1991 through 2004 would be the preferred period for analysis of recent salinity characteristics for this study. The historical sampling patterns for this period are shown in Figure 3-3. Although more complete than the years prior to water year 1991, this figure clearly shows that many of the selected sites have less than ideal sampling records even during the selected study period. Given the lack of alternate data sources, some sites with inconsistent records had to be included in this work in order to provide at least a snapshot of recent salinity conditions throughout the basin. It was especially important to include monitoring sites located at the mouths of major tributaries (sites 6f, 7g, 8g) even though these sites had some of the most incomplete records during this time period.

Figure 3-3. Available records of specific conductance measurements at selected South Platte River Basin water-quality monitoring sites, water years 1991–2004.

3.3 HISTORICAL STREAMFLOW DATA

3.3.1 Data Sources

Daily flow values were obtained from the Colorado Decision Support System (CDSS) Hydrobase database (Colorado Water Conservation Board and Colorado

Division of Water Resources, 2007), a hydrologic database for river basins in Colorado. Hydrobase contains historical daily flow values for both USGS and non-USGS flow monitoring sites. Hydrobase proved to be a more complete resource for daily flow values than the flow data available via the USGS's NWIS because operational control for some USGS flow monitoring sites within Colorado has been transferred to the Colorado Division of Water Resources (DWR). Historical flow data for these transferred sites are stored in Hydrobase but not NWIS. Hydrobase is available as an online resource (http://cdss.state.co.us) and as a data DVD available from the DWR. The DVD version was used to obtain the data used in this study because at the time (2006) it provided greater flexibility in specifying output format. Improvements made to the Hydrobase web site since then have improved upon its limitations.

3.3.2 Site Selection

Daily streamflow records were not available for five of the 43 water-quality monitoring sites. Sites without daily flow values were located on the Big Thompson River (sites 7c, 7e, and 7f) and Cache la Poudre River (sites 8c and 8e). Daily flow records for the remaining 38 sites were compiled for water years 1990–2004.

3.3.3 Data Processing

Daily flow values were converted from cubic feet per second to cubic meters per day. Daily values were aggregated by month and also by year to provide monthly and annual flow volumes for use in statistical and trend analysis.

3.3.4 Historical Streamflow Monitoring Patterns

Figure 3-4 graphically displays the patterns in streamflow measurement during the study period. Most of the sites along the mainstem and major tributaries had consistent monitoring during the selected study period. Some of the sites on smaller tributaries and tributary sites in the mountains had significant gaps in streamflow monitoring. Sites without consistent historical monitoring were excluded from calculation and analysis of dissolved solids loads.

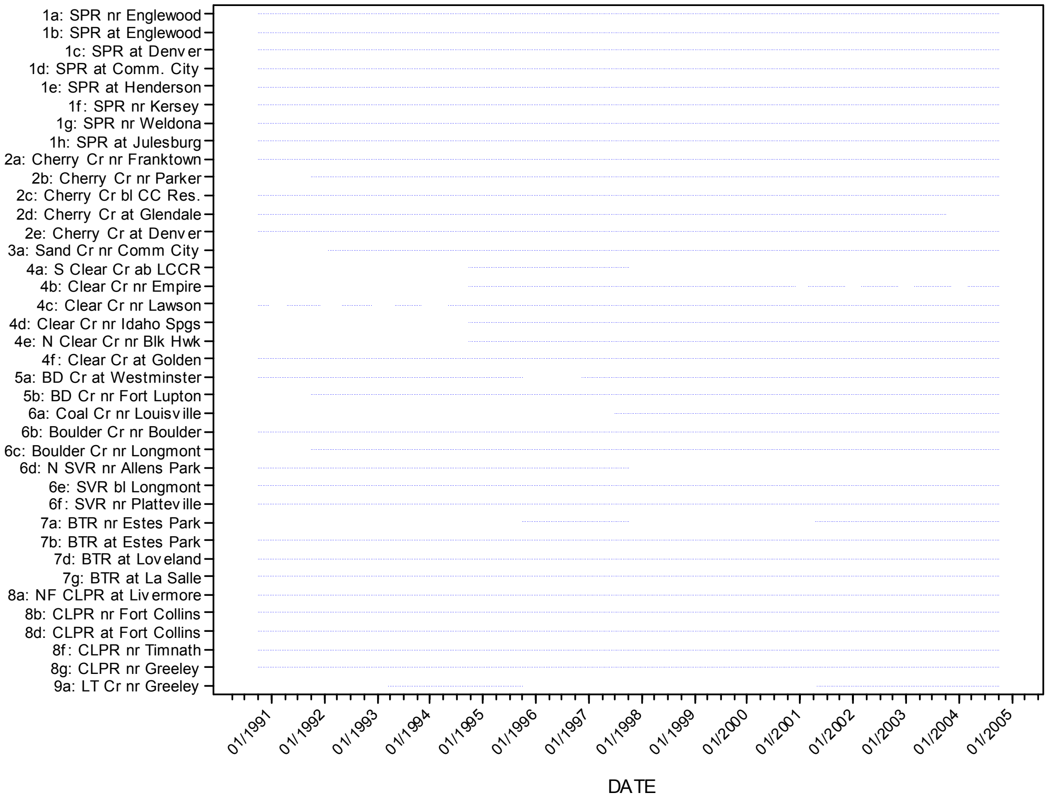


Figure 3-4. Historical patterns for streamflow measurement at selected South Platte River Basin water-quality monitoring sites, water years 1991–2004.

CHAPTER 4: STREAMFLOW

4.1 INTRODUCTION

Characterizing streamflow volume and variability is a necessary first step toward a comprehensive assessment of water-quality conditions in a river system. This chapter presents a comprehensive characterization of streamflow conditions in the South Platte River Basin from October, 1990 through September, 2004. The monitoring sites used in the characterization have been described in Chapter 3. Characterization techniques include time series plots, summary statistics, analysis of spatial patterns along the stream systems, analysis of seasonal patterns, and analysis of temporal trends.

4.2 METHODS

4.2.1 Time Series Plots

Time-series scatter plots of annual streamflow were produced for the 38 streamflow monitoring sites selected using the criteria described in Chapter 3. Locally weighted scatter-plot smoothing (LOWESS) lines were added to aid in the visualization of the general nature and trends of the data (Helsel and Hirsch, 1992).

4.2.2 Summary Statistics and Spatial Patterns

Spatial differences in streamflow conditions between monitoring sites in the South Platte River Basin were evaluated through the use of summary statistics and box plots. Seven distributional parameters were determined for historical streamflow values at each site. These parameters include the number of observations, mean, minimum, 25th percentile, 50th percentile (median), 75th percentile, and maximum. Box plots were produced to graphically display the distribution of streamflow values at each monitoring site.

4.2.3 Seasonal Patterns

Streamflow generally tends to follow seasonal patterns unless it is subject to regulation or the result of a relatively stable source such as ground water. Each of the streamflow monitoring sites were evaluated for seasonal patterns through the use of seasonal box plots which show the distribution of streamflow values on a monthly basis.

4.2.4 Trend Analysis

Trend analysis of annual (water year) streamflow values was performed to aid in the interpretation of trends in dissolved solids loads and concentrations presented in later chapters. Because trend analysis was conducted on total annual flow volume rather than seasonal, monthly, or daily streamflow, the use of a trend test that accounts for seasonality was not required. The non-seasonal, parametric procedure for determination of monotonic trend is simple linear regression analysis of the variable of interest as a function of time (Hirsch *et al.*, 1991). Trend significance can be determined by conducting a hypothesis test on the slope coefficient. The null hypothesis is that the slope coefficient is equivalent to zero. Significance of the slope coefficient as indicated by the t-statistic provides evidence for rejection of the null hypothesis. A measure of trend magnitude is provided by the regression slope. Because linear regression trend analysis is a parametric test, this method makes assumptions about the distribution of the variable of interest over time. As a result, it must be checked for normality of residuals, constant variance, and linearity of the relationship (Helsel and Hirsch, 1992). Failure of these assumptions requires a transformation of the data or use of a nonparametric method.

Because streamflow values are often not normally distributed, a nonparametric variation of linear regression trend analysis was used in this study for determination of trends in annual streamflow volume. This method involves regression on the ranks of the data instead of the actual values (Loftis, 2006). This method can be used to provide a measure of significance of a trend; however regression on the original (non-ranked) values is still required to provide an estimate of trend magnitude. This modified regression trend analysis methodology was used to perform trend analysis and significance testing on annual streamflow values for water years 1991 through 2004. Sites with less than ten years of continuous flow data were excluded from analysis. This resulted in the exclusion of six of the 38 sites (4a, 4b, 6a, 6d, 7a, and 9a) from analysis.

4.3 RESULTS AND DISCUSSION

4.3.1 Time Series Plots

Time series plots of annual streamflow for the selected monitoring sites are presented in Figure 4-1 through Figure 4-6. These plots are presented as a visual aid in interpreting historical streamflow over time and for use as a reference during the analysis of spatial differences between sites, seasonal variations, and trends presented in later sections. Evident in many of the plots is the decrease in annual streamflow toward the end of the study period corresponding with drought conditions in the basin. Additional time series plots showing daily streamflow during the study period is presented in Appendix A.

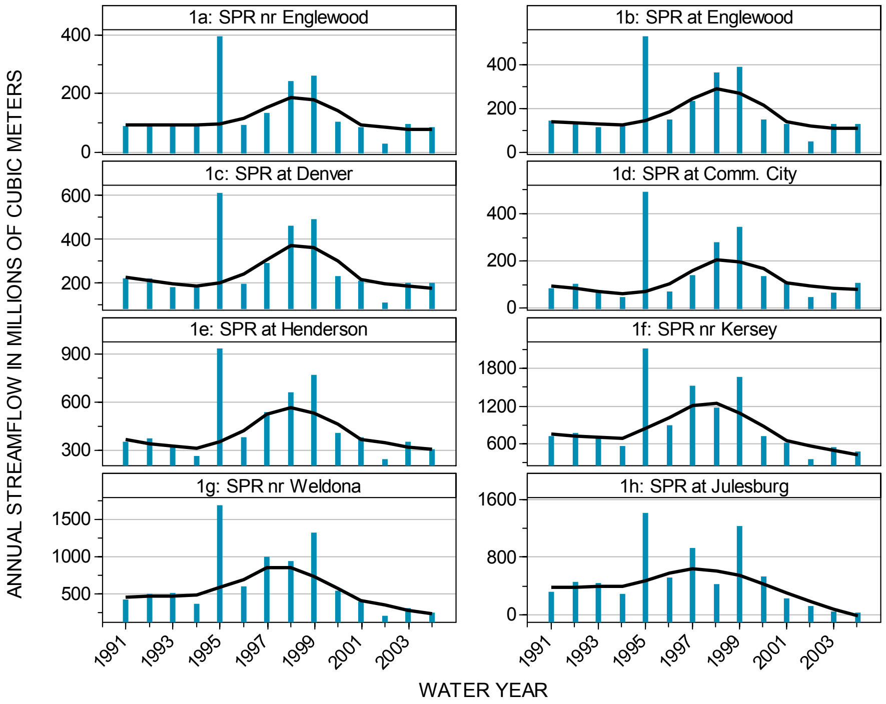


Figure 4-1. Annual flow volume for water years 1991 – 2004, at selected sites along the mainstem South Platte River.

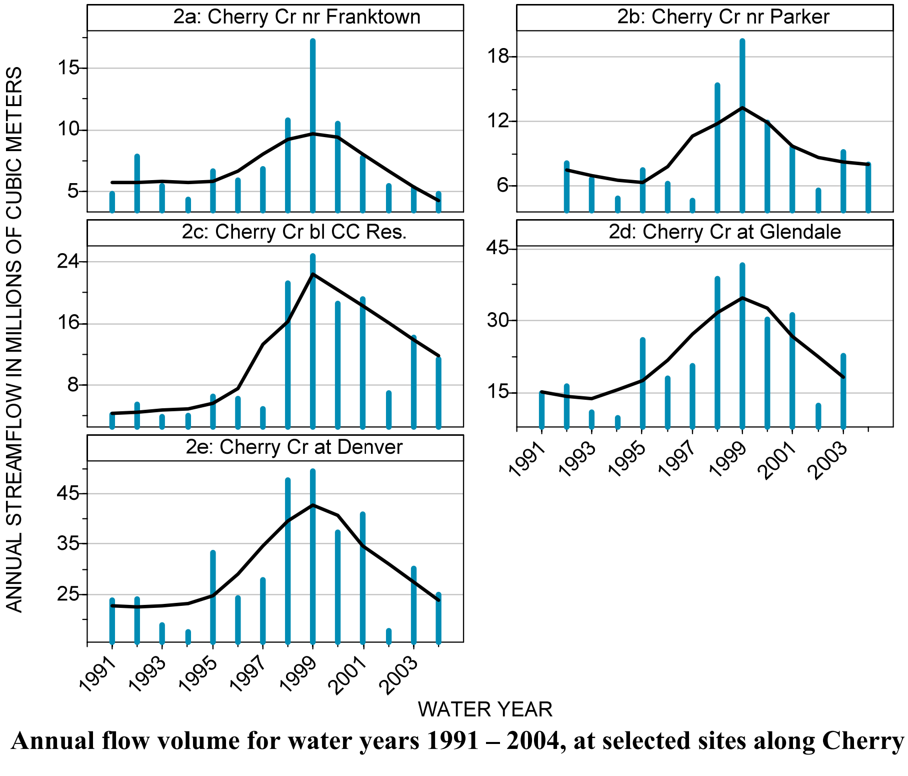


Figure 4-2. Annual flow volume for water years 1991 – 2004, at selected sites along Cherry Creek.

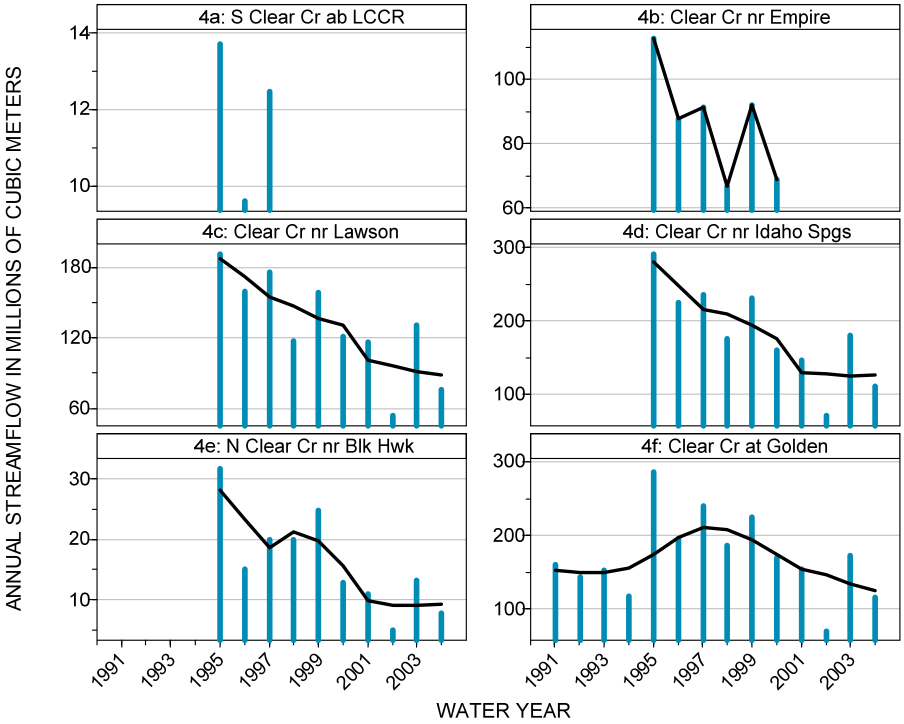


Figure 4-3. Annual flow volume for water years 1991 – 2004, at selected sites along Clear Creek.

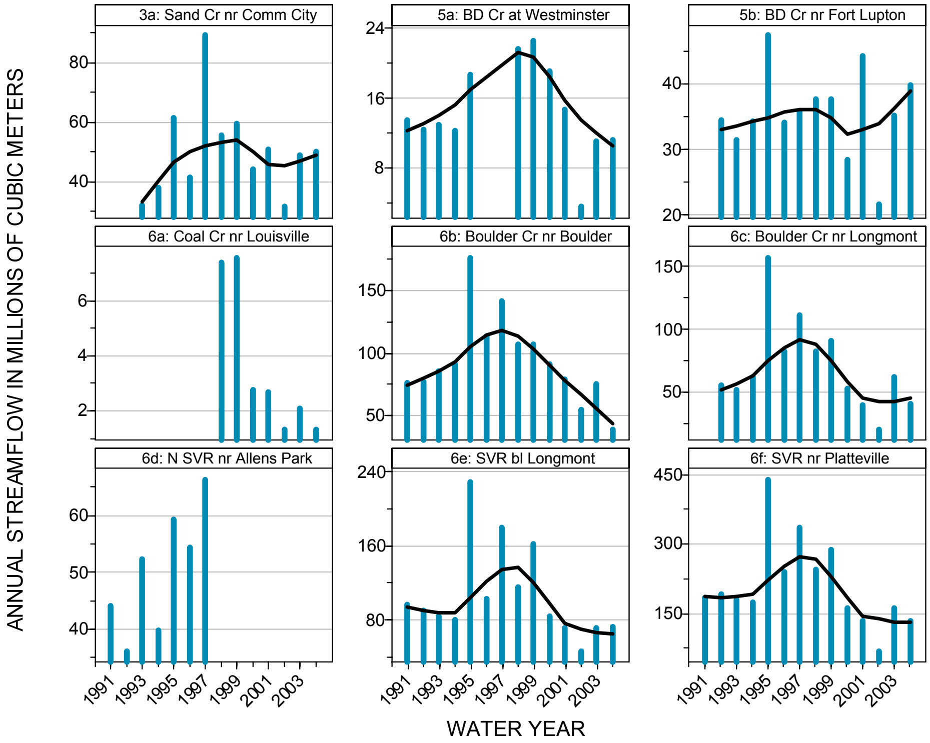


Figure 4-4. Annual flow volume for water years 1991 – 2004, at selected sites along Sand, Big Dry, Coal, and Boulder Creeks and the Saint Vrain River.

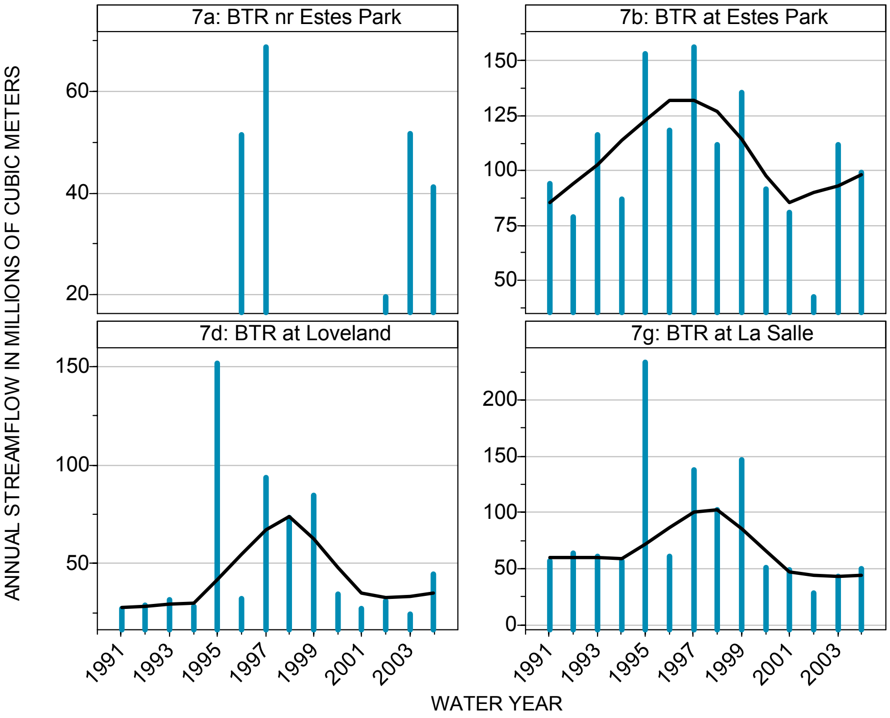


Figure 4-5. Annual flow volume for water years 1991 – 2004, at selected sites along the Big Thompson River.

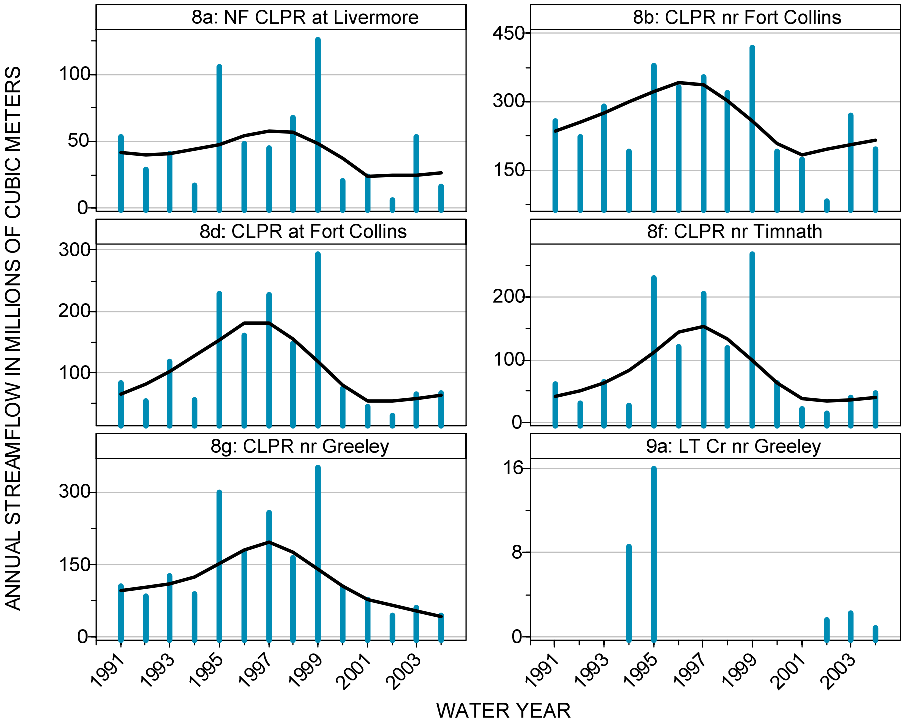


Figure 4-6. Annual flow volume for water years 1991 – 2004, at selected sites along the Cache la Poudre River and Lone Tree Creek.

4.3.2 Summary Statistics and Spatial Patterns

Summary statistics for the streamflow sites are presented in Table 4-1. Graphical representations of the spatial differences in flow distribution statistics are shown in Figure 4-7 through Figure 4-12 with the use of box plots. Box plots graphically display the central tendency of the values through the use of a line bisecting each of the boxes which represents the 50th percentile of the data. Box plots also provide an indication of the variation in the data through the display of lower and upper box limits which represent the 25th and 75th percentiles. A suggestion of the range in data is provided through the use of whiskers below and above the box representing the 10th and 90th percentiles of the data. Finally, any skewness in the data can be observed through comparison of the relative size of the box halves above and below the median line (Helsel and Hirsch, 1992). Side-by-side boxplots of sites along each river are presented in a downstream order (i.e. sites on the right are located downstream of sites on the left) so that the distributional statistics of streamflow values can be visually compared to upstream and downstream sites.

Table 4-1. Statistical summary of daily flow values at selected South Platte River Basin streamflow monitoring sites, water years 1991–2004.

				Flow (cubic meters per day)					
		Time Period			Minimum	Percentile			Maximum
Site	Site name	Begin	End	Mean	value	25th	50th	75th	value
1a	SPR nr Englewood	10/1990	02/1996	397,300	23,732	78,300	163,900	364,500	6,825,958
1b	SPR at Englewood	10/1990	09/2004	531,900	29,359	134,600	247,100	543,100	9,810,786
1c	SPR at Denver	10/1990	09/2004	741,200	102,756	281,400	435,500	781,100	9,737,388
1d	SPR at Comm. City	10/1990	09/2004	401,700	5,138	29,400	78,300	364,500	9,712,923
1e	SPR at Henderson	10/1990	09/2004	1,225,500	75,844	582,300	787,800	1,194,500	15,902,770
1f	SPR nr Kersey	10/1990	09/2004	2,505,200	139,455	1,162,100	1,739,500	2,356,700	52,601,470
1g	SPR nr Weldona	10/1990	09/2004	1,781,900	68,504	567,600	1,005,500	1,834,900	39,879,254
1h	SPR at Julesburg	10/1990	09/2004	1,374,500	24,466	146,800	589,600	1,585,400	34,496,778
2a	Cherry Cr nr Franktown	10/1990	09/2004	20,200	1,982	6,900	12,000	20,600	1,164,572
2b	Cherry Cr nr Parker	10/1991	09/2004	24,500	1,052	7,600	15,200	26,900	851,410
2c	Cherry Cr bl CC Res.	10/1990	09/2004	29,600	0	0	7,300	41,600	907,681
2d	Cherry Cr at Glendale	10/1990	09/2003	61,800	783	16,900	39,100	71,000	1,127,873
2e	Cherry Cr at Denver	10/1990	09/2004	82,000	6,116	34,300	56,300	88,100	1,365,192
3a	Sand Cr nr Comm City	01/1992	09/2004	137,300	9,786	39,100	75,800	166,400	2,691,238
4a	S Clear Cr ab LCCR	10/1994	09/1997	32,600	3,915	8,100	12,500	48,300	261,784
4b	Clear Cr nr Empire	10/1994	09/2004	224,700	16,147	53,800	90,500	247,100	2,167,670
4c	Clear Cr nr Lawson	10/1990	09/2004	378,900	39,145	88,100	151,700	425,700	3,523,075
4d	Clear Cr nr Idaho Spgs	10/1994	09/2004	500,800	58,718	117,400	195,700	522,300	5,088,886
4e	N Clear Cr nr Blk Hwk	10/1994	09/2004	44,200	0	8,100	14,200	34,300	1,015,331
4f	Clear Cr at Golden	10/1990	09/2004	467,500	29,359	122,300	200,600	474,600	5,627,134
5a	BD Cr at Westminster	10/1990	09/2004	40,500	391	4,200	8,600	56,300	763,333
5b	BD Cr nr Fort Lupton	10/1991	09/2004	97,100	783	53,800	71,000	112,500	1,110,747
6a	Coal Cr nr Louisville	07/1997	09/2004	9,800	24	2,700	4,900	7,800	677,703
6b	Boulder Cr nr Boulder	10/1990	09/2004	257,500	6,116	102,800	146,800	303,400	4,159,186
6c	Boulder Cr nr Longmont	10/1991	09/2004	191,500	2,226	51,400	129,700	190,800	3,669,870
6d	N SVR nr Allens Park	10/1990	09/1997	137,800	10,765	18,600	36,700	159,000	1,230,630
6e	SVR bl Longmont	10/1990	09/2004	290,700	48,932	105,200	149,200	293,600	6,312,176
6f	SVR nr Platteville	10/1990	09/2004	575,400	63,611	281,400	379,200	565,200	11,792,516
7a	BTR nr Estes Park	10/1995	09/2004	132,600	4,893	13,900	36,700	146,800	1,622,083
7b	BTR at Estes Park	10/1990	09/2004	287,900	15,658	39,100	80,700	322,900	3,669,870
7c	BTR at Drake	*							
7d	BTR at Loveland	10/1990	09/2004	139,400	1,174	12,500	39,100	144,300	9,052,346
7e	BTR bl Loveland	*							
7f	BTR at I-25	*							
7g	BTR at La Salle	10/1990	09/2004	223,400	2,251	102,800	137,000	188,400	15,095,399
8a	NF CLPR at Livermore	10/1990	09/2004	126,000	3,181	17,600	26,900	81,300	6,752,561
8b	CLPR nr Fort Collins	10/1990	09/2004	715,300	3,915	83,200	168,800	803,700	10,667,089
8c	CLPR at Shields-FTC	*							
8d	CLPR at Fort Collins	10/1990	09/2004	324,000	489	17,600	71,000	215,300	14,018,903
8e	CLPR bl Fort Collins	*							
8f	CLPR nr Timnath	10/1990	09/2004	257,600	73	10,000	20,800	144,300	14,067,835
8g	CLPR nr Greeley	10/1990	09/2004	390,100	14,190	141,900	220,200	345,000	11,523,392
9a	LT Cr nr Greeley	03/1993	09/2004	19,400	0	1,100	7,100	17,400	611,645

*** Streamflow data not available for this station during the study period**

As seen in Figure 4-7, median flow along the mainstem gradually increases through Denver until Commerce City (site 1d) where a decrease in median streamflow occurs. This site is just downstream from the Burlington Ditch which can divert a large portion of the streamflow in the river (Dennehy *et al.*, 1998). There are times when the flow in the river below this diversion point is minimal. Between Commerce City and Henderson the median flow increases to nearly 800,000 m^3/day due in large part to discharge from the Denver Metropolitan Wastewater Reclamation District's wastewater treatment plant just downstream from the monitoring site at Commerce City. During certain times of the year, most of the flow at Henderson is treated wastewater (Dennehy *et al.*, 1995). Between Henderson and Kersey, median flow increases by nearly 1 million m^3/day due in large part to the inflow of the South Platte's three major tributaries: the Saint Vrain, Big Thompson, and Cache la Poudre rivers. As seen in Figure 4-7, streamflow is more variable at Kersey than at the upstream sites. Downstream of Kersey the median flow declines at the Weldona site and again at Julesburg, however the variability in flow remains high.

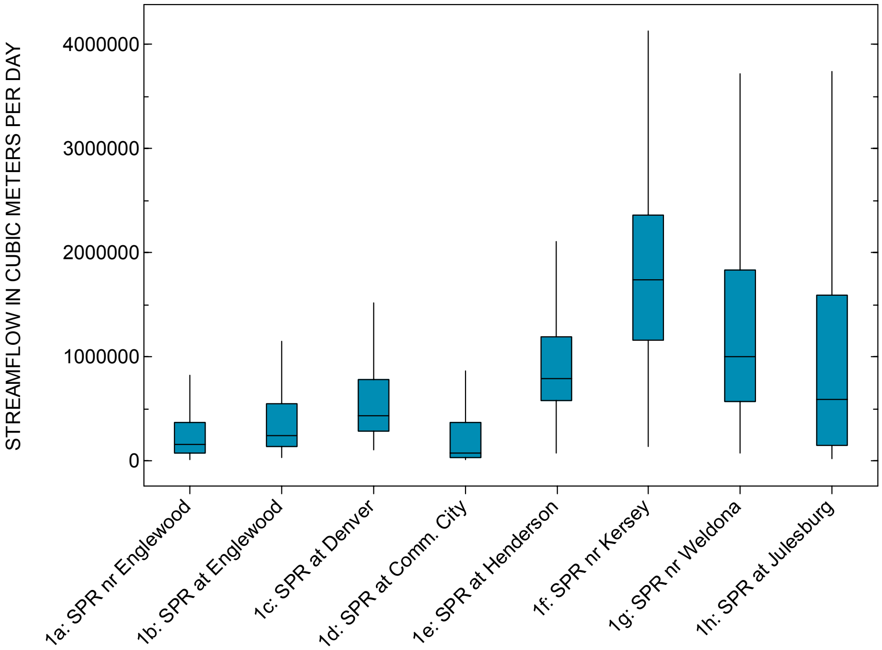


Figure 4-7. Boxplot of daily streamflow at selected sites along the South Platte River, water years 1991–2004.

Figure 4-8 shows streamflow volumes and variability for five locations along Cherry Creek between Franktown and Denver. As shown, trend in flow and variability in flow generally increase heading downstream on Cherry Creek, except at site 2c, below Cherry Creek Reservoir. Although the discharge flow from this lake is generally small, extreme variability has been recorded.

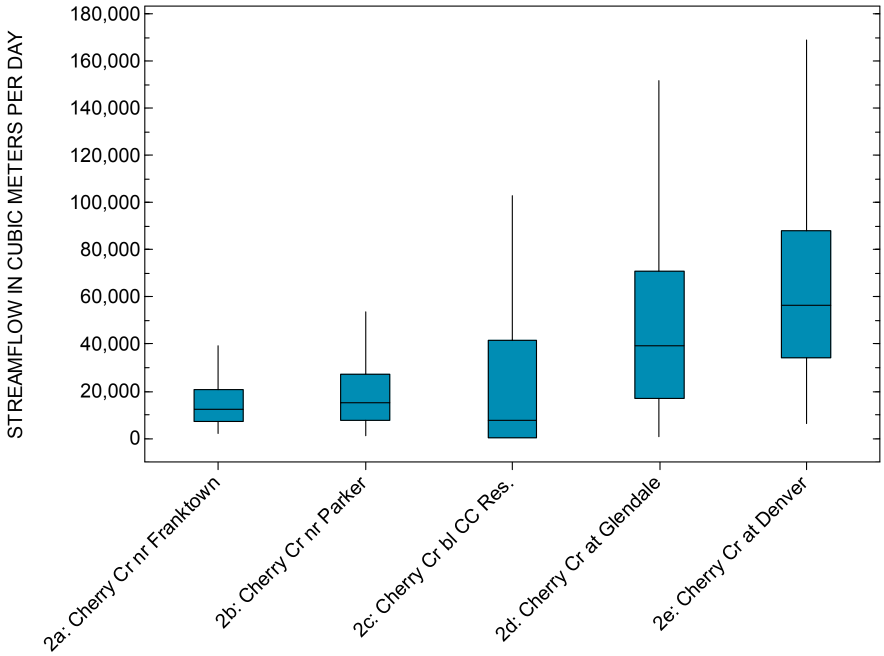


Figure 4-8. Boxplot of daily streamflow at selected sites along Cherry Creek, water years 1991–2004.

Figure 4-9 shows the streamflow volumes and variability for the six sites in the Clear Creek watershed including the South (4a) and North (4e) Clear Creek tributaries. Streamflow increases occur along most Clear Creek mainstem sites with the exception of Clear Creek at Golden which has median streamflow values similar to the upstream site at Idaho Springs despite the flow contribution from North Clear Creek in the intervening reach. Clear Creek at Golden is actually the second to the last site along Clear Creek. The site located nearest the mouth of Clear Creek is located near the town of Derby. The site at Derby did not have a regular monitoring program in place during the period used in this study so values from Clear Creek at Golden were used to provide the best estimates of streamflow and water-quality conditions near the confluence with the mainstem of the South Platte River.

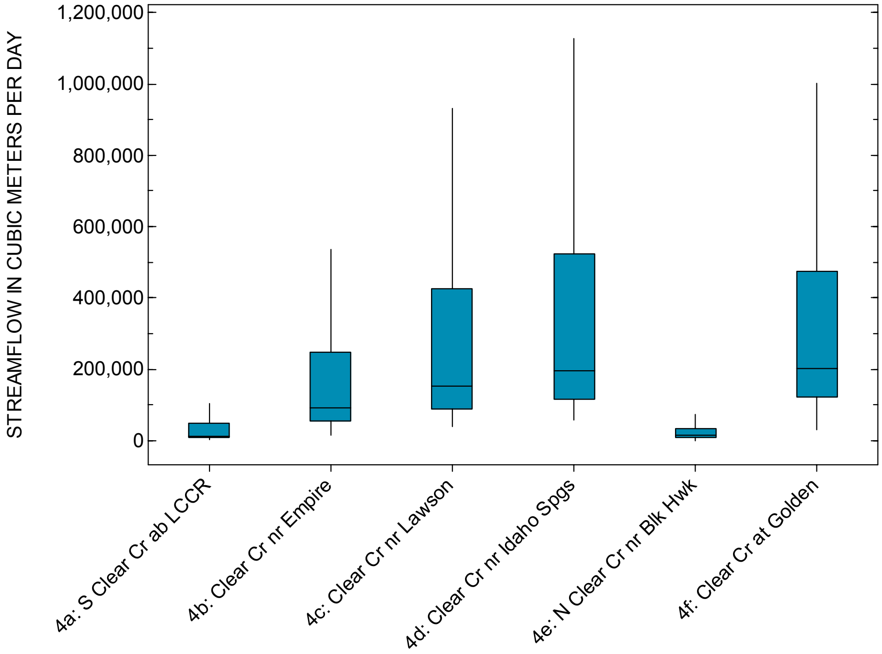


Figure 4-9. Boxplot of daily streamflow at selected sites along Clear Creek, water years 1991–2004.

Figure 4-10 shows streamflow volumes and variability for one site along Sand Creek, two sites along Big Dry Creek, one site along Coal Creek (tributary of Boulder Creek), two sites along Boulder Creek (tributary of the Saint Vrain River) and three sites along the mainstem of the Stain Vrain River. Site 5b on Big Dry Creek reflects flow conditions in the stream just before joining the South Platte. Flow volume in Coal Creek is negligible before joining Boulder Creek which has substantially higher streamflow. Site 6d is located in the mountains along the North Fork of the Saint Vrain River near Allenspark, Colorado just east of its headwaters in Rocky Mountain National Park. This accounts for the relatively low flow volume at this location. Also shown are flow conditions for two sites along the mainstem of the Saint Vrain River, Site 6e below

Longmont, and Site 6f at the mouth of the Saint Vrain near Platteville, Colorado. Median daily flow increases in a downstream direction, more than doubling between Longmont and Platteville. This may be due in large part to contributions from tributaries such as Boulder Creek, point-source discharges such as from wastewater treatment effluent, and groundwater inflows fed by irrigation return flow. With a median flow of 380,000 cubic meters per day, the Saint Vrain River typically provides the largest flow contribution to the South Platte River.

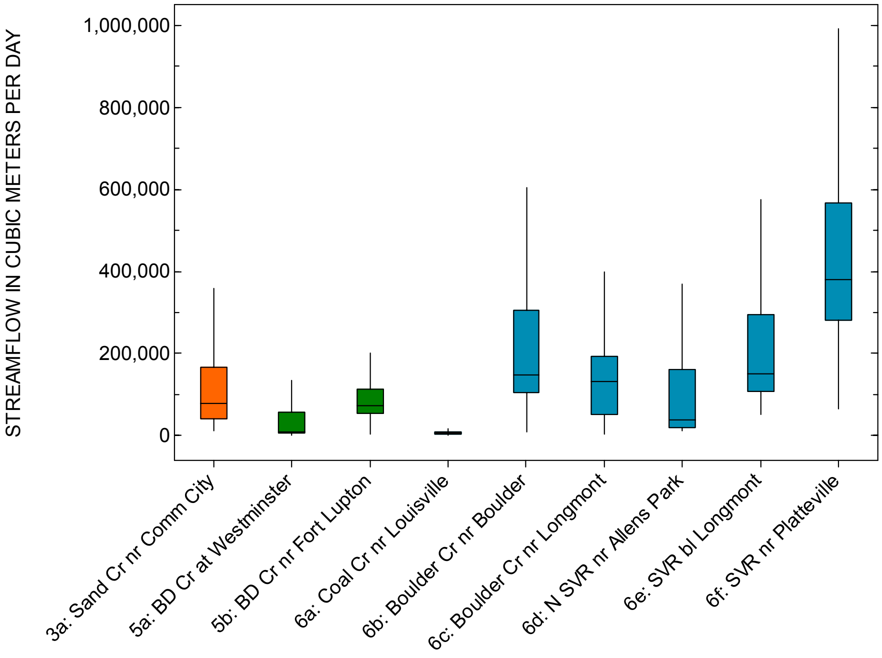


Figure 4-10. Boxplot of daily streamflow at selected sites along Sand, Big Dry, Coal, and Boulder Creeks and the Saint Vrain River, water years 1991–2004.

Flow conditions along the Big Thompson River are reflected in Figure 4-11. Because of its integration with a major trans-basin water project, flow in the Big Thompson River is highly regulated. Flow conditions at sites located in the mountains are shown for sites 7a and 7b. Site 7b at Estes Park has both greater flow volume and greater flow variability than site 7a located farther upstream. This is due to the influence of tributaries such as the Fall River which joins the Big Thompson River between these two sites. Median flow decreases in the Big Thompson between Estes Park and Loveland due to diversions. Flow volume increases and variability decreases between Loveland and the mouth of the Big Thompson near La Salle. This is probably a reflection of river gains via ground water return flows which tend to have a more constant flow rate than surface inflows that are often associated with storm events and seasonal effects which tend to result in more variable flow rates.

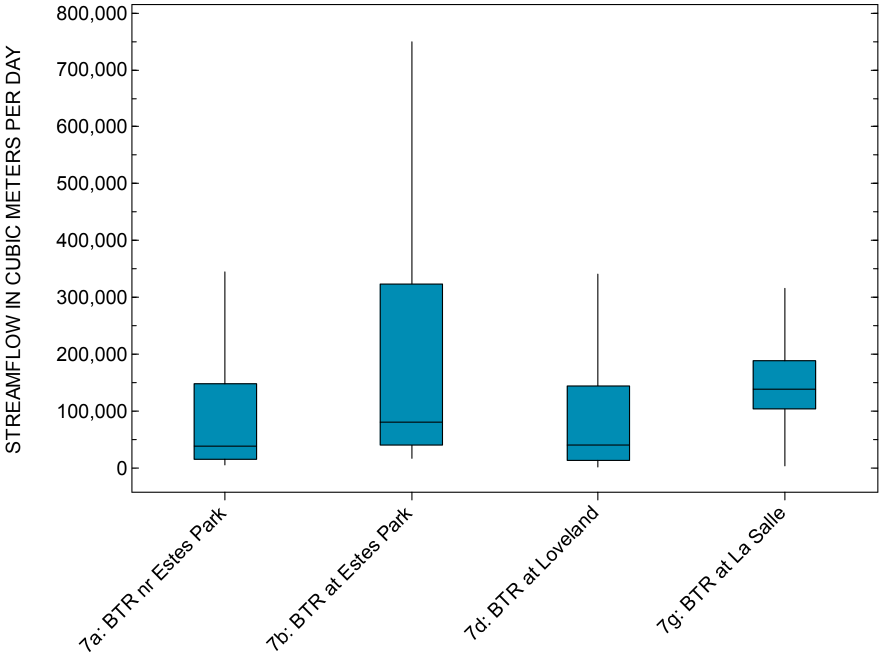


Figure 4-11. Boxplot of daily streamflow at selected sites along the Big Thompson River, water years 1991–2004.

Figure 4-12 shows streamflow volumes and variability for one site on the North Fork of the Cache la Poudre, four sites on the mainstem Cache la Poudre River, and one site along Lone Tree Creek near Greeley. As shown, flow is highly variable at the mouth of the Cache la Poudre Canyon. Variability and flow decrease as the river passes through Fort Collins due to diversions which tend to divert during the high-flows of spring and early summer. The decrease in flow and variability is continued at site 8f as the river passes from Fort Collins and flows through the town of Timnath where flow is often very low. Flows increase between site 8f and the mouth of the river near Greeley largely due to groundwater inflows primarily resulting from irrigation return flow. With a median daily flow of 220,000 cubic meters per day, the Cache la Poudre is the second largest flow contributor to the South Platte River. Figure 4-12 also shows the negligible contribution of Lone Tree Creek to the total flow of the South Platte River near Greeley.

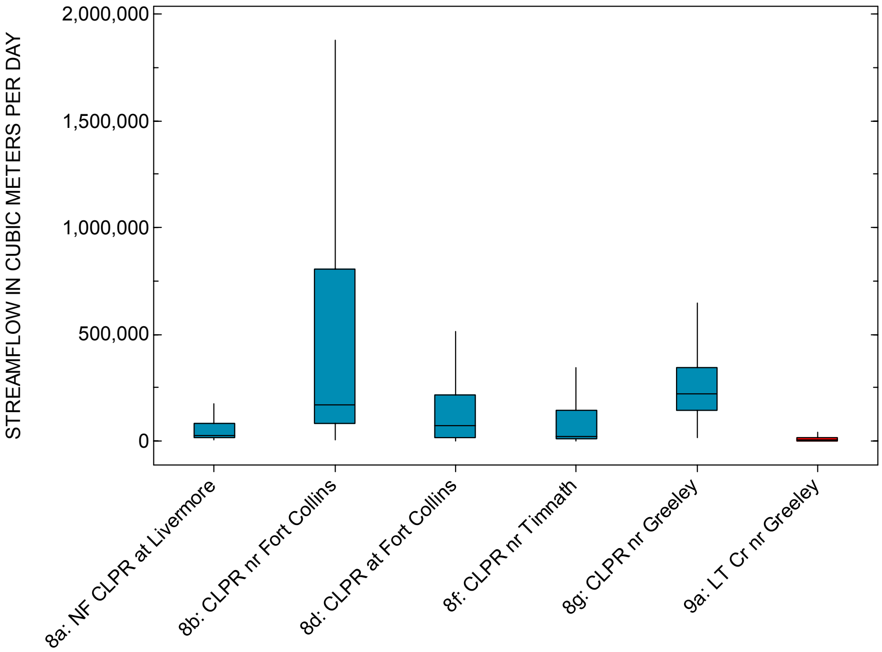


Figure 4-12. Boxplot of daily streamflow at selected sites along the Cache la Poudre River and Lone Tree Creek, water years 1991–2004.

4.3.3 Seasonal Patterns

Streamflow typically exhibits large changes in magnitude throughout the year due primarily to seasonal variation in precipitation and spring snowmelt. Seasonal streamflow changes can also be caused through management activities such as diversion, transfer, storage, and augmentation programs. Seasonal patterns in streamflow at the selected sites are illustrated via boxplots in Figure 4-13 through Figure 4-18. Most sites appear to exhibit some amount of seasonality, however there are differences in the timing and magnitude of seasonal differences. Many sites show peak streamflow occurring in May and June. These sites tend to be located in the higher-elevation portions of the basin where they are more likely to be impacted by spring snowmelt. These higher flows can last through July and even August at some sites. Downstream sites on the South Platte River exhibit a shifting of the seasonal flow pattern. Instead of occurring in the late spring and early summer, the downstream sites show the highest median flows occurring in the fall, winter, and early spring periods. Sites at the mouths of the Big Thompson and Cache la Poudre rivers exhibit this pattern, but to a lesser degree. This pattern is likely the result of diversion of flow for irrigation in the late spring and early summer. Throughout the rest of the year, groundwater inflow and to a lesser extent point discharge from major dischargers such as wastewater treatment facilities are the likely sources of flow. Much of the groundwater reaching the rivers in these irrigated areas is likely to be return flow from irrigation activities. Sites located on the downstream portions of the rivers generally have less variation in streamflow throughout the year than upstream sites. This is especially apparent for downstream sites on the South Platte, Big Thompson, and Cache la Poudre rivers (Figure 4-13, Figure 4-17, and Figure 4-18).

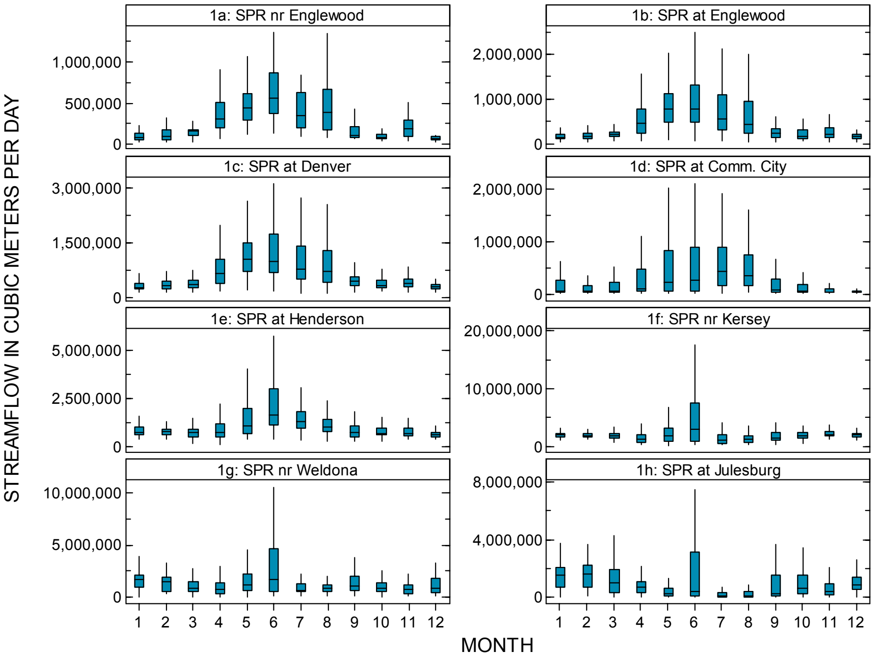


Figure 4-13. Boxplots showing seasonal patterns in streamflow at selected sites along the South Platte River, water years 1991–2004.

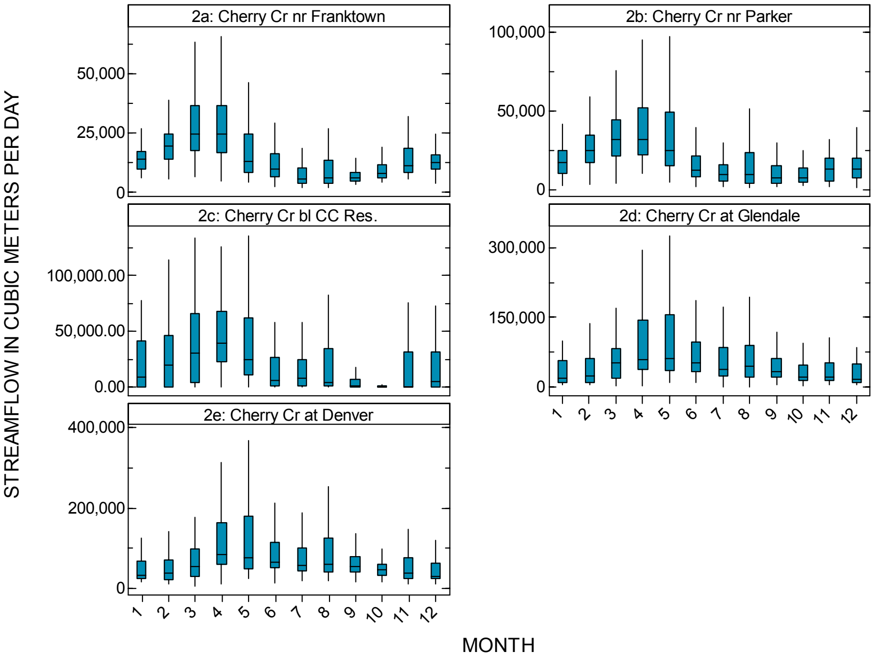


Figure 4-14. Boxplots showing seasonal patterns in streamflow at selected sites along Cherry Creek, water years 1991–2004.

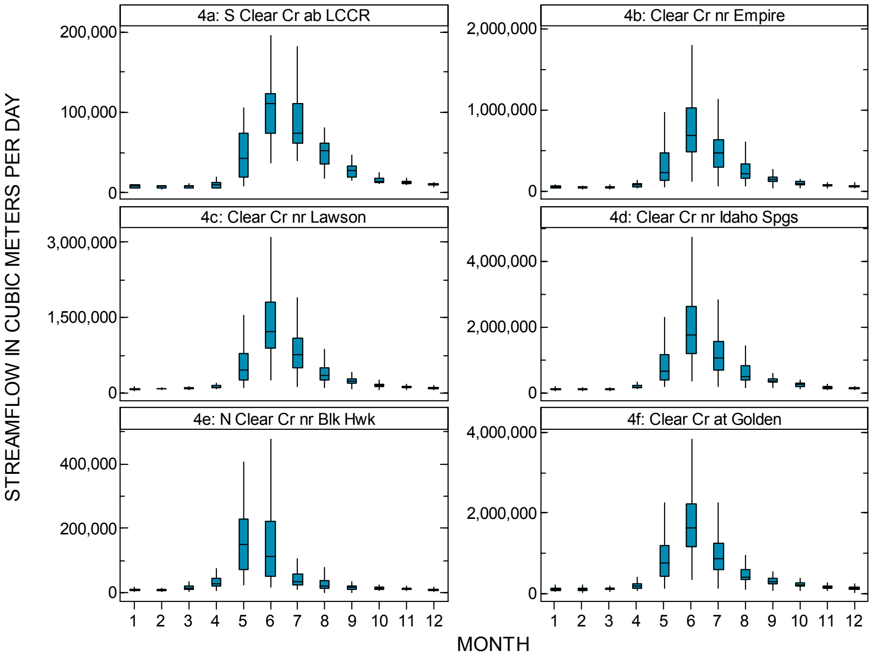


Figure 4-15. Boxplots showing seasonal patterns in streamflow at selected sites along Clear Creek, water years 1991–2004.

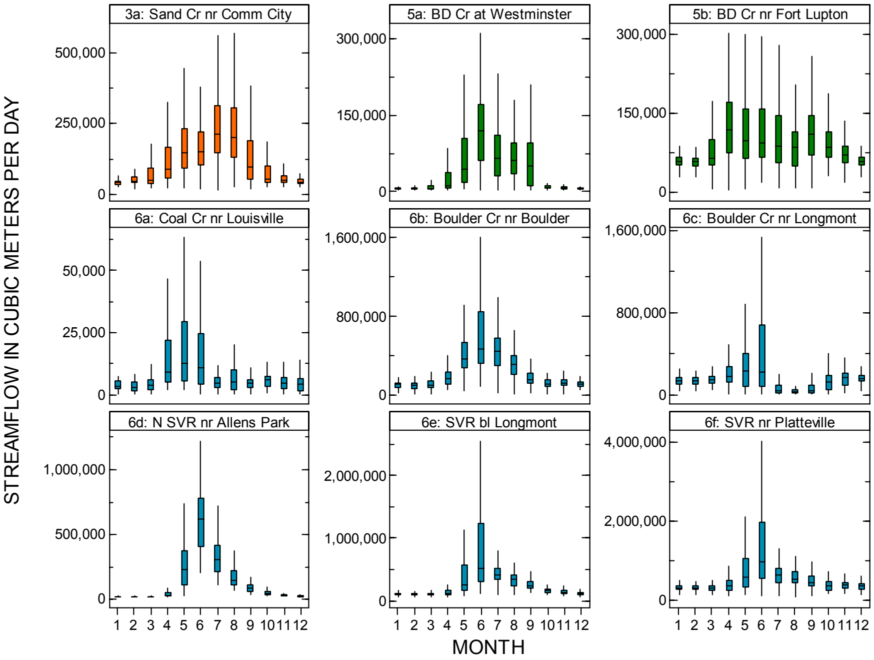


Figure 4-16. Boxplots showing seasonal patterns in streamflow at selected sites along Sand, Big Dry, Coal, and Boulder Creeks and the Saint Vrain River, water years 1991–2004.

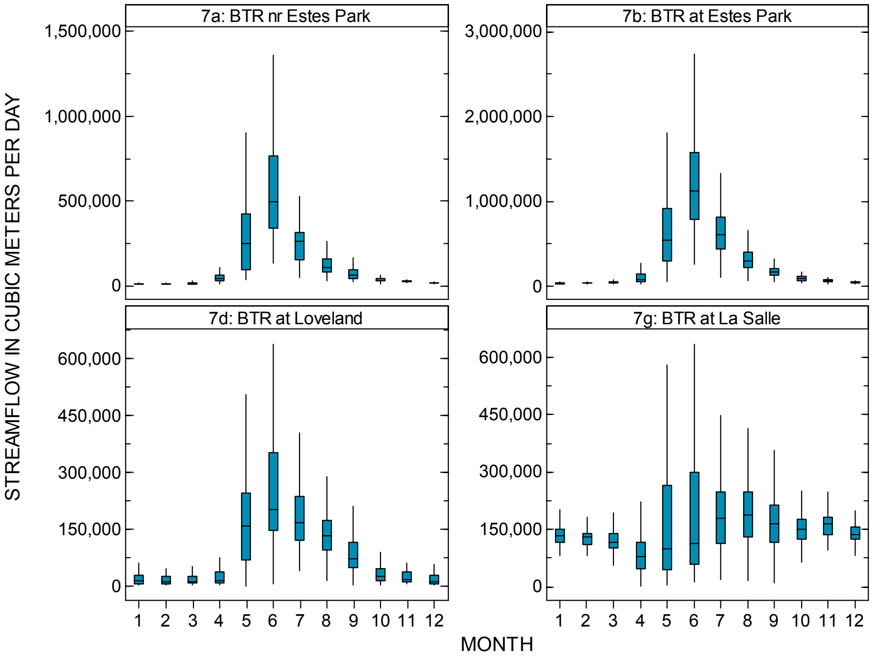


Figure 4-17. Boxplots showing seasonal patterns in streamflow at selected sites along Clear Creek, water years 1991–2004.

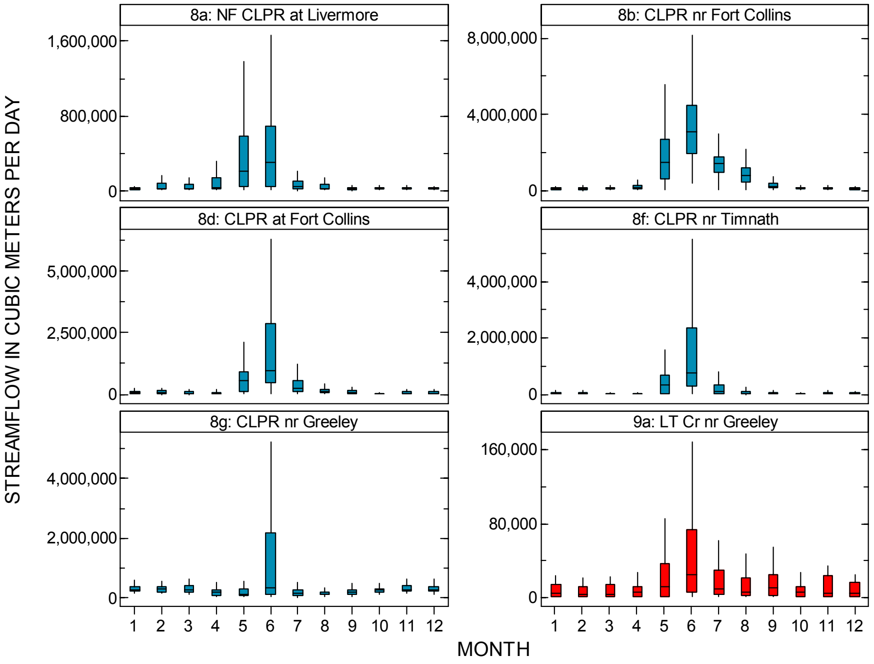


Figure 4-18. Boxplots showing seasonal patterns in streamflow at selected sites along the Cache la Poudre River and Lone Tree Creek, water years 1991–2004.

4.3.4 Trend Analysis

Results of linear regression trend analysis on the ranks of annual streamflow values for selected sites during water years 1991 through 2004 are listed in Table 4-2. Sites deemed to have a significant ($p <= 0.10$) trend in annual streamflow are shown in bold typeface and have the trend magnitude displayed in the right-most column. Based on this analysis, annual flow for most monitoring sites has remained relatively stable between water year 1991 and water year 2004. The only two significant upward trends were found along Cherry Creek at site 2c (Cherry Creek below Cherry Creek Reservoir) and site 2d (Cherry Creek at Glendale). The reason for this is unclear.

Eight significant downward trends in annual streamflow were found. The South Platte River at Kersey (site 1f) had a decrease in annual streamflow of 3.3 percent per year. Three sites in the upper portion of the Clear Creek watershed had decreasing trends: sites 4c, 4d, and 4e had decreasing trends of 8.8, 9.7, and 12.9 percent per year respectively. It should be noted, however, that trends at these three sites are based on only 10 years of available monitoring data instead of the 14 years of data available at most other sites so comparisons of trends determined using differing lengths of time should not be made. Two sites on the lower Saint Vrain River had decreasing trends: the Saint Vrain River at Longmont and the Saint Vrain River at Platteville (sites 6e and 6f) had downward trends of 3.2 and 3.8 percent per year. A slight downward trend of 3.7 percent per year was found for the Big Thompson River at its mouth near La Salle (site 7g). Similarly, the site at the mouth of the Cache la Poudre River (site 8g) had a decreasing trend of 3.7 percent per year.

As with any trend analysis, the choice of time period used for the analysis can have an impact on the results. Many of the significant downward trends found for this study period are likely to reflect the drought conditions experienced at the end of the study period. Analysis of a longer time period would provide a better picture of the overall long-term trends at these sites. Even with this limitation, these results do serve to document the overall trend in annual flow during the study period.

Table 4-2. Results of trend analysis on annual streamflow, water years 1990 – 2004.

[m^3, cubic meters; yr, year; %, percent]

Site Number	Site Name	Period (water years)	Number of years	Slope (million m^3/yr)	*p*-Value	Mean (million m3/yr)	Trend (%/yr) *
1a	SPR nr Englewood	1991 - 2004	14	-3.25	0.513	133.7	
1b	SPR at Englewood	1991 - 2004	14	-4.22	0.615	194.3	
1c	SPR at Denver	1991 - 2004	14	-3.88	0.725	270.8	
1d	SPR at Comm. City	1991 - 2004	14	-1.39	0.829	146.7	
1e	SPR at Henderson	1991 - 2004	14	-4.17	0.887	447.7	
1f	**SPR nr Kersey**	**1991 - 2004**	**14**	**-29.80**	**0.098**	**915.1**	**-3.3**
1g	SPR nr Weldona	1991 - 2004	14	-23.33	0.191	650.9	
1h	SPR at Julesburg	1991 - 2004	14	-32.03	0.106	502.1	
2a	Cherry Cr nr Franktown	1991 - 2004	14	0.11	0.946	7.4	
2b	Cherry Cr nr Parker	1992 - 2004	13	0.27	0.306	8.9	
2c	**Cherry Cr bl CC Res.**	**1991 - 2004**	**14**	**1.01**	**0.005**	**10.8**	**9.3**
2d	**Cherry Cr at Glendale**	**1991 - 2003**	**13**	**1.23**	**0.082**	**22.6**	**5.4**
2e	Cherry Cr at Denver	1991 - 2004	14	0.77	0.149	30.0	
3a	Sand Cr nr Comm City	1993 - 2004	12	0.02	0.897	49.9	
4c	**Clear Cr nr Lawson**	**1995 - 2004**	**10**	**-11.48**	**0.006**	**130.3**	**-8.8**
4d	**Clear Cr nr Idaho Spgs**	**1995 - 2004**	**10**	**-17.71**	**0.008**	**182.9**	**-9.7**
4e	**N Clear Cr nr Blk Hwk**	**1995 - 2004**	**10**	**-2.09**	**0.008**	**16.1**	**-12.9**
4f	Clear Cr at Golden	1991 - 2004	14	-2.83	0.681	170.8	
5a	BD Cr at Westminster	1991 - 2004	12	-0.18	0.508	14.4	
5b	BD Cr nr Fort Lupton	1992 - 2004	13	-0.11	0.616	35.5	
6b	Boulder Cr nr Boulder	1991 - 2004	14	-2.99	0.246	94.0	
6c	Boulder Cr nr Longmont	1992 - 2004	13	-3.52	0.223	70.0	
6e	**SVR bl Longmont**	**1991 - 2004**	**14**	**-3.37**	**0.059**	**106.2**	**-3.2**
6f	**SVR nr Platteville**	**1991 - 2004**	**14**	**-7.95**	**0.056**	**210.2**	**-3.8**
7b	BTR at Estes Park	1991 - 2004	14	-1.28	0.759	105.2	
7d	BTR at Loveland	1991 - 2004	14	-0.62	0.829	50.9	
7g	**BTR at La Salle**	**1991 - 2004**	**14**	**-3.00**	**0.047**	**81.6**	**-3.7**
8a	NF CLPR at Livermore	1991 - 2004	14	-1.41	0.288	46.0	
8b	CLPR nr Fort Collins	1991 - 2004	14	-6.55	0.358	261.3	
8d	CLPR at Fort Collins	1991 - 2004	14	-3.14	0.392	118.3	
8f	CLPR nr Timnath	1991 - 2004	14	-2.34	0.455	94.1	
8g	**CLPR nr Greeley**	**1991 - 2004**	**14**	**-5.32**	**0.098**	**142.5**	**-3.7**

* Trends shown only for sites with a significance level of 90% or higher

4.4 CONCLUSIONS

Although streamflow characterization was not the primary focus of this work, an understanding of streamflow conditions at the selected water-quality monitoring sites is important for proper interpretation of water quality and dissolved solids load conditions presented in later chapters. In general, streamflow conditions vary greatly throughout the basin, both seasonally and from year to year. For water years 1991 through 2004, ten sites had significant changes in annual streamflow. Two of these sites had upward trends while the remaining eight sites had decreasing trends. It is likely many of the decreasing trends were influenced by the occurrence of a severe drought at the end of the study period.

CHAPTER 5: DISSOLVED SOLIDS CONCENTRATIONS

5.1 INTRODUCTION

5.1.1 Overview

This chapter presents the results of the most comprehensive characterization of historical dissolved solids concentrations in the South Platte River Basin performed to date. Analysis of historical water-quality monitoring records allows for the determination of spatial, seasonal, and temporal changes in water quality. Characterization techniques include time series plots, summary statistics, analysis of spatial and seasonal patterns, and long-term temporal trend analysis. Most analysis is focused on the more recent period of water years 1991 through 2004 (October 1, 1990 through September 30, 2004); however time series plots and trend analysis for the entire period of record are also presented. Included as Appendix B are results from an additional field monitoring project that was conducted during the low-flow period of fall 2002 through early spring 2003 in an attempt to gain greater spatial resolution of TDS concentration increases along South Platte River tributaries in the middle portion of the basin.

5.1.2 Previous Studies

Over the years, there have been a handful of published studies that have characterized surface water-quality conditions including salinity in the South Platte River Basin. As part of an analysis of water resource development alternatives, Woodward-Clyde Consultants (1982) provided a report to the Colorado Water Conservation Board that included a cursory analysis of water-quality conditions including some characterization of historical TDS concentrations at selected locations. Gomez-Ferrer *et* *al*. (1983) characterized dissolved solids concentrations and spatial patterns at five mainstem monitoring sites and three tributary sites for the time period 1965 through 1979 as part of a flow and salt balance analysis of the lower South Platte River Basin between Henderson and Julesburg. Lord (1997) completed a similar study using the same geographic region and monitoring sites for the period 1963 to 1994 in order to perform spatial characterization of salinity concentrations and examine changes in salt concentration over time at the major monitoring sites. An additional component of the study by Lord looked at spatial and temporal trends in the ionic composition of dissolved solids. The U.S. Geological Survey, in conjunction with the Northern Colorado Water Conservancy District and the U.S. Bureau of Reclamation, completed a retrospective study (Mueller, 1990) which examined historical data from monitoring sites which were associated with the Colorado-Big Thompson Project (CBT). A total of ten sites were examined; four were on natural streams, three were on the CBT Project carriage facilities, and three were on CBT Project reservoirs. The four sites on natural streams were located on Boulder Creek and its mouth near Longmont, the South Platte River at Masters, and the South Platte River near Weldona. A site on the Colorado River was chosen to evaluate the impacts of water diversions by the CBT project on the Colorado River. The study included characterization and trend analysis of salinity and major ionic constituents and included all period of record data through 1987. As part of the U.S. Geological Survey's NAWQA program, Litke and Kimbrough (1998) collected monthly samples from twelve fixed sites in the South Platte River Basin for the period March 1993 to September 1995. The resulting data were used to provide water-quality summaries for each site and for the investigation of the effects of land use on constituent concentrations and the development of estimates of stream loads for selected constituents.

5.2 METHODS

5.2.1 Time Series Plots

One of the first steps when performing exploratory data analysis is graphical analysis of the data (Helsel and Hirsch, 1992). Time-series scatterplots of TDS concentrations were produced for all water-quality sites selected in Chapter 3. Locally weighted scatter-plot smoothing (LOWESS) lines were superimposed over the data points to aid in the visualization of the general nature and trends of the data (Helsel and Hirsch, 1992).

5.2.2 Summary Statistics and Spatial Patterns

Spatial differences in TDS concentrations among monitoring sites in the South Platte River Basin were evaluated through the use of summary statistics and box plots. Seven distributional parameters were determined for the historical TDS values at each site. These parameters were the number of observations, mean, minimum, 25th percentile, 50th percentile, 75th percentile, and maximum. Sites having fewer than 8 observations were excluded from this analysis. Box plots were produced to graphically display the distribution of TDS values at each monitoring site. Plots are grouped by sub-basin and monitoring sites are shown in an upstream to downstream order.

5.2.3 Seasonal Patterns

Seasonal variation in water quality is often driven by seasonal changes in the volume of streamflow. Seasonal decreases in TDS can arise due to phenomena such as the dilution of dissolved solids by large volumes of low-TDS runoff arising from summer precipitation or spring snowmelt. Seasonal increases can be caused by the domination of higher-TDS ground water seepage into a stream during fall and winter low-flow conditions. Seasonal variation in concentration not caused by changes in streamflow might be an indication of seasonal changes in the contribution from multiple streamflow sources. An understanding of seasonal water-quality changes can play an important role in management decisions, such as the timing of water diversion for storage in reservoirs.

Seasonal patterns were evaluated through the use of seasonal scatter plots rather than seasonal box plots because many sites had an insufficient number of data points (<5) to be plotted via box plots. Initially, seasonal box plots were produced by condensing sampling events into four defined seasons, however it was determined that the imposition of seasons tended to mask the seasonal distribution of the underlying data. As a result, seasonal scatter plots were produced instead to preserve the seasonal variation and distribution of the data. LOWESS lines (degree of smoothing = 0.5, number of steps =2) were superimposed over the data points to aid in the visualization of the general seasonal patterns.

5.2.4 Concentration – Flow Relations

The effect of streamflow on dissolved solids concentrations was evaluated for each of the monitoring sites through the creation of scatter plots showing dissolved solids concentrations versus streamflow at each of the monitoring sites. The concentration of constituents in streams is often correlated with streamflow. The nature of the relationship between constituent concentration and streamflow generally reflects the type of dominant constituent sources in the watershed. Constituents associated with sediments or in suspended form often increase in concentration as streamflow increases due to the effects of wash-off and erosion from streambanks or streambeds. Concentrations of dissolved constituents can sometimes increase with increasing streamflow due to wash-off of accumulated salt residue on soil or other surfaces. Increased dissolved solids concentrations and streamflow can both occur as a result of the transport of road deicing salts along with surface flow from melted ice and snow or rainfall events. More often, however, concentrations of dissolved constituents decrease with increasing streamflow due to dilution of relatively constant sources such as point sources or ground water discharge to the stream. Some constituents may exhibit a combination of these patterns due to differing effects of flow on multiple sources of the constituent (Helsel and Hirsch, 1992). An understanding of the relationship between constituent concentration and flow can sometimes provide insight into sources of the constituent and aid in interpretation of trend results.

5.2.5 Trend Analysis

Analysis of long-term temporal trends can provide important indications of changes to water quality resulting from natural and anthropogenic influences. Trend analysis can provide an indication of how water-quality conditions have changed in the past and possibly some insight into how they might continue to change in the future should current conditions continue. Trend analysis was conducted on the set of monitoring sites selected in Chapter 3 in order to determine if dissolved solids concentrations have significantly increased or decreased during the period of water years 1991 through 2004 and also during the entire period of water-quality monitoring at each site. Dissolved solids concentrations can vary seasonally, therefore the seasonal Kendall test (Hirsch *et al.*, 1991) was used to account for seasonality which might otherwise obscure long-term trends. A seasonal Kendall test is performed by computing the Mann-Kendall test on each defined season separately before combining the results (Helsel and

Hirsch, 1992). This methodology is appropriate for the detection of monotonic trends which are defined as gradual, continuous changes over time.

5.2.5.1 Data Criteria

Trend analysis was conducted on dissolved solids values for water years 1991 though 2004 as well as the entire period of record. Trends were only computed for sites meeting the following criteria (Schertz *et al.*, 1991):

1. The dissolved solids monitoring record must span a minimum of five years.
2. The minimum number of observations in the record must be at least three times the number of designated annual seasons and must be at least ten.
3. A minimum percentage of the total possible number of seasonal dissolved solids values in the beginning and ending fifths of the record must be present in the record.

Due to insufficient length of monitoring periods or inconsistent monitoring efforts, not all sites met the data requirements for trend analysis. Trend analysis was performed for shorter time periods at sites if consistent data for the entire study period were not available. Small breaks in the time series were allowed if they occurred in the middle one-third of the data. Possible outliers were not eliminated because the seasonal Kendall test is considered to be robust and therefore relatively unaffected by outliers (Schertz *et al.*, 1991). The seasonal Kendall test should not be used when there are more than 5 percent censored values or values are censored at multiple reporting levels (Schertz *et al.*, 1991). This was not a concern in this study because no censored dissolved solids values occur in this data set.

5.2.5.2 Seasonal Kendall Trend Analysis

Seasonal Kendall trend analysis procedures were conducted according to the guidance provided by Hirsch (1991) through the use of the USGS-developed software package S-ESTREND (Slack *et al.*, 2003) which runs as a library within the statistical analysis package S-PLUS® (Insightful Corporation). S-ESTREND is an updated version of the USGS program Estimate Trend (ESTREND) (Schertz *et al.*, 1991) which was a system of computerized statistical and graphical procedures for the investigation of trends in water-quality data. S-ESTREND and its predecessor ESTREND were both designed to facilitate operational decisions and procedures required in the analysis of trends.

Suitable beginning and ending periods for trend analysis were determined for each site. This was performed for both the common period of water years 1991 through 2004 as well as the available period of record for each site. S-ESTREND was used to confirm that historical dissolved solids data for the selected periods met the minimum requirements for trend analysis as defined above. Once time periods meeting the minimum data requirements were selected, a seasonal analysis procedure within S-ESTREND was used to assist in the determination of the optimal seasonal definition (2, 3, 4, 6 or 12 seasons per year) for each site. For seasons with multiple values, the seasonal Kendall test procedure requires that the most central value with respect to time be used to represent the season (Schertz *et al.*, 1991). All other values for the same season are excluded from the analysis. To avoid unnecessary exclusion of data from sites, the maximum number of seasons supported by the data was defined on a site by site basis rather than simply specifying a smaller number of seasons for all sites.

Following verification of minimum data requirements and selection of optimal season definitions, S-ESTREND was used to perform uncensored seasonal Kendall tests for each site during the period of water years 1991 through 2004 and then for the entire period of available data since 1950. Output from S-ESTREND included Kendall's tau statistic, the attained significance level (*p*-value) of Kendall's tau statistic, the median of the data used in the analysis, and the seasonal Kendall slope estimator. Computed according to the method of Sen (1968), the seasonal Kendall slope estimator or trend slope provides an estimate of the median rate of change per year in original units or in percent.

5.2.5.3 Flow Adjustment

Because of the effect of flow rate on constituent concentration, the detection of constituent trends can be complicated by the variability induced as a result of changing streamflow conditions. Flow-related variability in water-quality records can be much larger than the variability in water quality resulting from natural or anthropogenic changes in the underlying sources of the constituents. Flow-related variability can therefore mask water-quality trends resulting from these changes. Removal of the variation in water quality caused by extraneous variables such as streamflow is required in order to understand the underlying processes that may have affected water quality over time and will increase the chance of detecting a trend resulting from an influence other than streamflow (Schertz *et al.*, 1991).

Flow-related variability in water quality is removed by computing flow-adjusted constituent concentrations. Flow adjustment attempts to remove the effects of variability in streamflow from water-quality data by defining a relationship between concentration and flow. Deviations of water-quality concentrations from this relationship are assumed to be caused by factors other than variability in flow. Flow adjustment of constituent concentrations can be performed through the use of regression methods by fitting any number of models to the relationship between concentration and flow. A more robust alternative to this approach is the generation of a locally weighted scatterplot smoothing line (LOWESS). A LOWESS fit tracks the central tendency of the data without the need to specify a functional relationship between concentration and flow. The robust nature of the LOWESS procedure results from the use of both distance from the fitted line and residual-weighting functions using weighted least squares to minimize the influence of outliers when fitting a smooth line to the data (Schertz *et al.*, 1991). The number of observations used in the LOWESS regression calculation may be selected by specifying the value of the smoothness factor *f*.

Once a LOWESS smoothing line defining the relationship between constituent concentration and flow at each site is produced, the residuals (the observed dissolved solids concentration minus the LOWESS predicted dissolved solids concentration) are computed for every data pair. These residuals are termed the flow-adjusted concentrations. These flow-adjusted concentrations can then be subjected to trend analysis using the seasonal Kendall test (Butler, 1996).

Flow adjustment of dissolved solids concentrations was performed by defining a LOWESS smooth line for the relationship between TDS and flow (model option 13 within S-ESTREND). A LOWESS *f* value of 0.5 was used to define the relationship between concentration and flow. This value appeared to provide a reasonably good fit to the data and is in agreement with other reports examining optimal *f* values for water-quality constituents (Schertz *et al.*, 1991). Residuals between the TDS values and the LOWESS smooth line represent the flow-adjusted TDS values. These flow-adjusted TDS values were then subjected to uncensored seasonal Kendall trend analysis as described above for the non-flow adjusted TDS values.

5.3 RESULTS AND DISCUSSION

5.3.1 Time Series Plots

Time series plots of TDS concentration for water years 1991 through 2004 are presented in Figure 5-1 through Figure 5-6. A similar set of time series plots for the entire period of record beginning in calendar year 1950 are included in Appendix C. LOWESS smoothing lines were added to all plots to aid in the visualization of the data; however the smoothing lines do not imply the existence of statistically significant trends in TDS concentration. In addition to showing the behavior of TDS concentrations over time, the time series plots are necessary for interpretation of trend analysis results presented in Section 5.3.5. Analysis and discussion of time series plot results will be incorporated into the following sections.

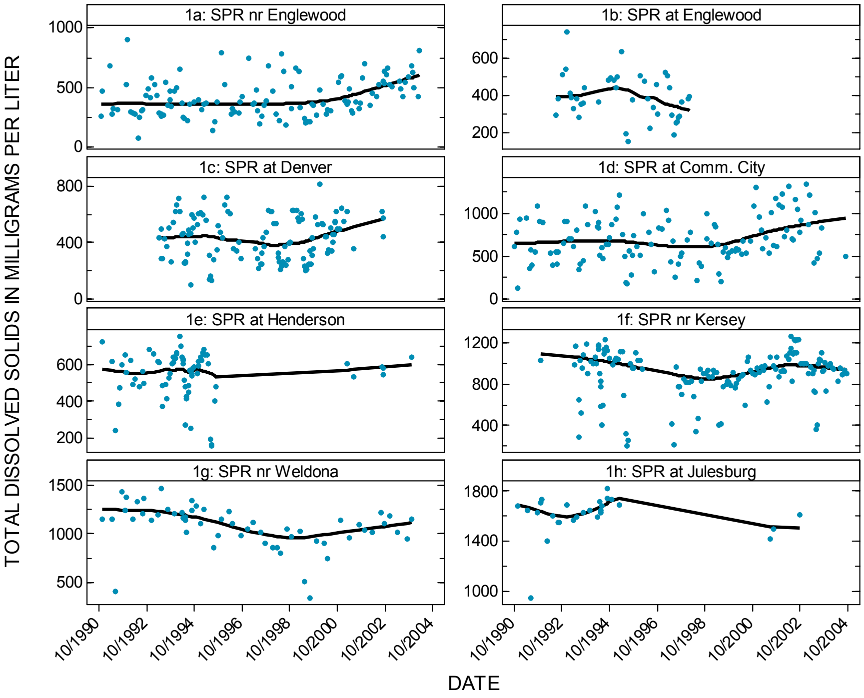


Figure 5-1. Time series plots of TDS concentration with LOWESS smoothing lines at selected monitoring sites along the mainstem of the South Platte River, water years 1991–2004.

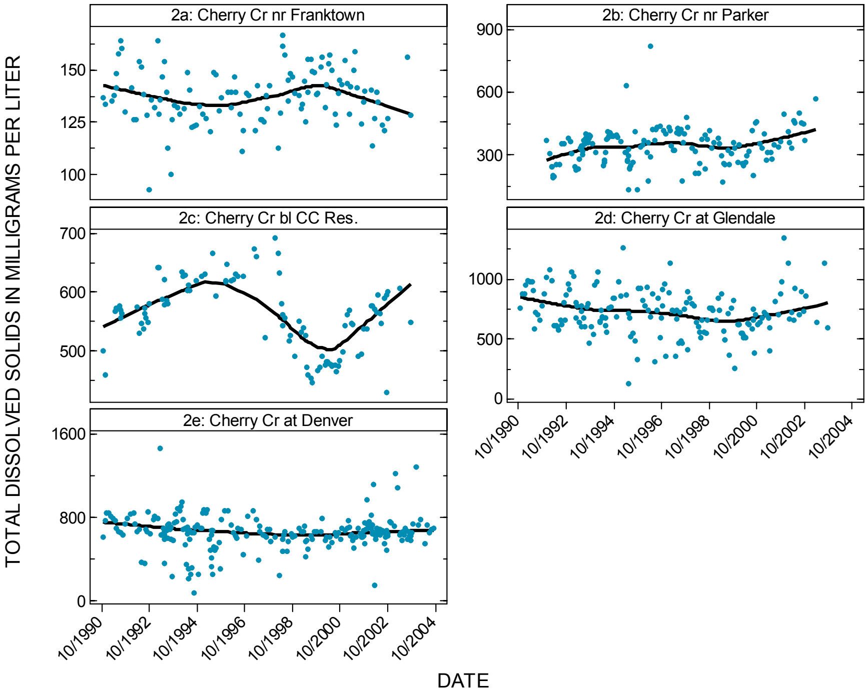


Figure 5-2. **Time series plots of TDS concentration with LOWESS smoothing lines at selected monitoring sites along Cherry Creek, water years 1991–2004.**

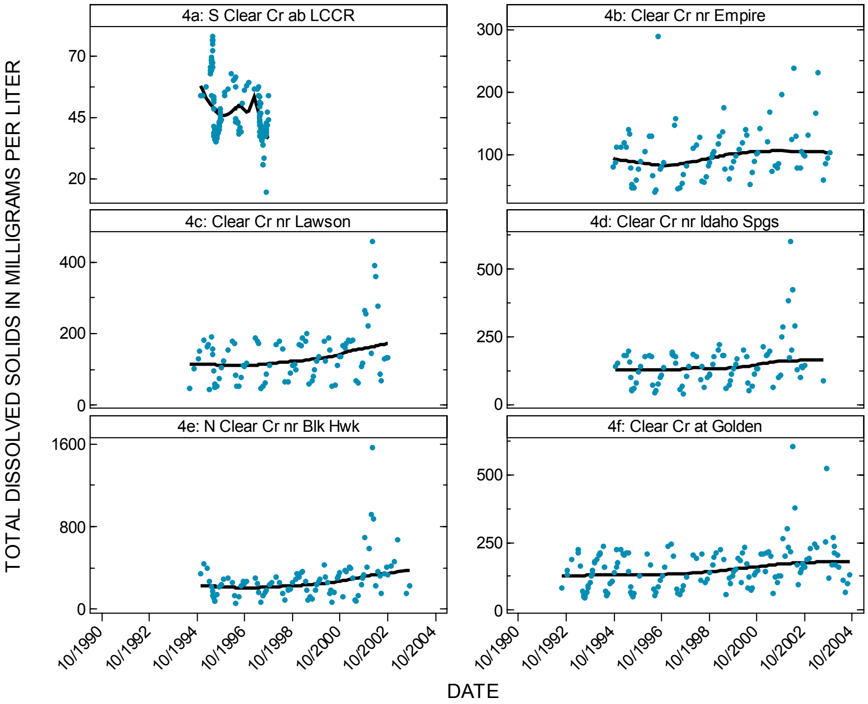


Figure 5-3. **Time series plots of TDS concentration with LOWESS smoothing lines at selected monitoring sites along Clear Creek, water years 1991–2004.**

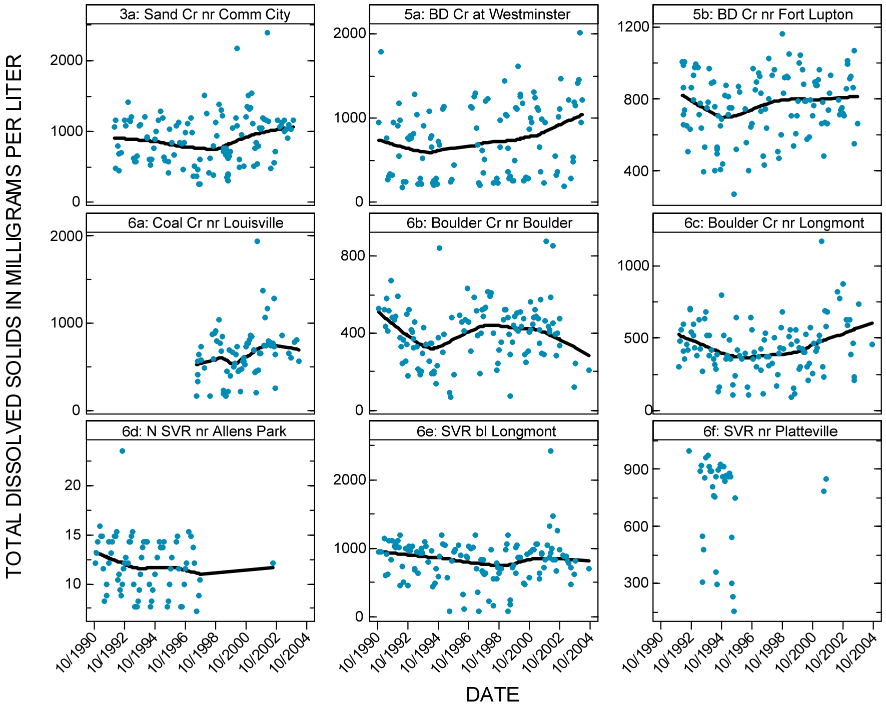


Figure 5-4. Time series plots of TDS concentration with LOWESS smoothing lines at selected monitoring sites along Sand, Big Dry, Coal, and Boulder Creeks, as well as the Saint Vrain River, water years 1991–2004.

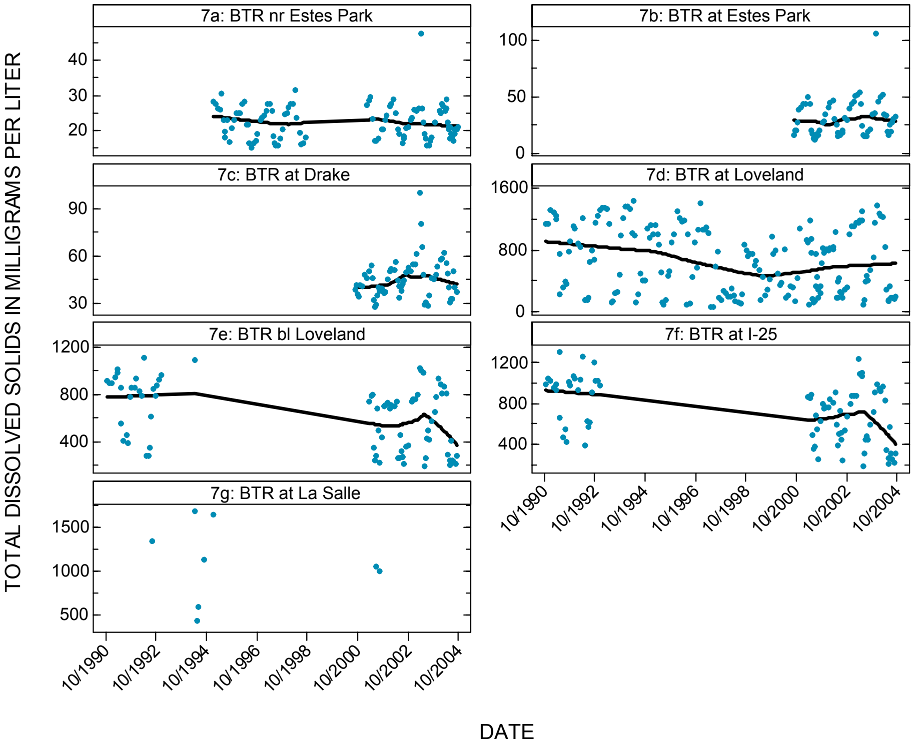


Figure 5-5. Time series plots of TDS concentration with LOWESS smoothing lines at selected monitoring sites along the Big Thompson River, water years 1991–2004.

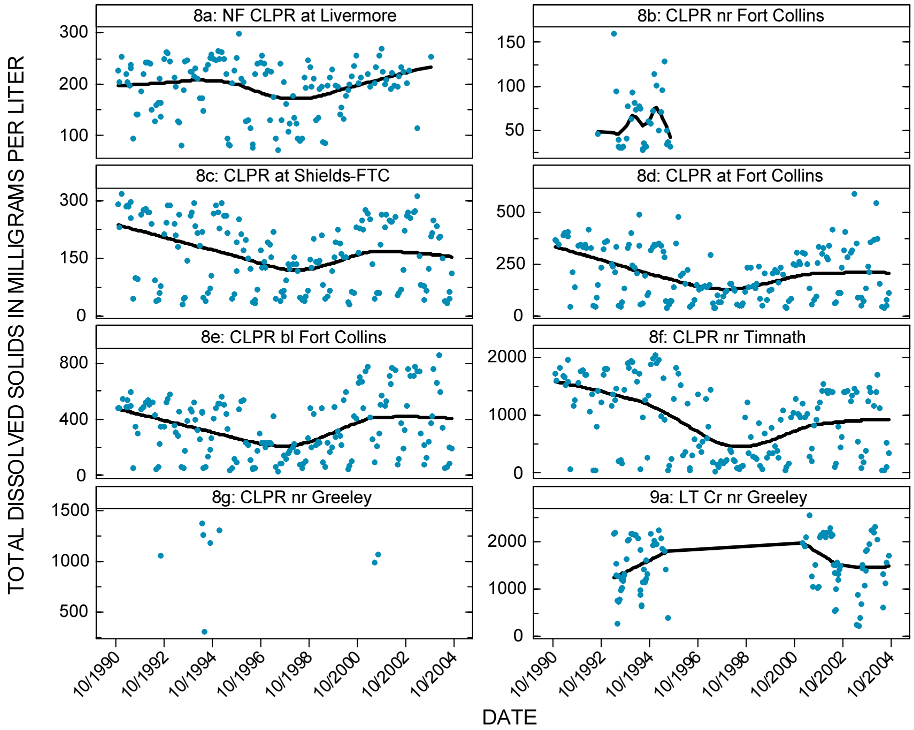


Figure 5-6. Time series plots of TDS concentration with LOWESS smoothing lines at selected monitoring sites along the Cache la Poudre River and Lone Tree Creek, water years 1991–2004.

5.3.2 Summary Statistics and Spatial Patterns

Summary statistics for TDS concentrations at selected monitoring sites are presented in Table 5-1. The spatial patterns of TDS concentrations along the mainstem of the South Platte River and along selected tributary sub-basins are shown via boxplots in Figure 5-7 through Figure 5-12. All sites are shown in an upstream to downstream order for each respective stream.

Median TDS values varied substantially within the South Platte River Basin. As typically observed with TDS values, the lower median values were found in the headwater sites with TDS values usually increasing in a downstream direction. The site with the lowest and also one of the least variable median TDS values was the North Saint Vrain River near Allenspark (site 6d). This site represents a hydrologic setting characterized by high-elevation snowmelt runoff as a water source, low rates of evapotranspiration, and crystalline bedrock geology. The highest median TDS was found at the South Platte River at Julesburg (site 1h) which is located downstream of all other sites and thus integrates all of the upstream natural and anthropogenic sources of dissolved solids. Water quality at this point also reflects the cumulative effects of evapoconcentration due to consumptive use and phreatophyte evapotranspiration.

Table 5-1. Summary statistics for total dissolved solids values in the South Platte River Basin, water years 1991–2004.

[N, total number of observations; mg/L, milligrams per liter]

			Total Dissolved Solids (mg/L)					
					Percentile			
Site	**Station Name**	**N**	**Mean**	**Minimum**	**25**	**50**	**75**	**Maximum**
1a	SPR nr Englewood	123	411	68	291	370	521	902
1b	SPR at Englewood	42	386	147	290	380	480	736
1c	SPR at Denver	126	433	95	288	436	568	817
1d	SPR at Comm. City	125	699	124	522	672	899	1,347
1e	SPR at Henderson	75	541	158	484	568	625	752
1f	SPR nr Kersey	147	898	198	816	942	1,040	1,267
1g	SPR nr Weldona	57	1,081	341	982	1,126	1,220	1,472
1h	SPR at Julesburg	27	1,611	949	1,570	1,638	1,699	1,825
2a	Cherry Cr nr Franktown	119	137	93	129	137	147	166
2b	Cherry Cr nr Parker	160	342	129	277	350	393	818
2c	Cherry Cr bl CC Res.	106	560	430	524	565	603	692
2d	Cherry Cr at Glendale	169	722	127	610	711	843	1,347
2e	Cherry Cr at Denver	248	662	72	614	672	717	1,474
3a	Sand Cr nr Comm City	126	890	237	592	904	1,144	2,392
4a	S Clear Cr ab LCCR	208	45	14	38	41	51	78
4b	Clear Cr nr Empire	85	101	38	75	95	125	289
4c	Clear Cr nr Lawson	91	133	42	74	122	172	459
4d	Clear Cr nr Idaho Spgs	86	160	37	95	139	180	1,262
4e	N Clear Cr nr Blk Hwk	94	284	52	158	260	342	1,576
4f	Clear Cr at Golden	154	155	47	98	151	205	605
5a	BD Cr at Westminster	114	725	161	269	726	1,102	2,010
5b	BD Cr nr Fort Lupton	119	762	265	652	775	905	1,165
6a	Coal Cr nr Louisville	76	634	160	449	649	776	1,940
6b	Boulder Cr nr Boulder	123	401	67	299	409	487	876
6c	Boulder Cr nr Longmont	112	434	88	306	419	549	1,170
6d	N SVR nr Allens Park	75	12	7	10	12	14	24
6e	SVR bl Longmont	127	825	76	643	875	1,005	2,433
6f	SVR nr Platteville	35	743	151	549	865	900	1,003
7a	BTR nr Estes Park	128	22	15	18	22	26	47
7b	BTR at Estes Park	64	30	11	17	27	42	106
7c	BTR at Drake	63	45	27	36	44	51	100
7d	BTR at Loveland	191	645	45	226	629	1,027	1,436
7e	BTR bl Loveland	83	621	187	343	700	856	1,118
7f	BTR at I-25	82	724	180	480	767	975	1,308
7g	BTR at La Salle	8	1,115	430	700	1,098	1,575	1,685
8a	NF CLPR at Livermore	140	192	71	147	204	233	297
8b	CLPR nr Fort Collins	33	62	27	33	58	80	159
8c	CLPR at Shields-FTC	165	159	27	63	152	244	317
8d	CLPR at Fort Collins	172	198	31	76	191	314	587
8e	CLPR bl Fort Collins	169	343	30	171	322	502	858
8f	CLPR nr Timnath	171	903	31	264	971	1,423	2,032
8g	CLPR nr Greeley	8	1,067	297	1,004	1,127	1,297	1,372
9a	LT Cr nr Greeley	101	1,485	223	1,064	1,496	2,071	2,560

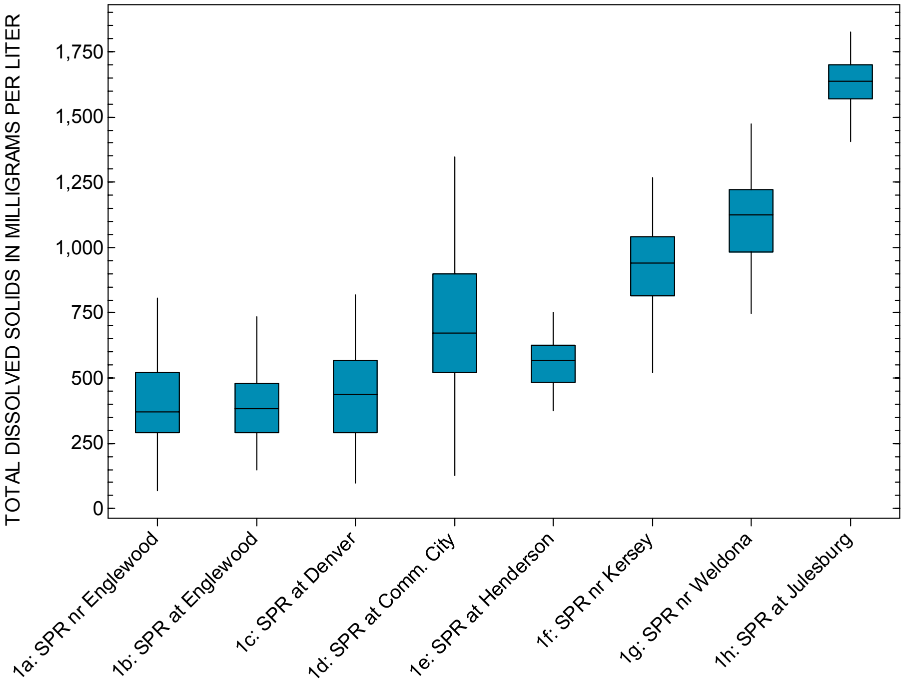


Figure 5-7. Boxplot of TDS concentration at selected monitoring sites along the mainstem of the South Platte River, water years 1991–2004.

Sites in the Denver metropolitan area (1a, 1b, and 1c) all had median TDS concentrations below 500 milligrams per liter (mg/L). Median TDS concentrations at these sites increase slightly in a downstream direction. Between Denver (site 1c) and Commerce City (site 1d), median TDS concentrations jumped from 440 mg/L to 670 mg/L. This large increase is likely explained by the existence of a major diversion structure between these two sites which supplies the Burlington Ditch. Diversions from the South Platte River to the Burlington Ditch can remove a large proportion of the total flow in the river at this point (Dennehy *et al.*, 1998). The flow remaining in the river is then more susceptible to the influence of higher-TDS inflows including ground-water return flows which reconstitute the river downstream from the diversion. The higher variability of TDS concentrations at Commerce City might be attributable to the influence and operational schedule of the diversion.

Between Commerce City and Henderson (site 1e), median TDS concentration decreases to nearly 570 mg/L. The flow at Henderson is often composed primarily of treated wastewater discharged from the Denver Metropolitan Wastewater Reclamation District's wastewater treatment plant just downstream from the monitoring site at Commerce City (Dennehy *et al.*, 1995). The decrease in median TDS concentration between Commerce City and Henderson is likely a reflection of the large proportion of lower-TDS effluent present in the river.

Beyond Henderson, median TDS concentration increases in a step-wise fashion with a large increase occurring in the 88 km segment between sites in Henderson and Kersey. A significant portion of the increase in median concentration from 568 to 942 mg/L between Henderson and Kersey can be attributed to the inflow of the three largest tributaries to the South Platte River along this river segment. The combined flow contributions from the Saint Vrain, Big Thompson, and Cache la Poudre Rivers nearly double the streamflow volume between Henderson and Kersey. With median TDS concentrations of 865, 1098, and 1127 mg/L respectively, this large volume of higher-TDS inflow is partially responsible for the jump in TDS along this river segment.

There is also a jump in median TDS from 1,126 to 1,638 mg/L in the farthest downstream segment between sites at Weldona and Julesburg. There are no major tributaries or point sources contributing water with high-TDS concentrations along this segment. The TDS increase is likely caused by evapoconcentration of salts already present in the river through irrigation and return flows with the possibility of some additional salt contribution from the leaching of irrigated agricultural lands. Analysis of dissolved solids flux in the following two chapters will help to further elucidate the predominant process.

TDS concentrations along Cherry Creek (Figure 5-8) exhibit a gradual increase between sites at Franktown and Glendale. As would be expected, variability in concentration decreases just below the outlet of Cherry Creek Reservoir. Variability and median concentration both increase between Cherry Creek Reservoir and Glendale and then decrease slightly between Glendale and the monitoring site near the mouth of Cherry Creek at Denver.

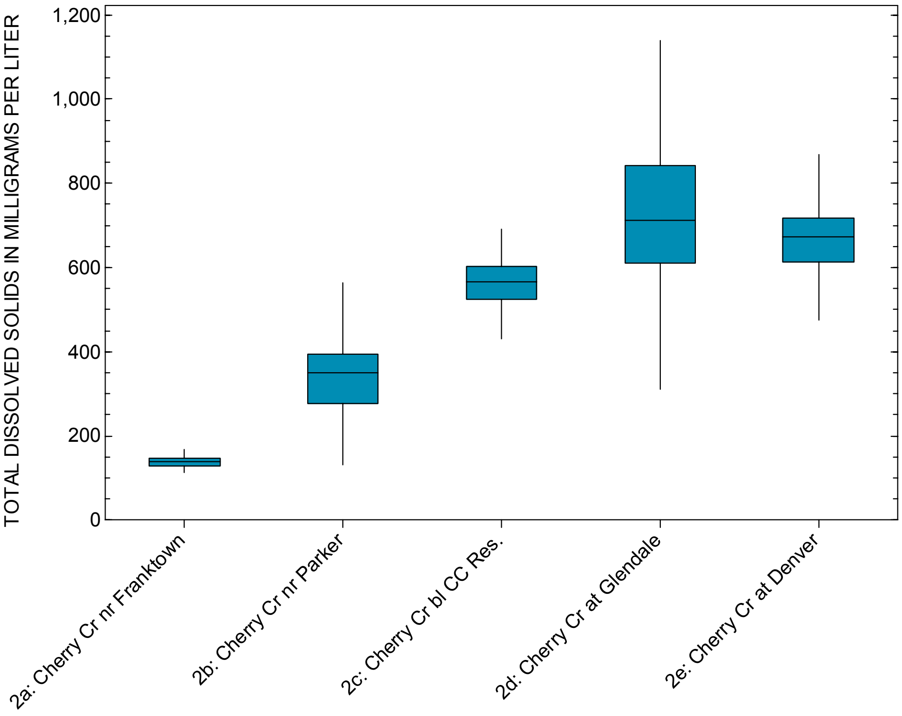


Figure 5-8. Boxplot of TDS concentration at selected monitoring sites along Cherry Creek, water years 1991–2004.

TDS concentrations along Clear Creek and its upper branches are shown in Figure 5-9. Median concentrations gradually increase along the creek but stay well below 200 mg/L with the exception of North Clear Creek near Blackhawk (site 4e) which has a median TDS concentration of 260 mg/L and greater variability in concentration as well.

The increased TDS found on North Clear Creek could be contributed by geologic features in the region, however the extremely large number of abandoned mining sites and associated spoil piles found in the watershed, dredge tailings along the creek, and treated wastewater effluent from the casino towns of Central City and Blackhawk are all likely contributors of dissolved solids as well.

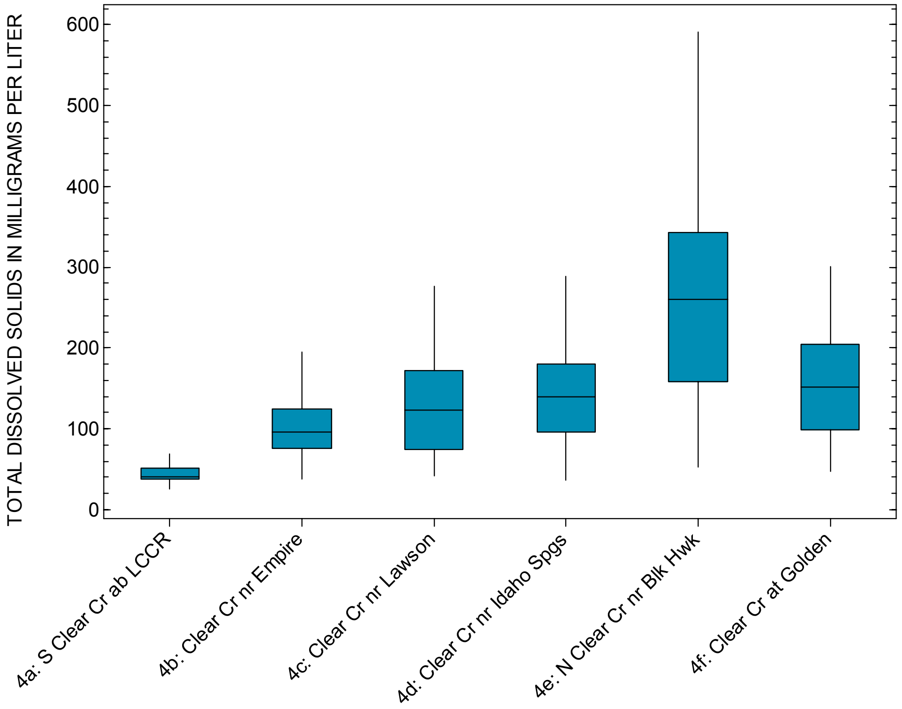


Figure 5-9. Boxplot of TDS concentration at selected monitoring sites along Clear Creek, water years 1991–2004.

Figure 5-10 displays TDS concentrations for several creeks (Sand Creek, Big Dry Creek, and Coal Creek) that flow through the urban areas of Denver and surrounding communities. Also included are sites along Boulder Creek and the Saint Vrain River. Plains-originating streams such as Sand and Big Dry Creek typically exhibit higher median TDS concentrations than streams originating in mountainous areas such as Clear Creek (Figure 4-15), Boulder Creek, and the Saint Vrain River (Figure 5-10). The Saint Vrain River originates in the mountains where it has extremely low TDS concentrations.

Concentrations increase dramatically in the Saint Vrain River at Longmont where the river flow has traversed the plains areas of the Front Range and has been subjected to inflow from groundwater return flows, inflow from other creeks and urban impacts such as point source discharges. Between Longmont and the mouth of the Saint Vrain River near Platteville, the median TDS remains constant; however it must be noted that the median TDS concentrations for the site near Platteville are based on a shorter period of active monitoring. During the period of active monitoring at Platteville, the TDS concentrations are actually lower than measurements taken upstream during similar time frames.

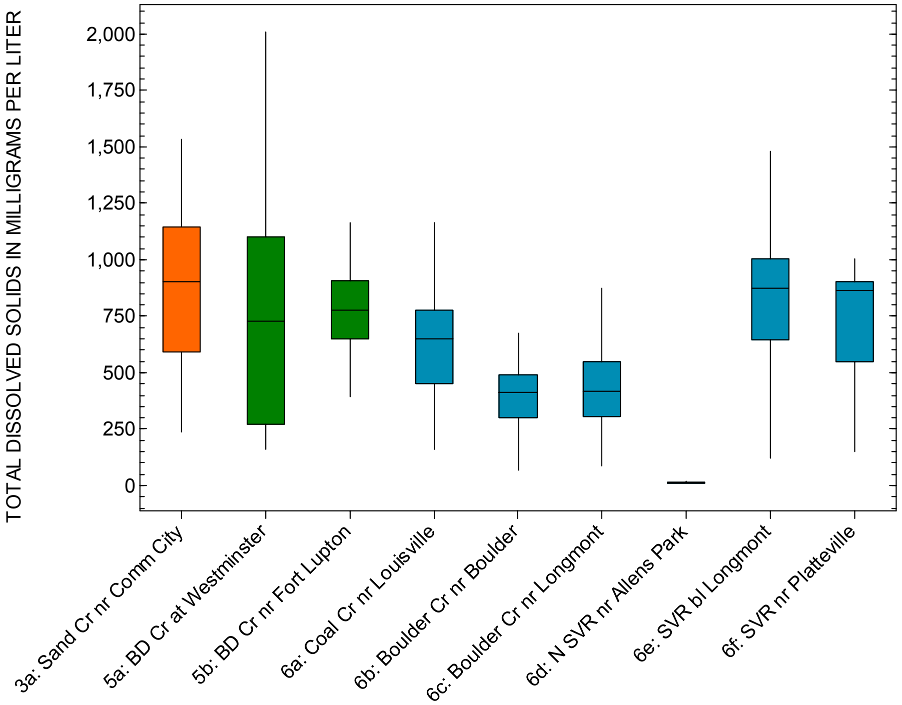


Figure 5-10. Boxplot of TDS concentration at selected monitoring sites along Sand, Big Dry, and Boulder Creeks and the Saint Vrain River, water years 1991–2004.

Another example of a dramatic increase in TDS concentrations in going from mountainous headwater sites to plains sites along the Front Range is shown for sites along the Big Thompson River (Figure 5-11). The first three sites (7a, 7b, and 7c), which are located in the mountains, maintain consistently low TDS values. Between the last mountainous site at Drake and the first urban plains site in Loveland, median TDS values jump considerably. Median TDS values continue to increase downstream, but the degree of increase is not as dramatic as it is between the mountain and plains sites. As with the site at the mouth of the Saint Vrain, data for the site at the mouth of the Big Thompson suffers from a lack of consistent sampling during this period. As a result, the TDS conditions at this site should be considered rough estimates.

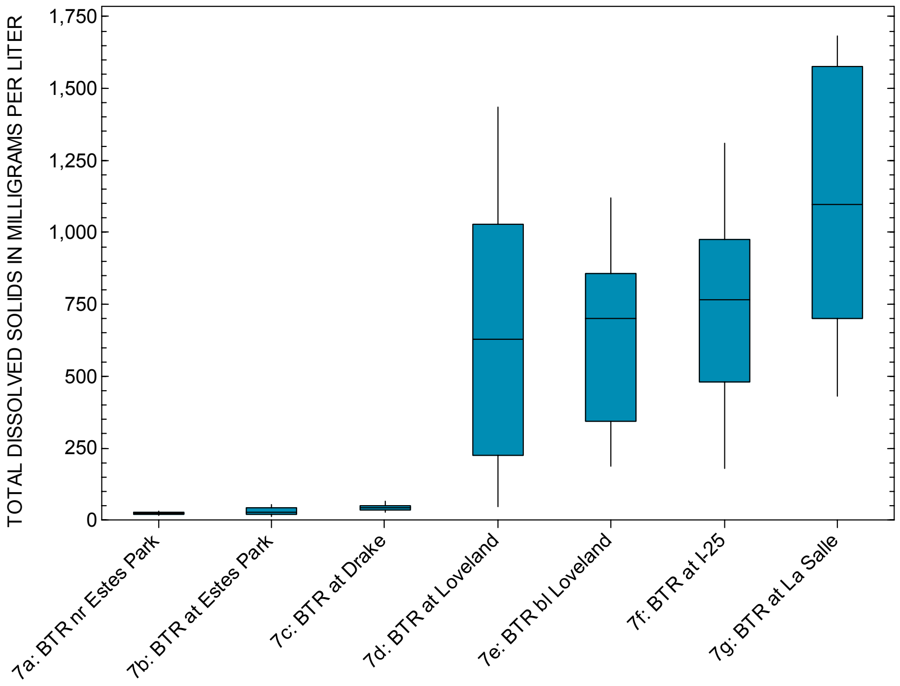


Figure 5-11. Boxplot of TDS concentration at selected monitoring sites along the Big Thompson River, water years 1991–2004.

The mainstem of the Cache la Poudre River (Figure 5-12) did not have any water-quality sites located in the mountains which meet the criteria for use in this study. The North Fork of the Poudre originates in the foothills northeast of Fort Collins. Site 8a on the North Fork of the Poudre is the farthest upstream site included in this study. TDS values in the North Fork of the Poudre are higher than typical values found for streams originating in more mountainous areas and higher than site 8b located on the mainstem of the Cache la Poudre River even though site 8b is located downstream from where the North Fork joins the mainstem. TDS concentrations tend to increase slightly as the river flows through Fort Collins; however a much larger increase occurs just downstream from Fort Collins between sites 8e and 8f even though these sites are less than two miles apart. Site 8e is located just outside of Fort Collins and downstream from most urban point sources, including treated wastewater effluent, so measurements here probably already reflect TDS increases resulting from urban point source contributions. It is likely that the sharp increase between site 8e and 8f is caused by the inflow of water with higher-TDS concentrations from Box Elder Creek and additional unnamed springs and groundwater seepage along this stretch. This hypothesis was explored further through additional field studies which are detailed in Appendix B. As with the Saint Vrain and Big Thompson Rivers, inconsistent monitoring during this period limit the ability to properly characterize TDS concentrations at the mouth of the Cache la Poudre River near Greeley.

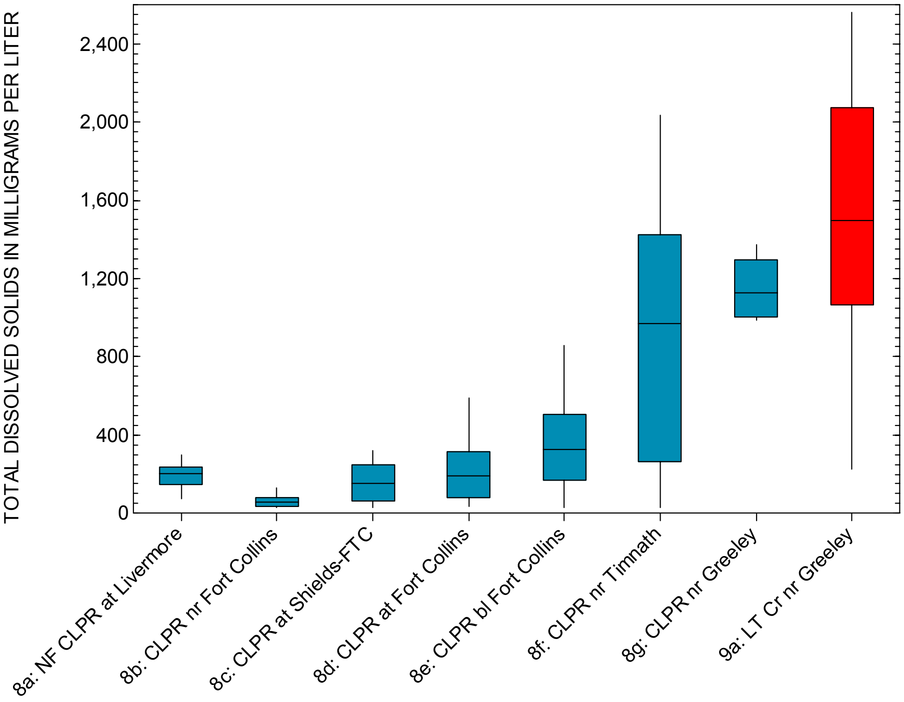


Figure 5-12. Boxplot of TDS concentration at selected monitoring sites along the Cache la Poudre River and Lone Tree Creek, water years 1991–2004.

5.3.3 Seasonal Patterns

Seasonal patterns in TDS concentrations at water-quality monitoring sites along the mainstem of the South Platte River and selected tributaries are shown in Figure 5-13 through Figure 5-18. Most sites exhibited some degree of seasonality with lower concentrations generally found in spring and summer and higher concentrations in fall and winter. Because TDS concentrations often vary with streamflow, it is not surprising that sites with seasonal patterns in TDS concentrations tend to be sites that exhibit seasonal patterns in streamflow. The relationship between streamflow and TDS concentration at each site will be examined in more detail in Section 5.3.4.

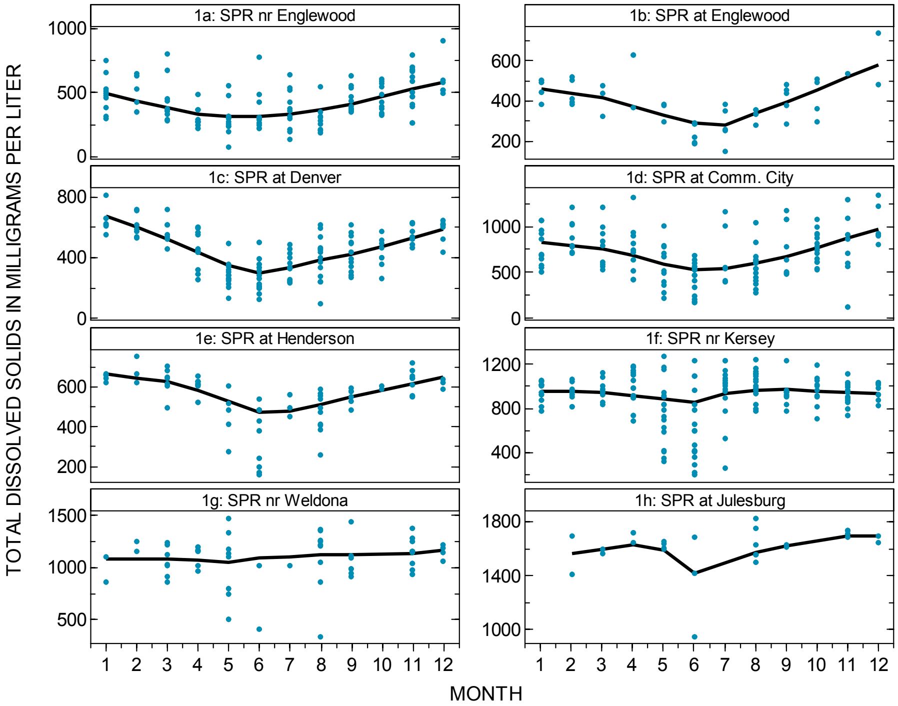


Figure 5-13. Plots showing seasonal patterns in dissolved solids concentration at monitoring sites along the South Platte River, water years 1991–2004.

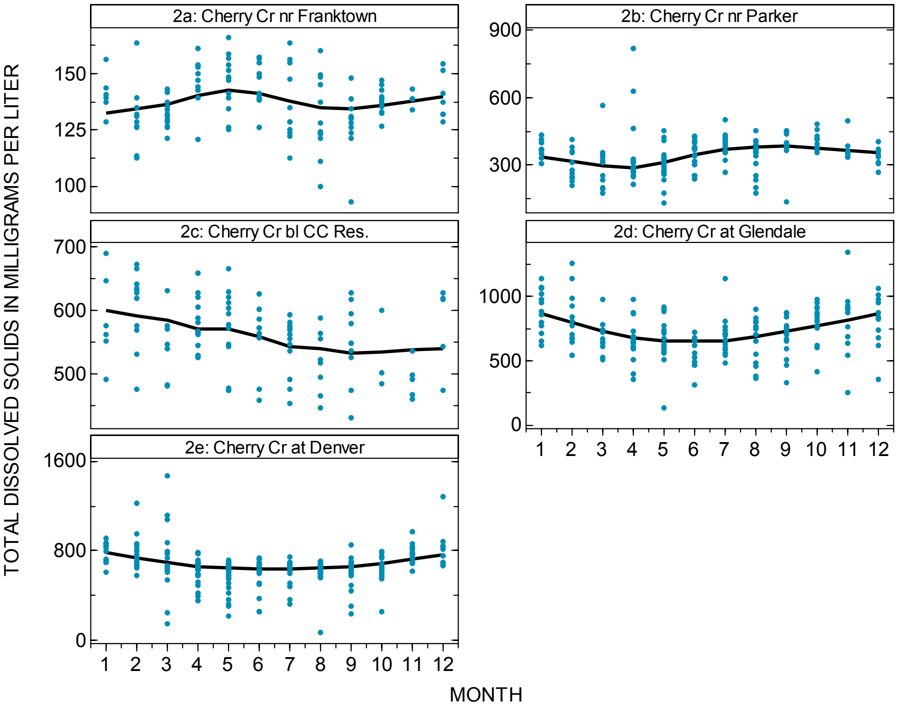


Figure 5-14. Plots showing seasonal patterns in dissolved solids concentration at monitoring sites along Cherry Creek, water years 1991–2004.

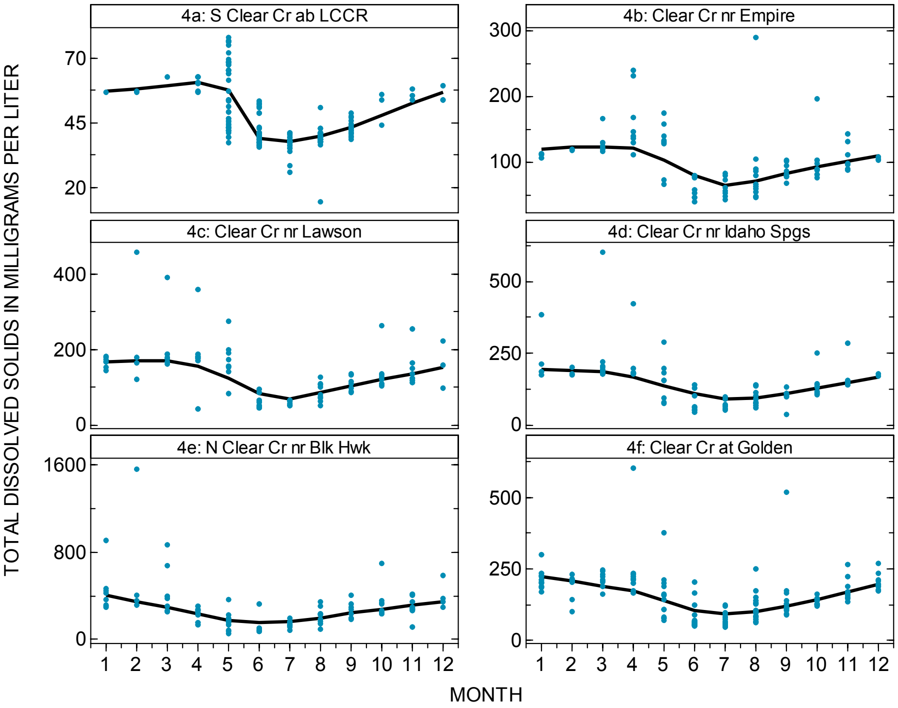


Figure 5-15. Plots showing seasonal patterns in dissolved solids concentration at monitoring sites along Clear Creek, water years 1991–2004.

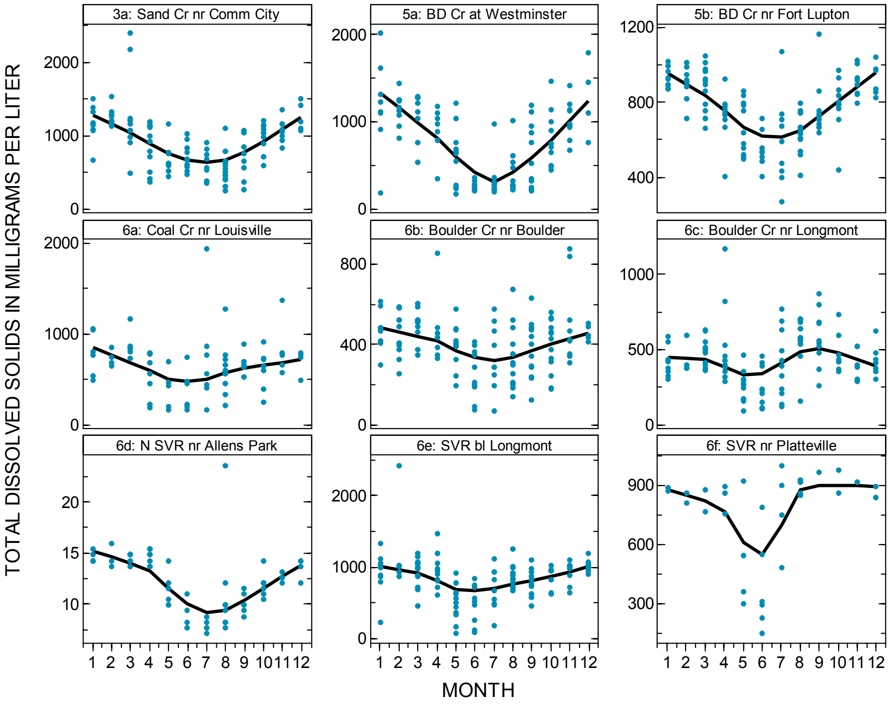


Figure 5-16. Plots showing seasonal patterns in dissolved solids concentration at monitoring sites along Sand, Big Dry, Coal, and Boulder Creeks and the Saint Vrain River, water years 1991–2004.

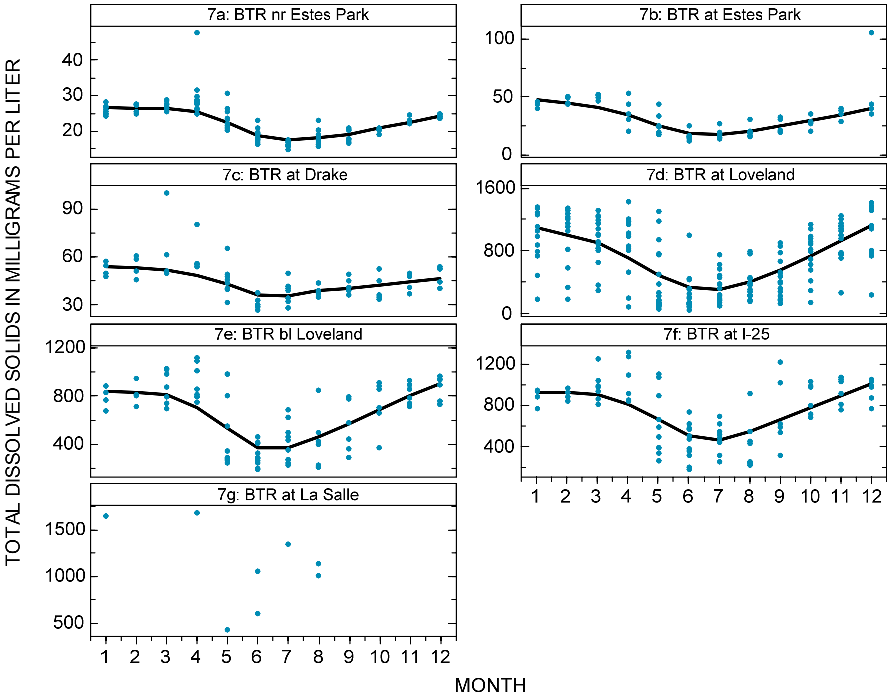


Figure 5-17. Plots showing seasonal patterns in dissolved solids concentration at monitoring sites along the Big Thompson River, water years 1991–2004.

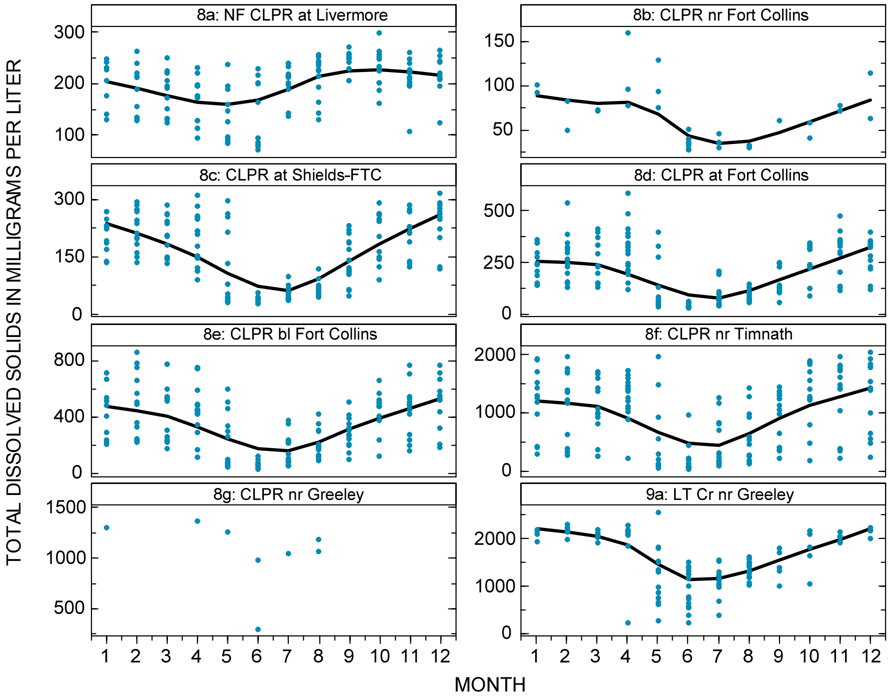


Figure 5-18. Boxplots showing seasonal patterns in dissolved solids concentration at monitoring sites along the Cache la Poudre River and Lone Tree Creek, water years 1991–2004.

5.3.4 Concentration – Flow Relations

The relationships between dissolved solids concentration and streamflow for each of the monitoring sites are presented in Figure 5-19 through Figure 5-24. A LOWESS smoothing line (degree of smoothing = 0.5, number of steps =2) is shown to aid in the visualization of patterns in the data. Patterns exhibiting a downward slope indicate a strong negative relationship between TDS concentration and streamflow. Good examples of this are the South Platte River at Denver and near Kersey (sites 1c and 1f) in Figure 5-19. Near-zero slope data patterns such as for the South Platte River at Julesburg (Site 1h) in Figure 5-19 indicate TDS concentrations that are more independent of streamflow than plots with a steeper slope. The South Platte River at Henderson (Site 1e) shows evidence of flow-independent TDS concentrations for streamflow conditions less than 10 m^3/s and a strong negative relationship for higher streamflows. This is likely a result of the large point-source discharge from the Denver Metropolitan Wastewater Treatment Plant located upstream from this site. Discharge from this point source is typically 3 to 4 m^3/s of water with TDS concentrations that generally range from 500 to 600 mg/L. When flow in the river is low due to seasonal conditions or large upstream diversions, the point-source discharge from the treatment plant is the predominate source of streamflow and control TDS concentrations. Some sites such as the South Platte River near Englewood (Site 1a) in Figure 5-19 exhibit strong negative relationships between concentration and streamflow, but also show occasional scattering of data points away from the trend. This suggests that there were times when TDS concentration was much less dependant on flow. These conditions could be caused by flushing of dissolved solids during precipitation, melting events, or increases in higher-TDS point-source discharges.

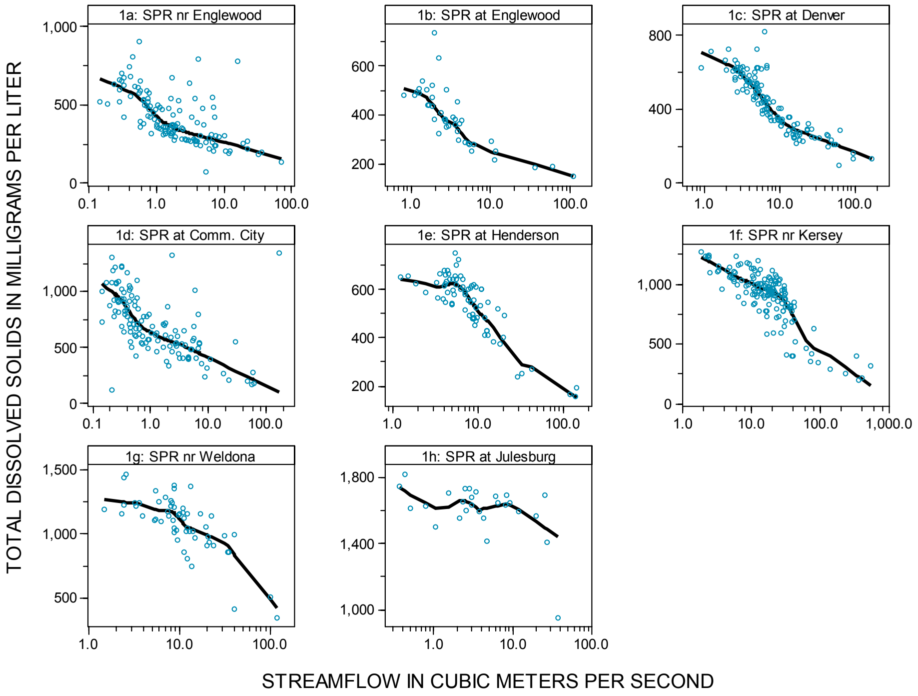


Figure 5-19. Concentration-flow relationships for selected South Platte River monitoring sites, water years 1991–2004.

Sub-basin sites generally exhibit the common negative relationship between TDS concentration and streamflow. Some sites have deviations from the general relationship similar to the deviations described for sites along the mainstem. Cherry Creek near Franktown (Site 2a) in Figure 5-20 appears to have a positive relationship between TDS concentration and streamflow indicating variable-flow sources with higher TDS concentrations than base-flow sources. Cherry Creek below Cherry Creek Reservoir (Site 2c) shows no correlation between TDS concentration and streamflow as might be expected downstream from a reservoir. South Clear Creek above Lower Clear Creek Reservoir (Site 4a) appears to have a bimodal correlation between TDS concentration and flow. Both relationships show a negative correlation, but there appears to be two distinct slopes. This could be a reflection of seasonal change in dominant water sources, however additional investigation would be required to determine the exact cause.

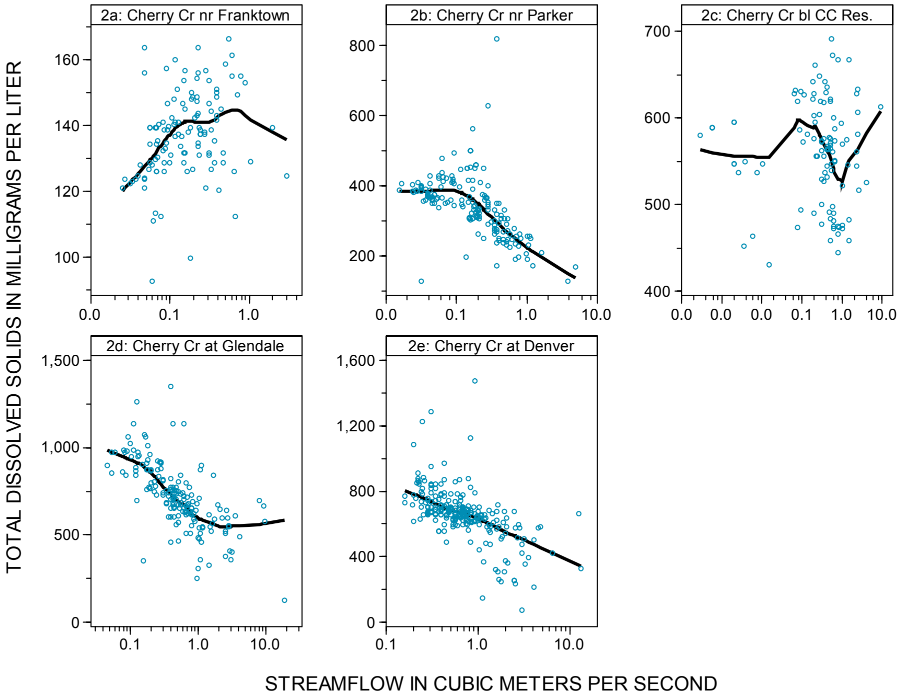


Figure 5-20. Concentration-flow relationships for selected Cherry Creek monitoring sites, water years 1991–2004.

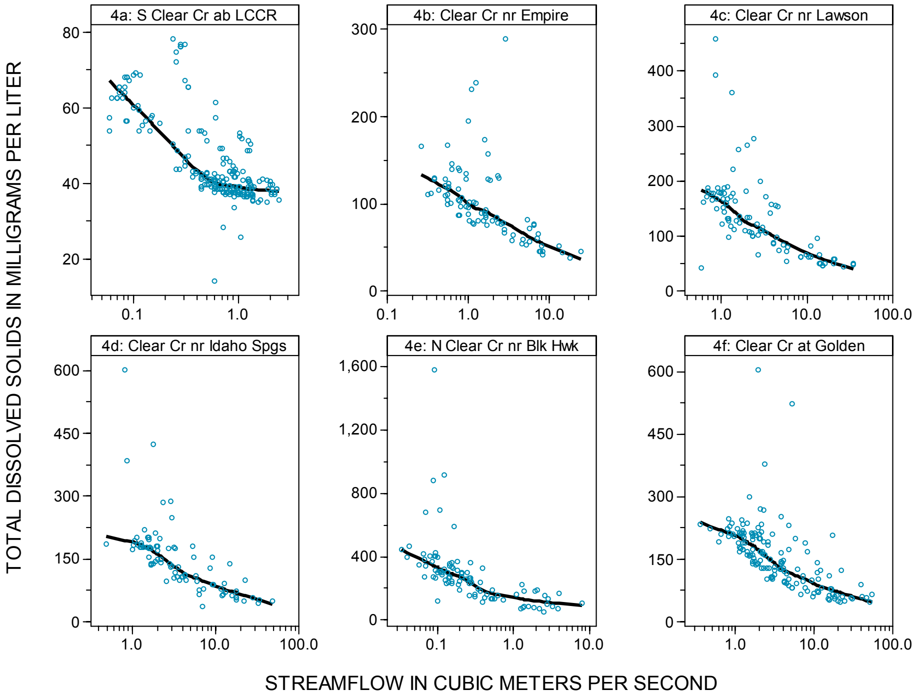


Figure 5-21. Concentration-flow relationships for selected Clear Creek monitoring sites, water years 1991–2004.

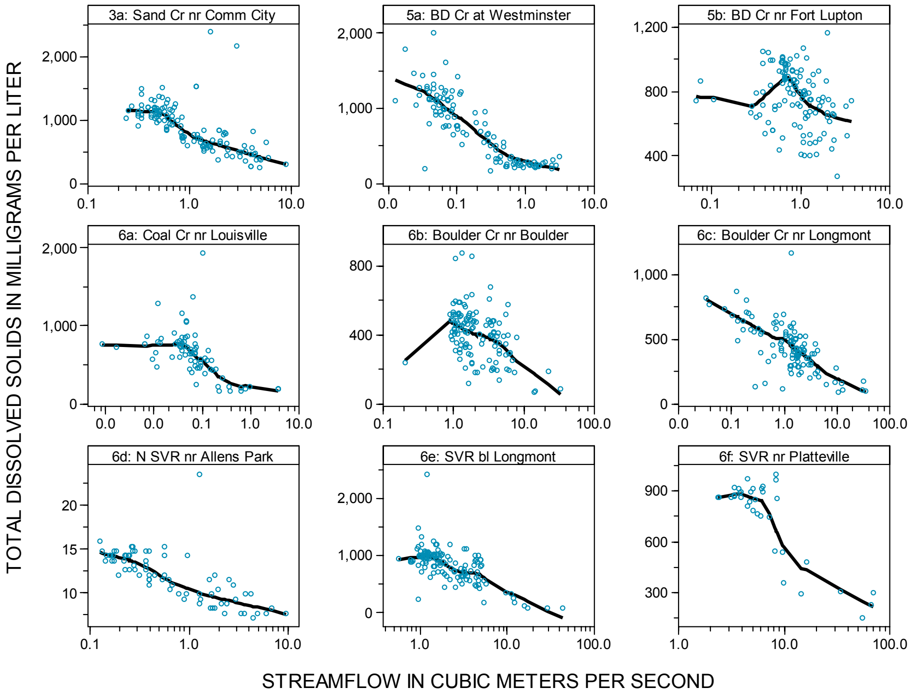


Figure 5-22. Concentration-flow relationships for selected Sand, Big Dry, Coal, and Boulder Creeks and Saint Vrain River monitoring sites, water years 1991–2004.

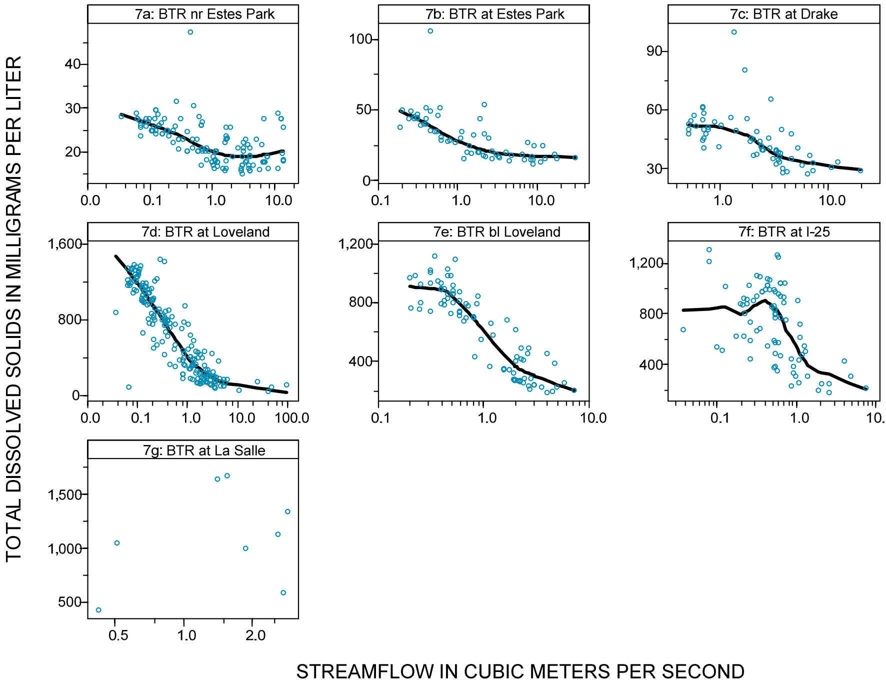


Figure 5-23. Concentration-flow relationships for selected Big Thompson River monitoring sites, water years 1991–2004.

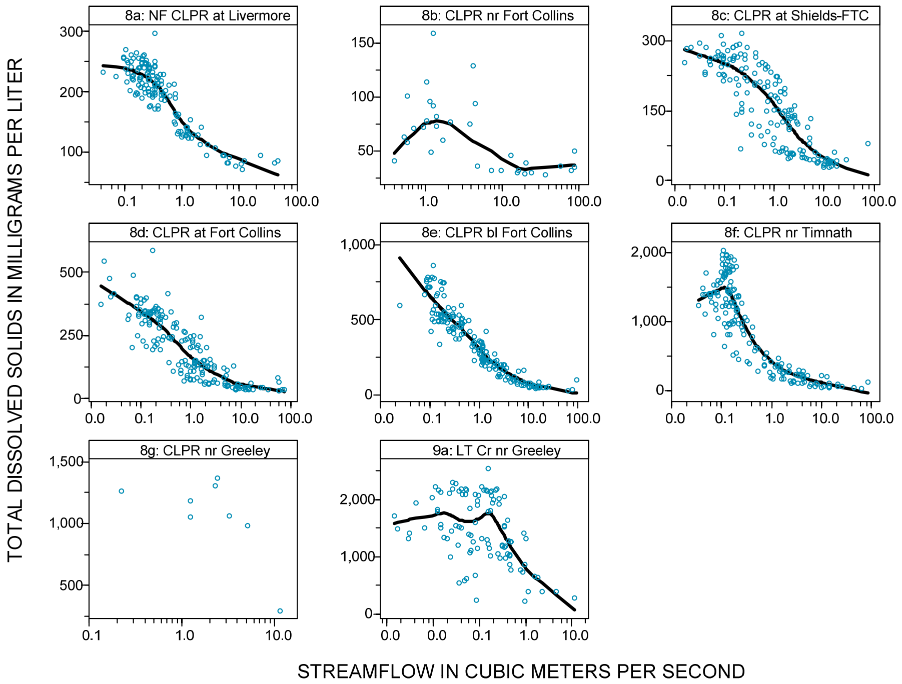


Figure 5-24. Concentration-flow relationships for selected Cache la Poudre River monitoring sites, water years 1991–2004.

5.3.5 Trend Analysis

5.3.5.1 Recent Trends

Results of seasonal Kendall trend analysis for non-flow-adjusted (NFA) and flow-adjusted (FA) TDS concentrations for the selected sites in the South Platte River Basin are presented in Table 5-2 for the "recent" common period of investigation covering water years 1991 through 2004. Trend analysis was performed only for active monitoring periods meeting the minimum data requirements as discussed in Section 5.2.5.1, even if occasional monitoring occurred over longer time periods. The time period used in trend analysis at each site is shown in the tables along with the number of years spanned by the period, the number of seasons defined in the analysis, and the number of observations included in the analysis. Eleven sites did not meet the minimum data requirements for seasonal Kendall trend analysis of the recent period. These sites are denoted with an asterisk in the "Period" column.

The null hypothesis of the seasonal Kendall test is that concentration of the water-quality constituent is independent of time. The *p*-value is the probability of incorrectly rejecting the null hypothesis of no trend when a trend actually exists (Lietz, 2000). The smaller the *p*-value, the stronger the evidence for rejection of the null hypothesis (Helsel and Hirsch, 1992). For this study, a *p*-value equal to or less than 0.10 was judged sufficient evidence for rejection of the null hypothesis. The "Slope" column provides an estimate of the direction and median rate of change in mg/L per year. It is also expressed in the tables as "Trend" in percent change per year to allow for greater comparability of trend magnitude between sites with similar periods of analysis. For trends deemed to be significant based on the *p*-value, the direction of the trend is indicated in the "Trend Direction" column of the results tables. It is important to note that the actual data may not change linearly and instead may change in steps or show reversals in portions of the selected period (Schertz *et al.*, 1991). This can cause small-scale trends to be masked when trend testing over longer periods is performed. Because of this, it is important to incorporate time series plots of the data (Section 5.3.1) in addition to the trend test results for proper evaluation of trends.

Table 5-2. Historical trends in total dissolved solids at selected sites in the South Platte River Basin, water years 1991 to 2004.

[obs, observations; TDS, total dissolved solids; mg, milligrams; L, liters; yr, year; %, percent; dir, direction]

					Non-flow adjusted TDS				Flow adjusted TDS			
Site	Site name	Analysis Period	Years	Obs	*p*-Value	Slope (mg/L/yr)	Trend (%/yr)	Trend dir	*p*-Value	Slope (mg/L/yr)	Trend (%/yr)	Trend dir
1a	SPR nr Englewood	1990-2004	14	123	0.00	10.11	2.74	Up	0.00	7.59	2.06	Up
1b	SPR at Englewood	*										
1c	SPR at Denver	1993-2002	9	126	0.75	2.46	0.53	-	0.20	2.93	0.63	-
1d	SPR at Comm. City	1990-2004	14	125	0.05	13.73	2.04	Up	0.01	9.02	1.34	Up
1e	SPR at Henderson	*										
1f	SPR nr Kersey	1993-2004	11	146	1.00	0.44	0.05	-	0.00	-12.26	-1.31	Down
1g	SPR nr Weldona	1990-2003	13	57	0.00	-23.60	-2.13	Down	0.00	-21.24	-1.91	Down
1h	SPR at Julesburg	*										
2a	Cherry Cr nr Franktown	1990-2003	13	119	0.15	0.39	0.29	-	0.07	0.31	0.22	Up
2b	Cherry Cr nr Parker	1991-2003	12	160	0.02	5.84	1.67	Up	0.00	8.90	2.55	Up
2c	Cherry Cr bl CC Res.	1990-2003	13	106	0.08	-4.82	-0.86	Down	0.06	-3.80	-0.67	Down
2d	Cherry Cr at Glendale	1990-2003	13	169	0.01	-11.11	-1.51	Down	0.44	1.34	0.18	-
2e	Cherry Cr at Denver	1990-2004	14	248	0.23	-2.50	-0.37	-	0.31	-1.17	-0.17	-
3a	Sand Cr nr Comm City	1992-2003	11	126	0.19	8.45	0.86	-	0.72	2.19	0.22	-
4a	S Clear Cr ab LCCR	*										
4b	Clear Cr nr Empire	1994-2003	9	85	0.00	4.01	4.17	Up	0.00	2.06	2.15	Up
4c	Clear Cr nr Lawson	1994-2002	8	91	0.00	5.40	4.25	Up	0.01	2.42	1.90	Up
4d	Clear Cr nr Idaho Spgs	1994-2003	9	86	0.00	4.74	3.43	Up	0.02	2.74	1.98	Up
4e	N Clear Cr nr Blk Hwk	1994-2003	9	94	0.00	12.79	4.86	Up	0.00	11.04	4.19	Up
4f	Clear Cr at Golden	1992-2004	12	154	0.00	3.02	1.89	Up	0.00	3.90	2.45	Up
5a	BD Cr at Westminster	1990-2004	14	114	0.00	13.81	1.90	Up	0.00	13.42	1.85	Up
5b	BD Cr nr Fort Lupton	1992-2003	11	119	0.02	9.53	1.22	Up	0.06	6.21	0.79	Up
6a	Coal Cr nr Louisville	1997-2004	7	76	0.02	44.33	6.39	Up	0.23	19.64	2.83	-
6b	Boulder Cr nr Boulder	1990-2004	14	123	0.14	5.60	1.36	-	0.06	7.01	1.71	Up
6c	Boulder Cr nr Longmont	1991-2004	13	112	0.15	4.56	1.09	-	0.71	-2.58	-0.62	-
6d	N SVR nr Allens Park	1990-1997	7	74	0.00	-0.18	-1.52	Down	0.15	-0.13	-1.07	-
6e	SVR bl Longmont	1990-2004	14	127	0.37	-5.48	-0.62	-	0.07	-7.52	-0.85	Down
6f	SVR nr Platteville	*										
7a	BTR nr Estes Park	1995-2004	9	128	0.07	0.10	0.42	Up	0.05	0.14	0.59	Up
7b	BTR at Estes Park	*										
7c	BTR at Drake	*										
7d	BTR at Loveland	1990-2004	14	191	0.00	-14.14	-1.91	Down	0.12	-4.50	-0.61	-
7e	BTR bl Loveland	*										
7f	BTR at I-25	1990-2004	14	82	0.00	-17.16	-2.09	Down	0.01	-11.27	-1.37	Down
7g	BTR at La Salle	*										
8a	NF CLPR at Livermore	1990-2003	13	140	0.41	-0.83	-0.41	-	0.00	-1.68	-0.82	Down
8b	CLPR nr Fort Collins	*										
8c	CLPR at Shields-FTC	1990-2004	14	165	0.14	-1.11	-0.74	-	0.37	-0.60	-0.40	-
8d	CLPR at Fort Collins	1990-2004	14	172	0.14	-1.16	-0.60	-	0.01	-2.13	-1.10	Down
8e	CLPR bl Fort Collins	1990-2004	14	169	0.09	2.84	0.93	Up	0.02	3.06	1.00	Up
8f	CLPR nr Timnath	1990-2004	14	171	0.00	-25.81	-2.66	Down	0.00	-25.72	-2.65	Down
8g	CLPR nr Greeley	*										
9a	LT Cr nr Greeley	1993-2004	11	101	0.88	1.61	0.09	-	0.72	-6.05	-0.33	-

[*] **Station data for water years 1991 - 2004 did not meet the minimum data requirements for trend analysis**

Trend results for the more recent period of investigation (Table 5-2) are useful for understanding recent changes in dissolved solids concentrations. Because the trend analysis results for the recent study period span a similar time frame, these results can be used for comparison of trends between sites in order to get an overall picture of dissolved solids trends throughout the basin. Trend analysis results for the recent common period indicate there were almost twice as many significant upward trends (13 NFA, 14 FA) as significant downward trends (7 NFA, 8 FA) in the basin during this period. The magnitude of significant upward trends was generally between 1 to 4 percent change per year while significant downward trends generally ranged between -0.5 and -2 percent change per year for both NFA and FA results.

For sites along the mainstem of the South Platte River in the upper portion of the study area, significant upward trends were found for monitoring sites located in the urban areas of Englewood and Commerce City (sites 1a and 1d). The magnitude of these upward trends ranged from 2 to nearly 3 percent per year. Somewhat lower but still significant values were also found for FA values indicating the trends were not entirely a result of changes in flow during this period. The upward trends in TDS concentrations at the sites near Englewood and Commerce City appear to begin around water year 2001. Figure 5-25 shows the relative severity of drought and wet periods through the use of the Palmer Hydrological Drought Index (PHDI) (U.S. National Climatic Data Center, 2009). Negative PHDI values indicate drier-than-normal conditions. Beginning in the year 2000, the region experienced drier-than-normal conditions including a short, but relatively severe drought in 2002. Although the increased TDS concentrations appear to coincide with the drought conditions, it is beyond the scope of this work to prove if this was actually the cause.

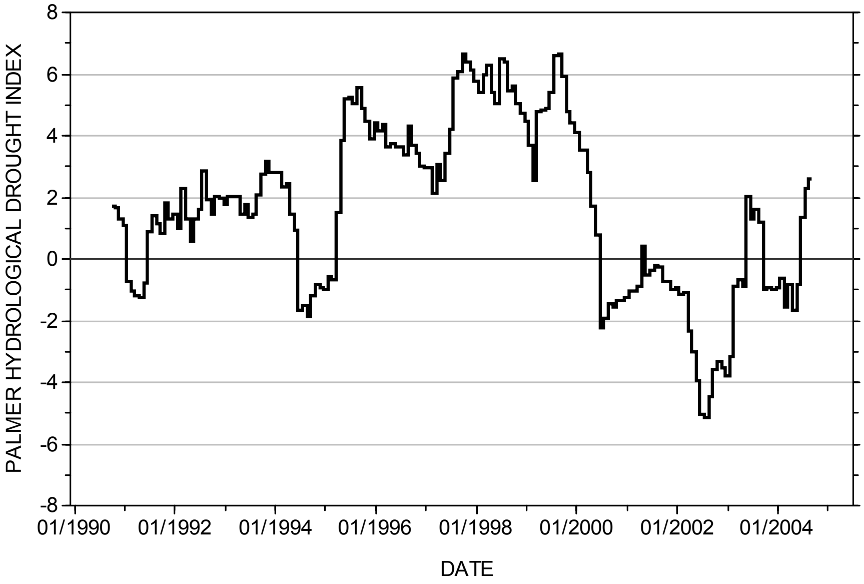


Figure 5-25. Palmer Hydrological Drought Index for the Platte River Drainage, water years 1991–2004.

Sampling programs were inadequate to perform trend analysis on sites at the second site at Englewood (Site 1b) and the site at Henderson (Site 1e) for water years 1991 through 2004. No significant trend was found at Denver (Site 1c), however regular monitoring did not begin until 1993 and it was discontinued in 2002 so the time period included in trend analysis was not the same as for the site upstream from Denver near Englewood and the site downstream from Denver at Commerce City. The time series plot of TDS concentrations at Denver (Figure 5-1) shows an upward shift in concentrations starting around the year 2000 in a pattern similar to that seen in plots for Englewood and Commerce City; however since monitoring was discontinued at Denver in 2002 it is unknown if the upward pattern continued through water year 2004 as it did at the neighboring sites.

In the middle and lower portions of the study area, recent dissolved solids concentrations appear to be decreasing at some mainstem sites. A downward trend in FA

TDS concentrations was found for the site at Kersey (Site 1f) and downward trends in NFA and FA TDS concentrations were found for the site at Weldona (Site 1g). As with some of the sites farther upstream, both of these sites exhibit slight upward shifts in TDS starting around the year 2000 after trending downward during the 1990's, however the overall trend during the defined analysis period is slightly downward. The sampling program during this period was not adequate for analysis of trend at Julesburg (Site 1h).

A mixture of upward and downward trend results was found for tributary sites for water years 1991 to 2004. Along Cherry Creek, upstream sites had some very slight upward trends while the middle portion had some very slight downward trends. The final site at the mouth of Cherry Creek had no trends. Sand Creek had no evidence of trends. All sites along Clear and Big Dry Creeks had evidence of upward trends. Because of monitoring program deficiencies, trend analysis at many of these sites had to be performed for periods starting in 1992, 1994, or even 1997. Most of the trends at sites along these creeks were found for both NFA and FA dissolved solids concentrations, therefore providing evidence that the increases were not due to a decreasing flow trend. No trend was observed for Boulder Creek near Longmont (Site 6c). Some evidence of downward trends in the upper and middle portion of the Saint Vrain River was found. Trend analysis could not be conducted at the mouth of the river near Platteville (Site 6f) due to insufficient monitoring. Along the Big Thompson River, slightly upward trends were found in the headwaters near Estes Park (Site 7a) for the shortened period of water years 1995 – 2004 while downward trends were found in the middle portion of the basin at Loveland (Site 7d) and near Interstate 25 (Site 7f). Insufficient monitoring prevented trend analysis for sites at Estes Park, near Drake, below Loveland, and at the mouth near

LaSalle (Sites 7b, 7c, 7e, and 7g respectively). A slight downward trend in FA TDS concentrations was found on the North Fork of the Cache la Poudre River near Livermore (Site 8a) and the mainstem Cache la Poudre River at Fort Collins (Site 8d); however no significant trend was found just upstream at Site 8c in Fort Collins. Just downstream from Fort Collins at Site 8e, slight upward trends were found for both NFA and FA concentrations. Just miles downstream from Site 8e, the site at Timnath (Site 8f) had strong downward trends of -2.7 percent per year in both NFA and FA concentrations. Trend analysis could not be performed for Site 8b near Fort Collins and at the mouth near Greeley (Site 8g) due to insufficient monitoring data. No significant trends were found for Lone Tree Creek near Greeley for this study period.

5.3.5.2 Long-Term Trends

Results of seasonal Kendall trend analysis for the longer-term period of investigation covering all available data since calendar year 1950 are summarized in Table 5-3. Regular salinity monitoring programs at the selected sites did not occur before 1950. For some sites without regular monitoring programs in place before water year 1991, the period of analysis for long-term trends is actually the same as it was for recent trends (Table 5-2). Long-term time series plots of available dissolved solids measurements since 1950 at each site are presented in Appendix C.

Table 5-3. Historical trends in total dissolved solids at selected sites in the South Platte River Basin for the available period of record.

[obs, observations; TDS, total dissolved solids; mg, milligrams; L, liters; yr, year; %, percent; dir, direction]

					Non-flow adjusted TDS				Flow adjusted TDS			
Site	Site name	Analysis period	Years	Obs	*p*-Value	Slope (mg/L/yr)	Trend (%/yr)	Trend dir	*p*-Value	Slope (mg/L/yr)	Trend (%/yr)	Trend dir
1a	SPR nr Englewood	1989-2004	15	140	0.00	9.13	2.48	Up	0.00	6.61	1.79	Up
1b	SPR at Englewood	1981-1998	17	83	0.64	1.83	0.49	-	0.71	0.56	0.15	-
1c	SPR at Denver	1993-2002	9	126	0.75	2.46	0.53	-	0.20	2.93	0.63	-
1d	SPR at Comm. City	1982-2004	22	218	0.00	17.01	2.73	Up	0.01	4.39	0.71	Up
1e	SPR at Henderson	1962-1995	33	225	0.01	-3.71	-0.58	Down	0.02	-2.38	-0.37	Down
1f	SPR nr Kersey	1950-2004	54	400	0.00	-6.57	-0.60	Down	0.00	-4.74	-0.44	Down
1g	SPR nr Weldona	1967-2003	36	284	0.00	-8.33	-0.73	Down	0.00	-8.58	-0.76	Down
1h	SPR at Julesburg	1950-1995	45	498	0.00	6.76	0.46	Up	0.00	7.65	0.52	Up
2a	Cherry Cr nr Franktown	1977-2003	26	354	0.00	0.73	0.54	Up	0.00	0.76	0.56	Up
2b	Cherry Cr nr Parker	1991-2003	12	160	0.02	5.84	1.67	Up	0.00	8.90	2.55	Up
2c	Cherry Cr bl CC Res.	1983-2003	20	153	0.00	10.35	1.93	Up	0.00	8.00	1.49	Up
2d	Cherry Cr at Glendale	1985-2003	18	231	0.91	0.00	0.00	-	0.00	6.00	0.83	Up
2e	Cherry Cr at Denver	1980-2004	24	335	0.05	2.12	0.32	Up	0.00	3.54	0.53	Up
3a	Sand Cr nr Comm City	1992-2003	11	126	0.19	8.45	0.86	-	0.72	2.19	0.22	-
4a	S Clear Cr ab LCCR	*										
4b	Clear Cr nr Empire	1994-2003	9	85	0.00	4.01	4.17	Up	0.00	2.06	2.15	Up
4c	Clear Cr nr Lawson	1994-2002	8	91	0.00	5.40	4.25	Up	0.01	2.42	1.90	Up
4d	Clear Cr nr Idaho Spgs	1994-2003	9	86	0.00	4.74	3.43	Up	0.02	2.74	1.98	Up
4e	N Clear Cr nr Blk Hwk	1994-2003	9	94	0.00	12.79	4.86	Up	0.00	11.04	4.19	Up
4f	Clear Cr at Golden	1981-2004	23	195	0.00	2.19	1.50	Up	0.00	2.39	1.64	Up
5a	BD Cr at Westminster	1987-2004	17	152	0.00	10.10	1.34	Up	0.00	12.05	1.59	Up
5b	BD Cr nr Fort Lupton	1992-2003	11	119	0.02	9.53	1.22	Up	0.06	6.21	0.79	Up
6a	Coal Cr nr Louisville	1997-2004	7	76	0.02	44.33	6.39	Up	0.23	19.64	2.83	-
6b	Boulder Cr nr Boulder	1987-2004	17	163	0.03	5.07	1.25	Up	0.00	6.85	1.68	Up
6c	Boulder Cr nr Longmont	1979-2004	25	226	0.72	0.48	0.11	-	0.52	-0.63	-0.15	-
6d	N SVR nr Allens Park	1990-1997	7	122	0.00	-0.18	-1.52	Down	0.02	-0.14	-1.16	Down
6e	SVR bl Longmont	1976-2004	28	243	0.00	-6.69	-0.72	Down	0.00	-6.11	-0.66	Down
6f	SVR nr Platteville	1965-1982	17	183	0.17	-3.63	-0.36	-	0.14	-2.88	-0.29	-
7a	BTR nr Estes Park	1995-2004	9	128	0.07	0.10	0.42	Up	0.05	0.14	0.59	Up
7b	BTR at Estes Park	*										
7c	BTR at Drake	*										
7d	BTR at Loveland	1979-2004	25	328	0.15	2.44	0.39	-	0.04	-2.04	-0.32	Down
7e	BTR bl Loveland	1979-2004	25	217	0.24	2.21	0.32	-	0.00	-3.53	-0.52	Down
7f	BTR at I-25	1987-2004	17	123	0.00	-11.66	-1.34	Down	0.00	-10.98	-1.26	Down
7g	BTR at La Salle	1967-1982	15	158	0.02	-9.35	-0.58	Down	0.19	-4.87	-0.30	-
8a	NF CLPR at Livermore	1986-2003	17	188	0.15	-0.83	-0.41	-	0.09	-0.45	-0.22	Down
8b	CLPR nr Fort Collins	1971-1995	24	166	0.89	0.01	0.02	-	0.72	-0.08	-0.12	-
8c	CLPR at Shields-FTC	1979-2004	25	297	0.21	-0.35	-0.23	-	0.00	-0.89	-0.59	Down
8d	CLPR at Fort Collins	1975-2004	29	355	0.00	-1.44	-0.70	Down	0.00	-0.84	-0.41	Down
8e	CLPR bl Fort Collins	1978-2004	26	322	0.18	0.99	0.28	-	0.38	-0.43	-0.12	-
8f	CLPR nr Timnath	1979-2004	25	303	0.08	-3.83	-0.38	Down	0.00	-15.15	-1.52	Down
8g	CLPR nr Greeley	1963-1982	19	194	0.02	-6.01	-0.46	Down	0.07	-2.88	-0.22	Down
9a	LT Cr nr Greeley	1993-2004	11	101	0.88	1.61	0.09	-	0.72	-6.05	-0.33	-

* **Station data did not meet the minimum data requirements for trend analysis**

The longest-term monitoring records were found for sites on the mainstem of the South Platte River. Some sites had long-term records going back to the early 1950's. The longer-term trend analysis allows for determination of historical trends and interpretation of trends with respect to changes in historical water sources or management practices. However, comparisons between monitoring sites should not be made when the historical periods used for determination of trends are dissimilar as is the case for most of the longer-term results in Table 5-3.

Along the mainstem of the South Platte River, all long-term trends determined to be significant were significant for both NFA and FA values, suggesting that all trends are not simply a reflection of underlying trends in streamflow. Long-term trend analysis for the site near Englewood (Site 1a) resulted in only one more year of analysis (1989) and found a positive upward trend of similar magnitude to the trend found in the analysis of recent trends. No trend was found for the site at Englewood (Site 1b) for the period 1981 – 1998. The site at Denver (Site 1c) did not have any additional data beyond the period included for the recent trend analysis. For the site at Commerce City, an upward trend of 2.7% per year in NFA concentrations and 0.7% per year for FA concentrations was found for the period 1982 – 2004. This indicates that most of the upward trend could be a result of a downward trend in streamflow, however there was still a significant upward trend at this site even after accounting for the effects of streamflow. Downstream from Commerce City, long-term trends at Henderson, Kersey, and Weldona (Sites 1e, 1f, and 1g respectively) all had significant downward trends of less than 1% per year although the period of analysis was different for all three, thus limiting the ability to compare trends among these sites. The analysis period for Henderson only included 1962 – 1995; while Kersey had suitable data which allowed the entire period of analysis to be included. Data used for trend analysis at Weldona spanned the period 1967 – 2003. Long-term trend analysis at Julesburg for the period 1950 – 1995 found a significant upward trend of

0.5% change per year. This translates to an increase of approximately 300 mg/L during this 45-year period.

Although the period of analysis is different at each of the sites in the middle and lower portions of the study area, it is tempting to speculate on causes of the differences in trend directions. The downward long-term trends in the middle and downstream portions of the study area might be attributable to the increased use of low-TDS irrigation water made available by the completion of the Colorado-Big Thompson Project which went online in the mid 1950's. Whereas the upward trend at Julesburg could be an indication that consumptive use and reuse of the increased volume of irrigation water is leaching salts and concentrating them in the downstream portion of the river. Additional analysis of salt sources and flux will be presented in Chapters 7 and 8.

Long-term trend analysis for sites located along tributaries generally revealed similar patterns of direction and significance as observed for trend analysis for the recent period, but sometimes the longer period of analysis revealed significant trends at sites without significant trends during the recent period. Along Cherry Creek, all sites were found to have significant upward trends in both NFA and FA TDS concentrations except for Cherry Creek at Glendale which only had a significant upward trend in FA TDS. The time periods used in the analysis varied due to sampling program limitations, however most spanned a period starting roughly around 1980 and going through 2003. The uniformity of the long-term trend results contrast with the recent-period trend results which contained a mixture of upward, downward, and no trend findings. In the Clear Creek drainage, the time periods used for the long-term trend analysis were generally the same as the period used for the recent-period trend analysis because regular monitoring at these sites did not begin until after water year 1991. The only exception to this is the site on Clear Creek at Golden which for the period spanning 1981 – 2004 had a significant upward trend of 1.5 and 1.6% change per year for NFA and FA adjusted TDS concentrations respectively. This is lower than the upward trend found at this site for the recent-period analysis which found upward trends of 1.9 and 2.5% change per year for NFA and FA TDS concentrations. Period of record analysis allowed for the inclusion of several more years of monitoring data for sites along Big Dry and Boulder Creeks, however this changed only the finding of no significant trend in NFA TDS concentrations at Boulder Creek near Boulder (Site 6b) under the recent-period analysis to a significant upward trend of 1.25% change per year. Along the Saint Vrain River, analysis of long-term trends revealed significant downward trends in both NFA and FA TDS concentrations at the headwater site and near Longmont (Sites 6d and 6e) compared to a mixture of downward and no trends under the recent-period analysis. The use of all historical data allowed trend analysis to be performed for the Saint Vrain River at the mouth near Platteville over the period 1965 – 1982, however no significant trends were detected. Use of the longer-term historical period did not provide additional data for the first three sites along the Big Thompson River; however it did expand the analysis period for the three sites in the middle of the study area between Loveland and Interstate 25. These sites were all found to have significant downward trends in FA TDS concentrations but only the site at Interstate 25 (Site 7f) had a significant downward trend in NFA concentrations as well. The expanded period allowed for trend analysis of the site at the mouth of the Big Thompson at LaSalle (Site 7g) for the period 1967 – 1982 where a significant downward trend in NFA was found but not a corresponding significant trend in FA concentrations. Use of results over the entire period of record for sites along the Cache la Poudre River allowed for the inclusion of more results at all of the sites. Most monitoring programs allowed for trend analysis to begin in the late 1970's. Surprisingly, the addition of longer-term period of record results did not change many of the trend patterns detected during trend analysis of the more recent common period except for the site below Fort Collins (Site 8e). This site had a significant positive trend for the more recent period, but for the long-term period spanning 1978–2004 no significant trend was detected. The only other changes were the change from no trend to a downward trend for FA concentrations at Site 8c in Fort Collins and a change from no trend to a downward trend in NFA concentrations at Site 8d in Fort Collins. As was the case for the sites at the mouths of the Saint Vrain River and Big Thompson River, the use of long-term monitoring results allowed for trend analysis at the mouth of the Cache la Poudre River near Greeley where significant downward trends were found in NFA and FA TDS concentrations for the period 1963–1982. No significant upward trends in long-term TDS values were found for any sites along the Cache la Poudre River.

5.3.5.3 Comparison to Previous Studies

Mueller (1990) applied seasonal Kendall trend analysis to original and flow-adjusted specific conductance data from the early 1970s through 1987 at a variety of sites associated with the Colorado-Big Thompson Project. Most of the sites examined by Mueller did not meet the criteria for this study with the exception of Boulder Creek at the mouth near Longmont (Site 6c) and the South Platte River near Weldona (Site 1g). Similar trend results were found by both studies even though different analysis periods were included. Mueller found no significant trend in flow-adjusted salinity at the Boulder Creek site for the period 1979 – 1987, and this study found no significant trend in flow-adjusted salinity for the period 1979 – 2004. A significant downward trend in flow-adjusted salinity at the South Platte River at Weldona was found for the period 1971 – 1987 by Mueller and for the period spanning 1967 – 2003 by this study.

Lord (1997) conducted seasonal Kendall trend analysis on flow-adjusted TDS concentrations for several major monitoring sites along the mainstem of the South Platte River for the historical period 1963 – 1994. Contrary to the present study which found a decreasing trend at Henderson for the period 1962 – 1995, Lord reported a significant increasing trend at Henderson. Other results by Lord were similar to this study including the finding of decreasing trends at Weldona and an increasing trend at Julesburg.

Litke and Kimbrough (1998) reported trends in specific conductance at several sites along the mainstem of the South Platte River for the period 1963 to 1996. The authors found a significant downward trend in specific conductance at the site at Denver during their chosen historical period. Unlike Litke and Kimbrough, the present study utilized only data contained in the NWIS which limited trend analysis at the Denver site to the period 1993 – 2004. No detectable trend in salinity was found for that period in this study. As in the present study, Litke and Kimbrough found downward trends in flow-adjusted specific conductance data at Henderson and Kersey. No significant trend was found for the site at Balzac which was not included in the present study due to a lack of monitoring during the period of interest. It should be noted that Litke and Kimbrough utilized a higher significance level of 0.05 in their study which would reduce the number trends deemed to be significant. The Weldona site used in this analysis is located approximately 30 miles upstream from the site at Balzac. It was not included in the analysis by Litke and Kimbrough, but was found by this study to have a significant downward trend for the period 1967 - 2003. Litke and Kimbrough did not perform trend analysis on specific conductance for the site at Julesburg where the present study found a significant upward trend in dissolved solids, however they did include a site downstream from Julesburg at the mouth of the South Platte River near North Platte, Nebraska where they detected a significant upward trend in specific conductance. This site was beyond the study area of the present study.

5.4 CONCLUSIONS

Dissolved solids concentrations were found to have substantial spatial variation throughout the basin. In general, the lowest concentrations were found in headwater sites and the highest levels were observed at the downstream sites. As would be expected, monitoring sites located near the headwaters of stream originating in mountainous regions had lower TDS values than monitoring sites near the headwaters of streams originating in the plains along the Front Range. This is likely a reflection of the differences in the predominant geology of the two regions with crystalline bedrock found in the mountainous regions and salt-bearing shale formations common in the plains (see Figure 2-2). Strong seasonal patterns in dissolved solids concentrations were observed at many sites. Generally, the lowest concentrations occur during the high-streamflow periods of late spring and early summer and the highest concentrations occur during the low-streamflow periods of fall and winter. Most sites exhibited a strong negative relationship between concentration and flow which generally suggests that these sites consist of two types of water sources: 1) a base-flow of lower-volume, higher-TDS water and 2) variable-volume contributions from a lower-TDS water source such as might be contributed from snowmelt contributions. Some sites seem to show evidence of occasional flow-independent TDS concentrations even at sites that normally have a strong inverse relationship between dissolved solids and streamflow. This could be the result of salt-flushing and wash-off due to precipitation events or variation in the volume of higher-TDS water entering the system from sources such as point sources, groundwater or tributaries.

Analysis of temporal trends found that salinity concentrations at many study locations throughout the basin are changing over time. It also found that for the recent common study period there are twice as many sites with statistically significant increasing trends than sites with significant decreasing trends. Along the mainstem of the South Platte, a mixture of upward and downward trends were found. Significant upward trends were found in the upstream portion of the study area for both the recent and longer-term trend analysis periods. While some portion of this increase in dissolved solids concentrations can be attributed to decreasing streamflow, there was still evidence of increasing concentrations even after the effects of decreasing streamflow have been removed. With the exception of Julesburg, sites along the middle and lower portions of the study area have slight decreases in both short- and long-term dissolved solids concentrations that are not entirely attributable to increases in flow. The most downstream site at Julesburg had a slightly upward long-term trend in concentration of roughly one-half of one percent change per year from 1950 through 1995. Trend analysis of tributary sub-basins also indicates a mixture of upward and downward trends. Tributaries in the central portion of the basin were found to have mostly upward trends in both recent and long-term dissolved solids concentrations while sites along the three largest tributaries originating in the more-northern portion of the basin generally had no trend or decreasing trends in both recent and long-term dissolved solids concentrations. The reasons for these differences are unclear.

An additional finding resulting from this characterization work was the revelation of how many seemingly important water-quality monitoring sites in the basin had inconsistent monitoring programs. This problem was encountered for mainstem sites as well as monitoring sites along many tributaries. It is particularly unfortunate that there has been a lack of systematic sampling at sites located at the mouths of the major tributaries. Because of their locations, these sites serve as integrator sites that will reflect all processes occurring in the upstream sub-basin that have an impact on water quality. These sites are also important for determination of concentrations and loads of water-quality constituents contributed to the mainstem of the river by each of the tributaries.

A lack of systematic sampling can preclude formal trend analysis at sites by causing the historical data record to fail the minimum data requirements. Even if trend analysis can be performed, the results are less useful if they can not be compared to other sites because of differences in the time periods in which regular monitoring was performed. In the evaluation of future monitoring priorities for water quality in the South Platte River Basin, consideration should be given to the importance of consistency in monitoring and the importance of sites located near the mouths of tributaries. This might necessitate a reduction in the number of upstream sites monitored or a reduction in the number of water-quality constituents measured at some upstream sites in order to allow sufficient resources for systematic monitoring at important sites at the mouths of tributaries. At the very minimum, all sites currently equipped for automated daily streamflow measurements could also be equipped for automated daily measurement of specific conductance without an excessive increase in the costs associated with maintaining the site.

CHAPTER 6: DISSOLVED SOLIDS LOADS

6.1 INTRODUCTION

6.1.1 Overview

Characterization of the mass of water-quality constituents can provide insight into the sources, transport, and ultimate fate of the constituents. This chapter details the procedures used to estimate daily dissolved solids loads for twenty water-quality monitoring sites within the South Platte River Basin using daily streamflow measurements and intermittent measurements of dissolved solids concentrations. The resulting load estimates were analyzed for spatial patterns and temporal trends to provide a greater understanding of the patterns of salt movement within the basin. These load estimates will also provide the foundation for a dissolved solids mass budget presented in the following chapter.

6.1.2 Previous Studies

There have been several previous published studies that estimated dissolved solids loads at selected sites in the South Platte River Basin. Research conducted by a Colorado State University civil engineering professor and graduate students in the early 1980s (Gomez-Ferrer *et al.*, 1983; Gomez-Ferrer and Hendricks, 1983; Turner and Hendricks, 1983) provided the earliest determination and assessment of dissolved solids loads in the South Platte River Basin. These studies used seasonal log-log regression to relate daily streamflow values with periodic TDS concentrations. Daily load estimates were made for five mainstem sites and three tributary sites in the region between Henderson and Julesburg for the 15-year period of 1965 through 1979. This work found that most of the salt loading of the South Platte River occurs upstream along the Front Range region of Colorado rather than the majority of the salt loading occurring in the lower regions of the River as is common in many salinity-affected rivers. Loads were found to decrease slightly at the most downstream sites, suggesting the possibility of salt accumulation in downstream soils. Lord (1997) provided an update to this work to include the period 1963 to 1994 using similar methodology, geographic region and monitoring sites and reported largely similar results.

As part of the U.S. Geological Survey's NAWQA program, Litke and Kimbrough (1998) collected monthly samples from twelve fixed sites in the South Platte River Basin for the period March 1993 to September 1995. The resulting data were used to develop estimates of stream loads for selected constituents including dissolved solids at 11 of the 12 sites including five mainstem sites and six tributary sites. Daily concentrations were estimated by using a linear, time-based interpolation between monthly measured concentrations modified by discharge-based interpolation for days in which storm events occurred. The pattern of dissolved solids loading was found to be similar to the previously mentioned studies: loads increased from Denver downstream to Kersey, then decreased at sites downstream from Kersey.

This study updates the previous dissolved solids load characterization efforts to include more recent data. It also expands the geographic scope of load estimation to include more monitoring sites including upstream tributary sites which have not been included in previously published dissolved solids load characterization efforts. Finally, this study utilizes recent innovations in load estimation techniques and software to develop what is believed to be more precise estimates of daily loads.

6.2 METHODS

6.2.1 Load Estimation

Constituent loads are computed as the product of constituent concentration and discharge. Ideally, annual loads would be calculated using daily measurements of constituent concentration and discharge. Streamflow is normally measured daily, however constituent concentrations are generally collected only periodically due to funding constraints inherent in most monitoring programs. Fortunately, constituent concentrations can often be correlated with surrogate variables such as discharge, time, and occasionally other variables such as season. Therefore, when daily constituent concentrations are not available, instream loads can be estimated using statistical regression techniques that correlate daily streamflow measurements with occasional constituent measurements.

6.2.1.1 Selection of Load Model

Estimates of daily dissolved solids loads were made using the U.S. Geological Survey's Load Estimator (LOADEST) software package (Runkel *et al.*, 2004). LOADEST assists in the selection and calibration of the optimal regression model. The selected regression model is then used to calculate estimates of daily loads during a user-specified time interval. LOADEST contains nine pre-defined regression models (Table 6-1) which uses combinations of explanatory variables such as various functions of streamflow, decimal time, and optional user-specified data variables. In addition to the nine defined regression models, the user can choose from several forms of the regression models that allow for user-defined seasons and the use of user-defined regression models.

Table 6-1. Load estimation regression models considered by LOADEST in this study.

[ln(load) = ln(estimated daily load in kilograms per day); β_0 - β_6 = calibration coefficients of the regression; lnQ = ln(mean daily streamflow) - center of ln(mean daily streamflow); *dtime* = decimal time - center of decimal time]

Model number	Regression model
1	$\ln(\text{load}) = \beta_0 + \beta_1 \ln Q$
2	$\ln(\text{load}) = \beta_0 + \beta_1 \ln Q + \beta_2 \ln Q^2$
3	$\ln(\text{load}) = \beta_0 + \beta_1 \ln Q + \beta_2\, dtime$
4	$\ln(\text{load}) = \beta_0 + \beta_1 \ln Q + \beta_2 \sin(2\pi\, dtime) + \beta_3 \cos(2\pi\, dtime)$
5	$\ln(\text{load}) = \beta_0 + \beta_1 \ln Q + \beta_2 \ln Q^2 + \beta_3\, dtime$
6	$\ln(\text{load}) = \beta_0 + \beta_1 \ln Q + \beta_2 \ln Q^2 + \beta_3 \sin(2\pi\, dtime) + \beta_4 \cos(2\pi\, dtime)$
7	$\ln(\text{load}) = \beta_0 + \beta_1 \ln Q + \beta_2 \sin(2\pi\, dtime) + \beta_3 \cos(2\pi\, dtime) + \beta_4\, dtime$
8	$\ln(\text{load}) = \beta_0 + \beta_1 \ln Q + \beta_2 \ln Q^2 + \beta_3 \sin(2\pi\, dtime) + \beta_4 \cos(2\pi\, dtime) + \beta_5\, dtime$
9	$\ln(\text{load}) = \beta_0 + \beta_1 \ln Q + \beta_2 \ln Q^2 + \beta_3 \sin(2\pi\, dtime) + \beta_4 \cos(2\pi\, dtime) + \beta_5\, dtime + \beta_6\, dtime^2$

The relation of concentration to streamflow and season is often confounded because season and streamflow do not normally operate independently of one another. Generally, high and low flows are associated with specific seasons. As a result, the addition of a seasonal regression term in addition to regression terms based on flow may not always increase the predictive ability of a load regression model. The multiple linear regression approach used by LOADEST provides a way to interpret the influence of each variable independently by examination of the significance of the parameter estimates (Hoos *et al.*, 2000). Statistical significance of parameter estimates related to flow would indicate that streamflow, independent of other influences, is a good predictor of load. Significance of parameter estimates related to time would provide evidence of significant temporal trends in load. Significance of parameter estimates related to time of year would indicate significant seasonal patterns in concentration data independent of any flow variation which also tends to vary seasonally.

Within LOADEST, the user can specify a specific regression model or allow the program to select the optimal regression model from among the models listed in Table 6-1. Determination of the optimal model is made using the Akaike Information Criterion

(AIC) (Akaike, 1973). The AIC is a model goodness-of-fit statistic used to select the best model from among a set of predefined candidate models having the same set of dependent variables. By including a penalty for the addition of parameters, the AIC seeks to identify a model which fits well but has a minimum number of parameters (Burnham and Anderson, 2002). In doing so, it seeks a balance between model under-fit in which important effects are missed and model over-fit which might include spurious effects and higher variance in the model estimate. The AIC calculated for each regression model is a relative number which can only be used to compare to AIC values calculated for other regression models. The use of the AIC in model selection is preferred over the use of the coefficient of determination (R^2) because the latter can often increase along with the number of variables in the model even when the additional explanatory variables are independent of the response variable (Freedman, 1983). The inclusion of extraneous explanatory variables can result in higher variance in the estimated response.

After the selection of a regression model, LOADEST calibrates the selected model via user-supplied, paired observations of flow, constituent concentration, and any optional explanatory observations. LOADEST uses three calibration and estimation methods: Adjusted Maximum Likelihood Estimation (AMLE), Maximum Likelihood Estimation (MLE), and Least Absolute Deviation (LAD). AMLE and MLE are suitable for use when the residuals of the calibration model are normally distributed. AMLE is the preferred method when the calibration data contain censored values. The LAD method is the preferred method when the model residuals are not normally distributed. The LOADEST user’s manual (Runkel *et al.*, 2004) contains further details on the load estimation procedures contained within LOADEST including discussions regarding the handling of retransformation bias, data censoring, multicollinearity, and nonnormality.

Using the three load estimation methods (MLE, AMLE, and LAD), daily load estimates are calculated within LOADEST using the chosen regression model and the time series of explanatory variables. Residual errors of the model (periodic observed load minus the corresponding estimated daily load) are stored by LOADEST in an output file for use in model diagnostics. The values and significance levels for each of the parameter estimates are also included in the output. When significantly different from zero, these parameter estimates and their signs are useful in interpreting basin characteristics and hydrologic processes (Cohn *et al.*, 1992).

6.2.1.2 Selection of Sites and Time Periods

Model calibration within LOADEST requires a minimum of 12 non-zero observations per constituent, seven of which must be uncensored. For estimation of daily loads, a minimum of one observation per day for each explanatory variable (mean daily flow) is required. A subset of the water-quality monitoring sites selected for characterization of TDS concentrations was selected for load estimation. Selection of sites for load estimation was based on the availability of sufficient dissolved solids concentration and corresponding daily flow data during the desired load estimation period as well as the relevance of the locations with regard to understanding the flux of dissolved solids in the basin. One of the primary objectives of this study is to understand the flux of dissolved solids along the mainstem of the South Platte River as it flows along the Front Range and then through the eastern plains. As a result, all eight monitoring sites along the mainstem of the South Platte River selected in Chapter 3 were included in this analysis. Load estimation was also performed for sites near the mouths of the tributaries when sufficient data were available. Additional upstream sites located along major tributaries in the Front Range region were also selected in order to provide additional insight into where load increases occur along these tributaries. Dissolved solids concentrations and flow are comparatively low at upstream sites located in the mountains; therefore these sites were not included since they play a minor role in understanding the major sources and sinks of dissolved solids within the basin. The selection criteria resulted in the inclusion of twenty sites for estimation and analysis of dissolved solids loads.

Some sites critical to the understanding of dissolved solids flux in the basin had limited calibration data available during the study period. For these cases, the calibration period was extended to include several years prior to water year 1991 in order to provide LOADEST with sufficient calibration points. Some sites of interest had large gaps in their dissolved solids monitoring records within the study period. In both of these situations, LOADEST was used to extrapolate daily loads for the periods without water-quality monitoring data; however limitations on the reliability of these results due to the use of extrapolation should be kept in mind during the interpretation of results at these sites.

6.2.2 Trend Analysis

Long-term changes in dissolved solids loads are of interest for understanding the dynamics of dissolved solids flux within the basin. Daily load estimates derived from the procedures used above were totaled by water year to produce annual load values. These annual load values were evaluated for significant long-term trends using the same rank-based, nonparametric linear regression trend analysis techniques previously described in Chapter 4 for determination of trend in annual flow volumes.

6.3 RESULTS AND DISCUSSION

6.3.1 Model Selection

The optimal load regression model number (Table 6-1) is shown in Table 6-2 for each of the sites in which load estimation was performed. The significance of each of the coefficients in the selected load model provides an indication of the importance of each model term. The coefficient of determination and probability plot correlation coefficient (PPCC) provide indications of model suitability.

Table 6-2. Regression model selection and diagnostics.

[AMLE, adjusted maximum likelihood estimation; PPCC, probability plot correlation coefficient]

Site Number	Site Name	Model Number (Table 6-1)	AMLE Regression Statistics								
			p-Value of Load Model Coefficient								
			β_0	β_1	β_2	β_3	β_4	β_5	β_6	R^2	PPCC
1a	SPR nr Englewood	7	< 0.01	< 0.01	0.02	0.56	< 0.01			0.92	0.94
1b	SPR at Englewood	1	< 0.01	< 0.01						0.89	0.74
1c	SPR at Denver	8	< 0.01	< 0.01	0.06	< 0.01	< 0.01	0.04		0.95	0.98
1d	SPR at Comm. City	9	< 0.01	< 0.01	0.16	< 0.01	< 0.01	< 0.01	< 0.01	0.95	0.92
1e	SPR at Henderson	9	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.46	< 0.01	0.97	0.93
1f	SPR nr Kersey	9	< 0.01	< 0.01	< 0.01	0.02	< 0.01	< 0.01	< 0.01	0.96	0.93
1g	SPR nr Weldona	9	< 0.01	< 0.01	< 0.01	0.10	< 0.01	< 0.01	0.06	0.96	0.97
1h	SPR at Julesburg	9	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.99	0.88
2e	Cherry Cr at Denver	7	< 0.01	< 0.01	0.09	< 0.01	0.07			0.84	0.84
4f	Clear Cr at Golden	9	< 0.01	< 0.01	0.03	< 0.01	0.23	< 0.01	0.07	0.89	0.92
5b	BD Cr nr Fort Lupton	9	< 0.01	< 0.01	0.92	< 0.01	< 0.01	0.01	0.04	0.93	0.97
6c	Boulder Cr nr Longmont	9	< 0.01	< 0.01	0.09	< 0.01	0.04	0.61	0.01	0.90	0.95
6e	SVR bl Longmont	9	< 0.01	< 0.01	< 0.01	< 0.01	0.14	< 0.01	0.09	0.65	0.91
6f	SVR nr Platteville	9	< 0.01	< 0.01	< 0.01	0.02	< 0.01	< 0.01	0.01	0.86	0.97
7d	BTR at Loveland	7	< 0.01	< 0.01	0.27	< 0.01	0.03			0.78	0.96
7g	BTR at La Salle	9	< 0.01	< 0.01	< 0.01	< 0.01	0.34	< 0.01	< 0.01	0.84	0.95
8a	NF CLPR at Livermore	9	< 0.01	< 0.01	0.39	< 0.01	< 0.01	0.16	< 0.01	0.99	1.00
8d	CLPR at Fort Collins	7	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01			0.96	0.99
8f	CLPR nr Timnath	9	< 0.01	< 0.01	0.04	< 0.01	0.13	< 0.01	0.02	0.89	0.98
8g	CLPR nr Greeley	6	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01			0.96	0.94

Load regression model #1 (Table 6-1) was selected as the optimal model for just one site: the South Platte River at Englewood (1b). Because load regression model #1 relies solely on the natural log of flow, it suggests that dissolved solids load at this site is controlled solely by streamflow and does not have additional seasonal or long-term time trends unrelated to streamflow. Load regression equation #6, which incorporates terms for flow and seasonality, was also selected for just one site: the Cache la Poudre River near Greeley (8g). The apparent lack of importance of a long-term time component in the regression equation provides evidence that loads at these sites have remained fairly constant during the listed periods. For the remaining sites, load regression equations 7, 8, or 9 were selected as optimal. These equations differ only in whether they included the squared flow and squared time components. As discussed earlier, because season and flow are often related, the inclusion of a seasonal term in a load regression equation might simply supply redundant information and may not provide better load estimates than would be achieved using flow as the only independent variable. In this study, however, with the exception of one site, the inclusion of a seasonality term was deemed to provide better load estimates than equations based solely on flow. Many of the regression model coefficients related to seasonality have a *p*-value of less than 0.01 (Table 6-2) and could be classified as highly significant. The significance of seasonality independent of variation in flow suggests the possibility of seasonal variation in the dissolved solids loading or seasonal variation in the relative contribution to total flow from each of the upstream sources of flow.

Based on the relatively high R^2 values (Table 6-2) observed for most sites, the selected regression models were able to estimate daily loads with an acceptable level of accuracy. Values of R^2 ranged from 0.65 to 0.99 with a mean value of 0.90. The sites where the models performed the worst were Saint Vrain River below Longmont ($R^2 = 0.65$) and Big Thompson River at Loveland ($R^2 = 0.78$). The weaker model performance at these sites suggests there are additional factors exerting a significant influence on the load of dissolved solids at these two sites. The poorer performance of load estimation models at these sites should be noted in the evaluation of load estimation results at these sites.

6.3.2 Time Series Plots

Time series plots of annual dissolved solids loads for water years 1991 through 2004 are presented in Figure 6-1 through Figure 6-3. Lowess regression lines were added to the plots to aid in the visualization of the general trends in the data.

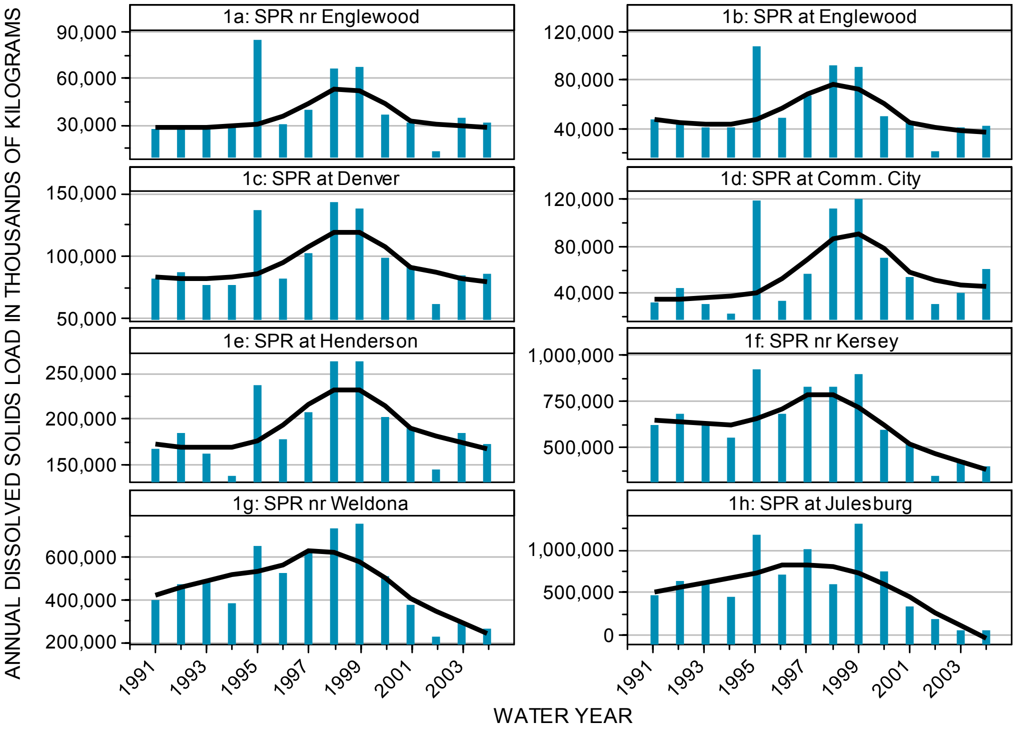


Figure 6-1. Plots of annual dissolved solids load and linear regression line for selected monitoring sites along the mainstem of the South Platte River, water years 1991–2004.

Figure 6-1 through Figure 6-3 illustrate the large year-to-year variability in load at each site. Also evident is the impact on loads from wetter-than-normal periods as seen in the late 1990’s. The effect of drought years of the early 2000’s can also be clearly seen. The strong dependence of load on streamflow is expected since streamflow values typically vary several orders of magnitude while TDS concentrations tend to remain much more constant.

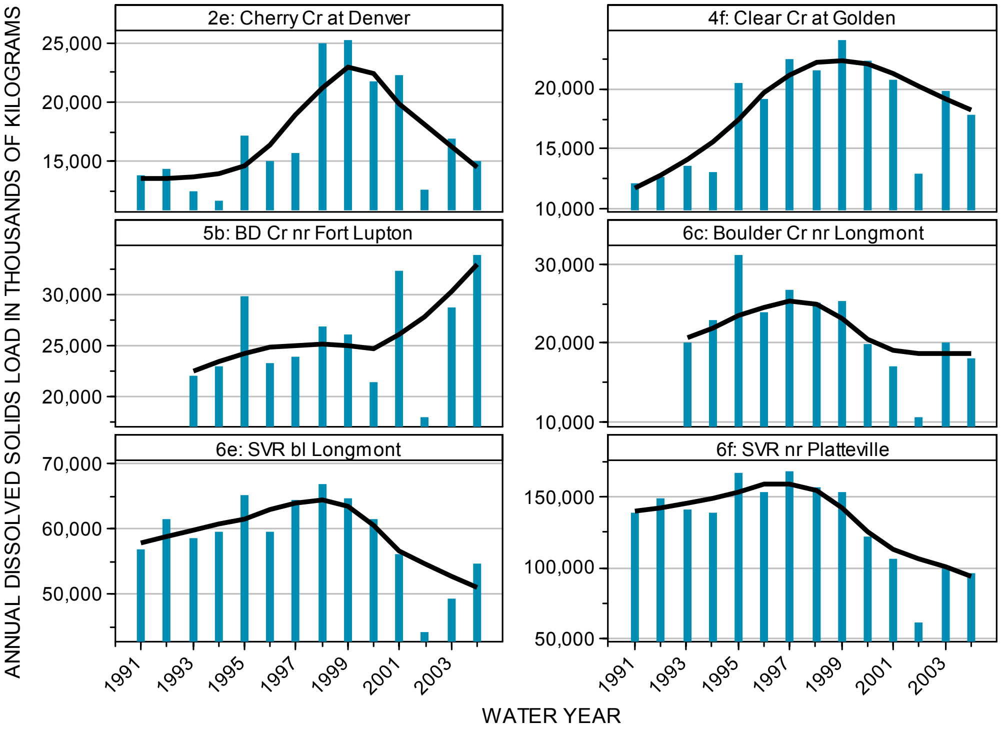


Figure 6-2. Plots of annual dissolved solids load and linear regression line for selected monitoring sites on Cherry, Clear, Big Dry, and Boulder Creeks as well as the Saint Vrain River, water years 1991–2004.

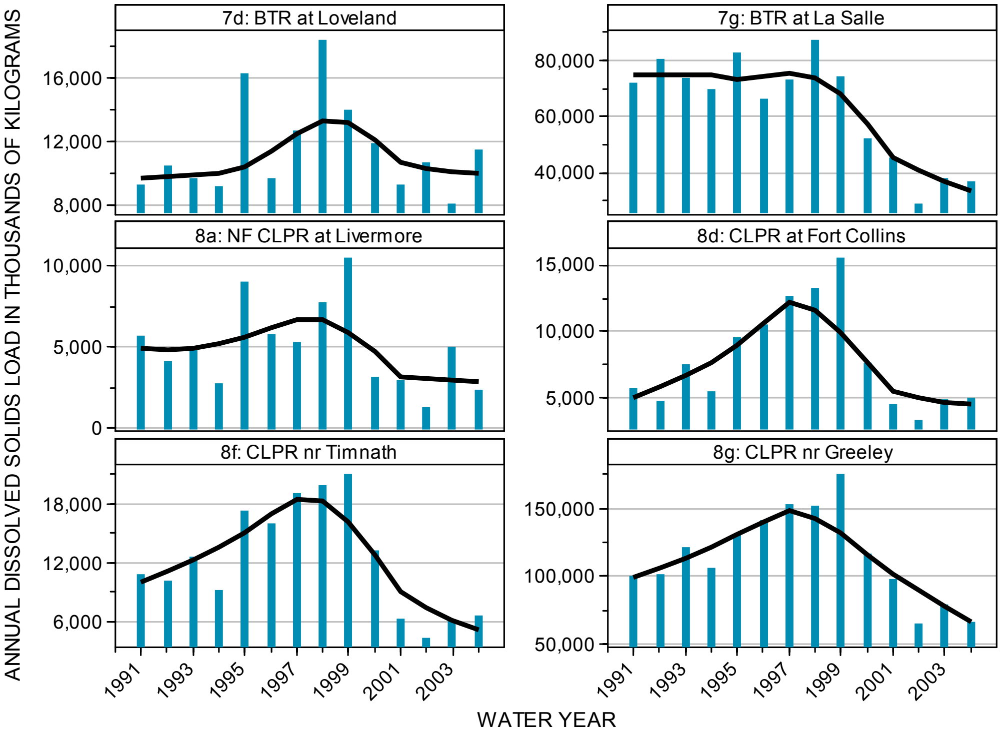


Figure 6-3. Plots of annual dissolved solids load and linear regression line for selected monitoring sites along the Big Thompson and Cache la Poudre Rivers, water years 1991–2004.

6.3.3 *Summary Statistics and Spatial Patterns*

Summary statistics for annual dissolved solids loads at the selected monitoring sites are presented in Table 6-3. As with TDS concentrations, a large amount of variation in dissolved solids loads was found among monitoring sites. As is typical with most streams, loads were found to generally increase in a downstream direction due to the fact that upstream sites tended to have lower TDS concentrations and less streamflow.

Table 6-3. Statistical summary of annual dissolved solids loads at selected sites within the South Platte River Basin, water years 1991–2004.

				Annual Dissolved Solids Load (thousands of kilograms)					
						Percentile			
Site Number	Site Name	Period (water years)	Number of Years	Mean	Minimum Value	25th	50th	75th	Maximum Value
1a	SPR nr Englewood	1991 - 2004	14	39,000	12,000	28,000	31,000	46,000	85,000
1b	SPR at Englewood	1991 - 2004	14	55,000	20,000	40,000	46,000	73,000	108,000
1c	SPR at Denver	1991 - 2004	14	96,000	61,000	80,000	86,000	110,000	143,000
1d	SPR at Comm. City	1991 - 2004	14	59,000	22,000	31,000	48,000	81,000	121,000
1e	SPR at Henderson	1991 - 2004	14	193,000	138,000	167,000	184,000	216,000	264,000
1f	SPR nr Kersey	1991 - 2004	14	642,000	346,000	497,000	629,000	834,000	928,000
1g	SPR nr Weldona	1991 - 2004	14	484,000	231,000	361,000	491,000	633,000	766,000
1h	SPR at Julesburg	1991 - 2004	14	610,000	60,000	307,000	626,000	824,000	1,323,000
2e	Cherry Cr at Denver	1991 - 2004	14	17,000	12,000	13,000	15,000	22,000	25,000
4f	Clear Cr at Golden	1991 - 2004	14	18,000	12,000	13,000	19,000	22,000	24,000
5b	BD Cr nr Fort Lupton	1993 - 2004	12	26,000	18,000	22,000	25,000	30,000	34,000
6c	Boulder Cr nr Longmont	1993 - 2004	12	22,000	11,000	18,000	21,000	25,000	31,000
6e	SVR bl Longmont	1991 - 2004	14	59,000	44,000	56,000	60,000	65,000	67,000
6f	SVR nr Platteville	1991 - 2004	14	133,000	62,000	105,000	141,000	155,000	169,000
7d	BTR at Loveland	1991 - 2004	14	11,000	8,000	9,000	11,000	13,000	18,000
7g	BTR at La Salle	1991 - 2004	14	63,000	29,000	43,000	71,000	76,000	87,000
8a	NF CLPR at Livermore	1991 - 2004	14	5,000	1,000	3,000	5,000	6,000	11,000
8d	CLPR at Fort Collins	1991 - 2004	14	8,000	3,000	5,000	7,000	11,000	16,000
8f	CLPR nr Timnath	1991 - 2004	14	12,000	4,000	6,000	12,000	18,000	21,000
8g	CLPR nr Greeley	1991 - 2004	14	115,000	65,000	93,000	112,000	144,000	176,000

Spatial patterns of annual dissolved solids loads at mainstem sites and sites located near the mouths of major tributaries are shown in Figure 6-4. In addition to the increases in median annual loads at downstream mainstem sites, variability in annual loads also increased. The increase in variability is primarily a reflection of variability in flow that occurs at these sites due to annual hydrologic conditions and the high degree of flow management in downstream portions of the river.

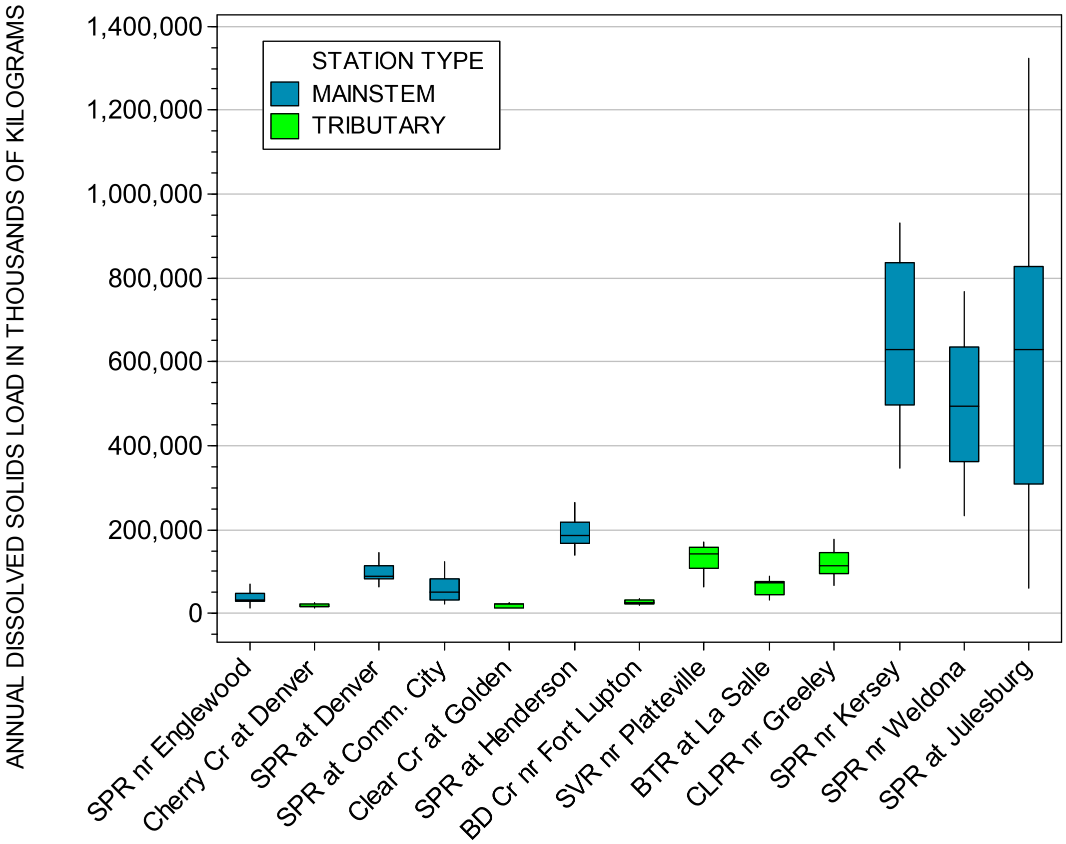


Figure 6-4. Boxplot comparing dissolved solids load contribution of tributaries to the mainstem of the South Platte River, water years 1991–2004.

Median annual loads remain relatively constant through the first three mainstem sites within the Denver metropolitan area. The decrease in median annual load of 38,000 metric tons between the site at Denver and the site at Commerce City is at least partially due to the presence of a large agricultural diversion in this reach. A jump in median load from 48,000 metric tons (4.8×10^7 kilograms) per year to 184,000 metric tons per year was found to occur between Commerce City and Henderson. This increase cannot be explained by the median load contribution of 19,000 metric tons per year from Clear Creek which enters along this reach. Much of the increase in load in this reach is likely a result of effluent discharge from the Denver metropolitan area and dissolved solids contributed through ground water inflow.

Figure 6-4 also compares the dissolved solids load contribution from tributaries as they occur along the mainstem to the loads observed at each of the mainstem monitoring sites in order to illustrate the contributions from tributaries to the total load in the mainstem. In the reach stretching from Henderson to Kersey, median annual dissolved solids loads more than tripled from 184,000 metric tons to 629,000 metric tons. This segment includes the load contributions from three of the basin's largest tributaries: the Saint Vrain, Big Thompson, and Cache la Poudre rivers. All three of these tributaries deliver substantial amounts of dissolved solids loads to the mainstem. The Saint Vrain River is the largest contributor with a median annual contribution of 141,000 metric tons followed by the Cache la Poudre River which contributes a median annual load of 112,000 metric tons and lastly the Big Thompson River with a median annual load of 71,000 metric tons. A minor tributary, Big Dry Creek, also joins the mainstem along this reach and contributes a median annual dissolved solids load of 25,000 metric tons. These four tributaries contribute a combined median load of 349,000 metric tons per year to this river segment which accounts for a large amount of the median annual load increase of 445,000 metric tons between Henderson and Kersey. The remaining 96,000 metric tons per year of dissolved solids added to the river along this reach is likely a result of minor tributaries, point sources, and ground water inflow.

The largest annual dissolved solids loads within the mainstem were found at Kersey. Annual median loads appear decrease at Weldona, however it is believed most of this drop is attributable to diversion of irrigation water upstream from Weldona which routes some of the dissolved solids load around the monitoring site in this region. At Julesburg, the median annual dissolved solids load returns to within 3,000 metric tons per year of the median annual loads observed at Kersey. Expressed as mean annual loads instead of median annual loads, the difference in loads between the sites is even greater due to non-normality of the data distribution. The mean annual load at Kersey is 642,000 metric tons while at Julesburg it is 610,000 metric tons for a difference of 32,000 metric tons per year. While not an excessively large difference during this period, the loss of dissolved solids load between Kersey and Julesburg has important implications for the salt balance of the region and the long-term productivity of the irrigated lands. These issues will be examined in more detail in Chapter 7.

Figure 6-5 displays annual loads for all tributary sites selected for load analysis in this study. The three smaller tributaries that enter the mainstem in the upstream portion of the study area all contribute median loads of 25,000 metric tons per year or less. The multiple sites along all three of the major tributaries show a similar pattern of large dissolved solids load increases in a downstream direction with an especially large increase in the last downstream reach of each tributary. The median dissolved solids load in the Saint Vrain River more than doubles from 60,000 metric tons per year to 141,000 metric tons per year between the site downstream from Longmont and the river’s mouth at Platteville. The median annual dissolved solids load in the Big Thompson River at its mouth near La Salle is more than six times higher than the median dissolved solids load at the next upstream site at Loveland. Dissolved solids loads gradually increase along the first three Cache la Poudre sites before rising sharply between the sites at Timnath and Greeley. In this final reach, median loads increase more than nine times from 12,000 metric tons per year to 112,000 metric tons per year.

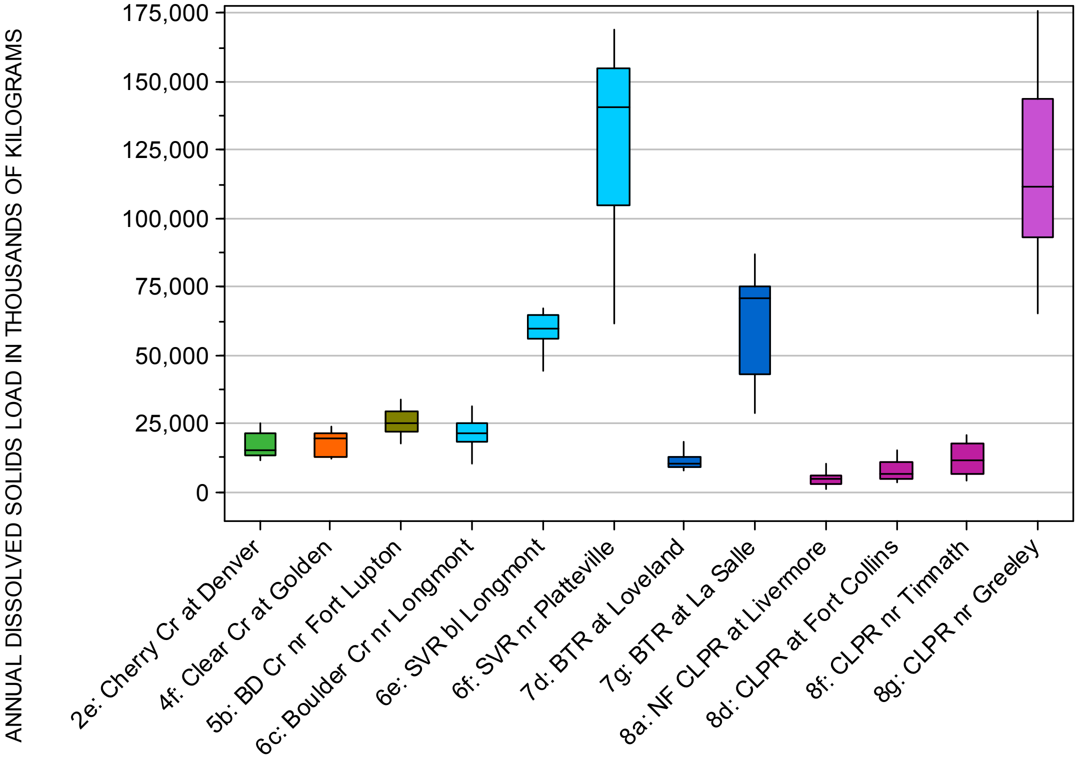


Figure 6-5. Boxplot of estimated annual dissolved solids loads at selected tributary sites, water years 1991–2004.

In the regions east of the foothills where tributaries exhibit large increases in dissolved solids concentration and load, it is believed that dissolved solids are leached from geologic shale deposits and carried into the river through groundwater inflows. Groundwater levels in the region have increased since the widespread adoption of irrigation for agricultural and urban lands. Higher groundwater levels result in increased groundwater contributions to the rivers. This has turned what were originally reported to be seasonally flowing rivers into rivers that flow year-round. The increased groundwater contributions are also likely to result in increased transport of dissolved solids from the geologic formations into the rivers.

6.3.4 Comparison to Previous Studies

Table 6-4 compares mean annual dissolved solids load values obtained from this study to values obtained from previous studies by Gomez-Ferrer *et al*. (1983) which covered calendar years 1965–1979 and Litke and Kimbrough (1998) covering water years 2004 and 2005. In general, the values from the two previous studies are relatively similar in value even though they covered different time periods and utilized different methods to estimate loads. The results from Litke and Kimbrough only cover a two-year subset (water years 1994 and 1995) of the 14-year period used in this study. Within the 14-year period of this study, water year 1994 had some of the lower annual dissolved solids loads at many of the sites while water year 1995 had some of the larger annual dissolved solids values at many sites (see Figure 6-1 through Figure 6-3). Within Table 6-4, a separate column lists the mean annual dissolved solids loads for only water years 2004–2005 as determined in this study for comparison with those from Litke and Kimbrough. This study estimated slightly lower mean annual loads along the mainstem at Denver and Henderson and a slightly higher value at Kersey whereas values for tributary sites were nearly identical. These slight differences are probably a result of differing load estimation methodology. Rather than developing regression-based relationships between streamflow and TDS concentration, Litke and Kimbrough estimated daily TDS concentrations through linear time-based interpolation between measured TDS concentrations and modified these values by discharge-based interpolation during storm events. Although this methodology appears to have produced generally comparable results at most sites, time-based interpolation of concentrations between sampling events might not always capture the dynamics of concentration values as they fluctuate between sampling events in response to variations in streamflow.

Table 6-4. Comparison of dissolved solids loads determined in the current study to loads determined in previous studies.

Site Number	Site Name	Mean Annual Dissolved Solids Load (thousands of kilograms)			
		This Study (water years 1991–2004)	Gomez-Ferrer *et al*., 1983 (calendar years 1965–1979)	This Study (water years 1994–1995)	Litke and Kimbrough, 1998 (water years 1994–1995)
1a	SPR nr Englewood	39,000	–	56,000	–
1b	SPR at Englewood	55,000	–	74,000	–
1c	SPR at Denver	96,000	–	106,000	109,000
1d	SPR at Comm. City	59,000	–	71,000	–
1e	SPR at Henderson	193,000	191,000	188,000	218,000
1f	SPR nr Kersey	642,000	733,000	740,000	735,000
1g	SPR nr Weldona	484,000	626,000	520,000	–
1h	SPR at Julesburg	610,000	595,000	824,000	–
2e	Cherry Cr at Denver	17,000	–	14,000	14,000
4f	Clear Cr at Golden	18,000	–	17,000	17,000
5b	BD Cr nr Fort Lupton	26,000	–	26,000	–
6c	Boulder Cr nr Longmont	22,000	–	27,000	–
6e	SVR bl Longmont	59,000	–	62,000	–
6f	SVR nr Platteville	133,000	170,000	154,000	154,000
7d	BTR at Loveland	11,000	–	13,000	–
7g	BTR at La Salle	63,000	114,000	76,000	–
8a	NF CLPR at Livermore	5,000	–	6,000	–
8d	CLPR at Fort Collins	8,000	–	7,000	–
8f	CLPR nr Timnath	12,000	–	13,000	–
8g	CLPR nr Greeley	115,000	120,000	119,000	–

Although the study by Gomez-Ferrer and others spanned the earlier time period of calendar years 1965–1979, some of the annual dissolved solids values are very similar to values obtained in this study. In particular, sites on the South Platte River at Henderson and Julesburg and the site on the Cache la Poudre River at Greeley had values that were within 5% of each other. At the remaining sites that the two studies had in common, the differences are much greater. Values for the South Platte River at Kersey are 14% lower and values for the South Platte River at Weldona are nearly 30% lower in this study than the values from the Gomez-Ferrer. Even greater differences occur for sites at the mouths of the Saint Vrain and Big Thompson Rivers where annual dissolved solids loads are 28% and 80% lower respectively, in this study than the earlier study.

Assuming the different methods used to estimate loads in this study and the Gomez-Ferrer study produce comparable results, the decreases in loads observed at some sites since calendar years 1965–1979 suggests the possibility dissolved solids concentrations, streamflow conditions, or both have decreased from the average conditions during the period of the earlier study. Formal trend analysis on loads for the time period between these two studies is beyond the scope of this study, however formal trend testing for the time period used in this study is presented in the next section.

6.3.5 Trend Analysis

Results of non-parametric, regression-based trend analysis of annual dissolved solids loads are presented in Table 6-5. A *p*-value equal to or less than 0.10 was used to judge significance. This *p*-value was chosen in order to provide a more inclusive standard for determination of significance versus using a *p*-value of 0.05. This allowed for the identification of sites that have some evidence of a trend even if the trend would not qualify as highly significant under the stricter *p*-value. Trends judged to be significant are shown in the final column in Table 6-5 as percent change per year. Only four significant trends in annual dissolved solids loads were detected during the period of study. All four trends were downward and occurred in the middle portion of the study area. One of the four trends found was for a tributary of the Saint Vrain River, Boulder Creek near Longmont, which had a downward trend of 4.0 percent per year. Two of the trends were found at the mouths of tributaries: a downward trend of 3.8 percent per year for the Saint Vrain River at Platteville and a downward trend of 5.7 percent per year for the Big Thompson River at La Salle. The final trend was found at the mainstem site South Platte River at Kersey which had a downward trend of 3.3 percent per year. The site at Kersey is located downstream from the confluence of the two tributaries which also had significant downward trends in dissolved solids loads. The combined average decrease in load for the Saint Vrain River at Platteville and the Big Thompson River at La Salle is 8,600 metric tons per year while the average decrease in dissolved solids load at the South Platte River at Kersey is 20,900 metric tons per year. Although not judged to be significant based on the standards of this study, there is evidence that loads might be decreasing at the mouth of the Cache la Poudre River at an annual average rate of 2,700 metric tons per year. Taken together, the decreasing dissolved solids load contributions from the three largest tributaries could account for just over half of the decreasing trend in dissolved solids load on the South Platte River at Kersey.

Table 6-5. Results of historical trend analysis on annual dissolved solids load at selected sites in the South Platte River Basin, water years 1991–2004.

[kg, kilograms; yr, year; %, percent]

Site Number	Site Name	Period (water years)	Number of years	Slope (x1000 kg/yr)	*p*-Value	Mean (x1000 kg)	Trend (%/yr) *
1a	SPR nr Englewood	1991 - 2004	14	-257	0.358	38,800	
1b	SPR at Englewood	1991 - 2004	14	-932	0.605	55,389	
1c	SPR at Denver	1991 - 2004	14	14	0.681	96,018	
1d	SPR at Comm. City	1991 - 2004	14	1,390	0.267	58,774	
1e	SPR at Henderson	1991 - 2004	14	878	0.626	192,723	
1f	**SPR nr Kersey**	**1991 - 2004**	**14**	**-20,892**	**0.064**	**641,611**	**-3.3**
1g	SPR nr Weldona	1991 - 2004	14	-13,657	0.197	484,297	
1h	SPR at Julesburg	1991 - 2004	14	-38,152	0.126	609,508	
2e	Cherry Cr at Denver	1991 - 2004	14	402	0.110	16,980	
4f	Clear Cr at Golden	1991 - 2004	14	497	0.140	17,981	
5b	BD Cr nr Fort Lupton	1993 - 2004	12	483	0.276	25,775	
6c	**Boulder Cr nr Longmont**	**1993 - 2004**	**12**	**-861**	**0.063**	**21,746**	**-4.0**
6e	SVR bl Longmont	1991 - 2004	14	-688	0.191	58,893	
6f	**SVR nr Platteville**	**1991 - 2004**	**14**	**-5,059**	**0.039**	**132,966**	**-3.8**
7d	BTR at Loveland	1991 - 2004	14	17	0.805	11,489	
7g	**BTR at La Salle**	**1991 - 2004**	**14**	**-3,561**	**0.011**	**62,807**	**-5.7**
8a	NF CLPR at Livermore	1991 - 2004	14	-177	0.227	5,029	
8d	CLPR at Fort Collins	1991 - 2004	14	-99	0.446	7,868	
8f	CLPR nr Timnath	1991 - 2004	14	-445	0.227	12,360	
8g	CLPR nr Greeley	1991 - 2004	14	-2,706	0.197	115,108	

* Trends shown only for sites with a significance level of 90% or higher

Because loads are dependant on both flow and concentration, evaluation of trends in flow and concentration at sites found to have significant trends in load should help elucidate the underlying cause for a trend in load. The South Platte River at Kersey site had a downward trend in load of 3.3 percent per year. No corresponding significant trend in annual flow was found, however there is some suggestion of a downward slope in annual flow values that did not meet the defined criteria for significance. A downward trend of 1.3 percent per year was detected in flow-adjusted TDS concentration, so it is likely the downward trend in TDS concentration and to a lesser extent decreasing flow are responsible for the downward trend in load. No significant trends in either flow or TDS concentration were found for Boulder Creek near Longmont, therefore the cause for the trend in loads at this site remains unclear. The Saint Vrain River near Platteville did not have a significant trend in flow although there is evidence of a downward pattern that did not meet the requirements for significance as defined by this study. Trend analysis on TDS concentrations could not be performed due to inadequate monitoring data. The Big Thompson River at LaSalle did have a significant downward trend in annual streamflow of 1.7 percent per year which at least partially accounts for the downward trend in load. Like the Saint Vrain River near Platteville, the Big Thompson River near LaSalle could not be tested for trends in TDS concentration due to inadequate historical monitoring data; therefore a comparison with load trends at these sites cannot be made.

6.4 CONCLUSIONS

This study provides the most comprehensive analysis of dissolved solids loads in the South Platte River Basin to date. It lays the groundwork for understanding the origins and ultimate destination of dissolved solids in the basin and provides a reference point for comparison with future dissolved solids load conditions. Mean annual load values were found to be generally comparable to past studies at corresponding sites, however it appears that loads at some sites have decreased significantly compared to the period 1965–1979. This study evaluated dissolved solids load conditions at more mainstem and tributary sites than past studies.

Unlike past studies, the inclusion of upstream tributary monitoring sites in addition to the sites at the mouths of the tributaries allowed this study to document the increase in loads as it occurs along the tributaries and identify areas with the greatest increases in loads. Most of the loading to the tributaries occurs along the Front Range just east of the foothills where most of the major urban areas are located. Most of the dissolved solids are thought to result from geologic formations in this area.

Annual load values typically exhibited large inter-site variation and often had large intra-site variation from year-to-year as well. Median annual loads and variability in annual load values generally increased in a downstream direction. Trend testing revealed no upward trends in annual dissolved solids loads but did detect four significant downward trends. The downward trends occurred in the mid-part of the basin at Kersey and in the Saint Vrain and Big Thompson tributary systems.

Due in large part to the load contribution of the three largest tributaries, the largest increase in dissolved solids loads occurs in the middle portion of the basin between Henderson and Kersey. As a result of this increase, the largest dissolved solids loads in the mainstem are typically found at Kersey. Even with the large dissolved solids load found at Kersey, dissolved solids concentrations are kept low in this part of the river by the large volume of streamflow. As the river flows through the irrigated agricultural region from Kersey to Julesburg, the dissolved solids concentrations increase due to consumptive use of the water resulting in evapoconcentration of the existing salts. Although TDS concentrations are increasing in this region, the dissolved solids load actually decreases slightly. This suggests that instead of contributing additional salts to the river, soils in this region are might be accumulating some of the salts leached from upstream sources.

The difference between loads at Kersey and Julesburg equate to a net positive or negative salt balance in the intervening stream reach. Based on mean annual values, this region has a slightly positive salt balance, meaning more salts are entering the region than are leaving it. Over the long term, a positive salt balance could result in a build-up of soil salinity levels in the irrigated soils of this region and subsequent reductions in crop yield. The salt balance of this region needs to continue to be monitored to ensure the salt balance does not become worse as a result of new water resource projects and changes in the use and management of upstream water supplies. Additional analysis of the dissolved solids balance in the basin is presented in Chapter 7.

CHAPTER 7: STREAMFLOW AND DISSOLVED SOLIDS MASS-BALANCE ANALYSIS

7.1 INTRODUCTION

In the United States, large-scale irrigated agriculture is only a century old and yet salt balance problems are already pervasive in many arid and semi-arid regions (Ghassemi *et al.*, 1995). Like much of the irrigated land in the western United States and in many parts of the world, soil salinization is a threat to the irrigated fields of northeastern Colorado. The process of soil salinization can be greatly accelerated when a proper salt balance of the soil is not achieved through irrigation with sufficient quantities of lower salinity water and adequate drainage (Tanji, 1996a). This study examines the overall salt balance status of the lower South Platte River Basin and creates a detailed, reach-by-reach accounting of both water and salt gains and losses via streamflow, tributaries, point sources, and diversions along the mainstem of the South Platte River. The differences between the gains and losses within each reach are used as estimates of unmeasured gains and losses to the river which are assumed to be primarily subsurface flows to and from ground water. This quantification of gains and losses of water and salt mass via ground water provides a critical component in the overall effort to create a process-based understanding of salinity behavior in the basin.

7.1.1 Purpose and Scope

This empirical study was performed in order to quantify the sources, movement, and ultimate fate of dissolved solids in the basin, as well as to provide insight into the mechanisms controlling these sources and sinks. Results of this work will provide a basis for predicting the potential impacts to river salinity resulting from changes in management, water use, and hydrologic regime.

This study uses mass balance techniques to develop a reach-by-reach discharge and dissolved solids budget for the lower South Platte River from Denver, Colorado to Julesburg, Colorado for water years 1991 through 2004. Components of the budget include historical measurements or estimates of upstream inflow to the reach, tributary contributions, major point source inflows, losses to diversions, and downstream outflow from the reach. The residual term in the mass balance equation provides an estimate of the net gain or loss of water and salt to the stream via ground water.

7.1.2 Environmental Setting

The focus of this study is the lower portion of the South Platte River Basin between Denver and Julesburg, Colorado. Downstream from Denver and before the monitoring site at Kersey, the river is joined by the four largest tributaries to the South Platte River (Clear Creek, the Saint Vrain River, the Big Thompson River, and the Cache la Poudre River) and also receives a large contribution of treated effluent from the Denver Metropolitan Wastewater Reclamation District (Denver Metro). Denver Metro is the largest point-source discharger to the South Platte River, contributing almost 70 percent of the total flow downstream from the outfalls on an annual basis. Because of a large diversion just upstream of the Denver Metro outfall, flow contributions from Denver Metro can at times account for nearly 100 percent of the total flow downstream from this point (Dennehy *et al.*, 1995). Downstream from Kersey, there are more diversions from the river than surface inflow sources. As a result, the maximum average annual flow along the river generally occurs at Kersey.

As the river flows across the plains of eastern Colorado, it passes through a large agricultural region for 250 km before reaching Julesburg. From Kersey to Julesburg the primary alterations to flow are removal of water via irrigation diversions and additions or pumping of ground water. At several locations, nearly the entire flow can be diverted during the high-demand irrigation season. Below these locations, the flow in the river gradually increases primarily due to ground water inflows. Much of the ground-water inflow is due to irrigation return flows with additional inflows coming from ground-water storage and recharge projects that are being installed to help maintain legal and ecological minimum flow requirements. Unlike the pre-irrigation condition, the aquifer continues to drain into the South Platte River year-round (Robson, 1989).

7.1.3 Previous Studies

7.1.3.1 Ground Water Inflow Estimates

Minges (1983) conducted a 3-year study of hydrologic characteristics for a 25-mile stretch of the South Platte River near Fort Morgan, Colorado for water years 1977 through 1979. One aspect of this work included conducting twenty-five monthly gain-and-loss investigations. These investigations were carried out through same-day measurement of all known inflows and outflows to the reach. This study found this segment to nearly always gain discharge as a result of ground water inflow. The average gain to the reach was approximately 8,500 m^3/d/km; however, seasonal and spatial differences were observed. Seasonal changes were attributed to irrigation return flows and seasonal well pumping. Spatial differences were correlated with saturated thickness of the alluvial aquifer in the valley-fill beneath the river. A follow-up study (Ruddy, 1984) of this segment conducted monthly from May, 1982, to October, 1982 resulted in similar ground-water inflow values.

According to Dennehy *et al.* (1993), the high rates of recycling and return flows in the basin have water-quality implications for the receiving water that have not been properly investigated on a basin-wide scale. Although anecdotal evidence suggests that the salinity problems are increasing in the basin, few attempts have been made to interpret historical monitoring data to provide a clear understanding of the salt-transport regime of the river.

7.1.3.2 Dissolved Solids Budgets

Gomez-Ferrer *et al.* (1983) performed the most comprehensive evaluation of dissolved-solids concentrations and salt loads to date for a 340-km stretch of the river between Henderson and Julesburg. Utilizing USGS records of salinity and flow for the period 1965 to 1979, they examined the flow and salt load profile of the river and quantified the salt balance from Kersey to Julesburg. The authors found that the largest salt load increase in the river occurs between Henderson and Kersey due to the salt load contribution from the three tributary streams that join the mainstem along this reach. This work determined that during the study period an average of 1,700 metric tons per day of salts was reaching the South Platte River by the time it reached Kersey. They also found that the load at Julesburg averaged 380 metric tons per day less than the load at Kersey, indicating a net accumulation of salt in the lower basin. Although the ultimate destination of the accumulated salt within the region is not known, if it was distributed evenly between Kersey and Julesburg on the 330,000 acres of land irrigated during this historical time period, the authors estimated each acre would receive a net salt gain of approximately 420 kilograms per year.

7.2 METHODS

7.2.1 River Reaches

Based on the location of monitoring sites along the mainstem South Platte River, six river segments or reaches were defined (Table 7-1) for use in the streamflow and dissolved solids mass balance. The division of the lower South Platte River into smaller reaches rather than conducting the mass balance over the entire lower South Platte River provided greater spatial resolution and allowed for the determination of changes in the relative contribution of streamflow and dissolved solids at various points along the river. The location of the river reaches are shown graphically in Figure 7-1.

Table 7-1. River reaches as defined in this study.

[km, kilometers]

Reach	Description	Length (km)	Cummulative Distance from Denver (km)
1	Denver to Commerce City	7.4	7.4
2	Commerce City to Henderson	17.2	24.6
3	Henderson to Kersey	88.3	113.0
4	Kersey to Weldona	66.1	179.1
5	Weldona to Balzac	50.0	229.1
6	Balzac to Julesburg	134.8	364.0

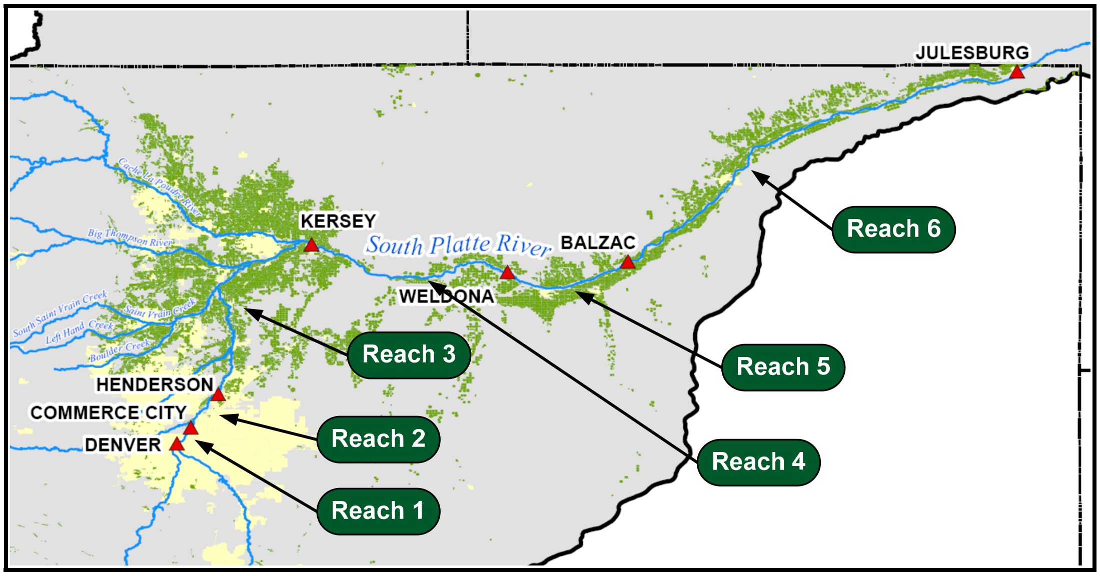


Figure 7-1. Location of river reach units used in the mass-balance analysis.

7.2.2 Data Compilation

Records of mean daily discharge measurements for river gauging sites used in this study (Table 7-2) were obtained from the State of Colorado's online hydrologic database Hydrobase (Colorado Water Conservation Board and Colorado Division of Water Resources, 2007) as described in Chapter 3. One additional site along the South Platte River near the town of Balzac (USGS Site ID 6759910 – South Platte River at Cooper Bridge near Balzac) was included in this analysis. It was excluded from the salinity characterization work described in Chapters 3 through 6 because periodic specific conductance measurements ended by 1996 except for two measurements in 2001. The site at Balzac was included in this mass balance analysis because it had continuous daily flow values and sufficient historical salinity measurements to allow for the determination of dissolved solids loads during the study period. It was also used because its inclusion would help to reduce the length of the final reach in the study area by 50 km which would increase the spatial resolution of this study.

Table 7-2. River gauging sites used in mass-balance analysis.

Site ID used in Previous Chapters	Station Description	Station Type	Common Name Used in this Study	USGS Station Number
1c	South Platte River at Denver, Colorado	Mainstem	Denver	6714000
1d	South Platte R at 64th Ave., Commerce City, Colorado	Mainstem	Commerce City	6714215
3a	Sand Creek at mouth near Commerce City, Colorado	Tributary	Sand Creek	394839104570300
4f	Clear Creek at Golden, Colorado	Tributary	Clear Creek	6720000
1e	South Platte River at Henderson, Colorado	Mainstem	Henderson	6720500
5b	Big Dry Creek at mouth near Fort Lupton, Colorado	Tributary	Big Dry Creek	6720990
6f	St. Vrain Creek at mouth, near Platteville, Colorado	Tributary	St. Vrain Creek	6731000
7g	Big Thompson River at mouth, near La Salle, Colorado	Tributary	Big Thompson River	6744000
8g	Cache La Poudre River near Greeley, Colorado	Tributary	Cache la Poudre River	6752500
1f	South Platte River near Kersey, Colorado	Mainstem	Kersey	6754000
1g	South Platte River near Weldona, Colorado	Mainstem	Weldona	6758500
n/a *	South Platte River at Cooper Bridge near Balzac	Mainstem	Balzac	6759910
1h	South Platte River at Julesburg, Colorado	Mainstem	Julesburg	6764000

* Site not included in previous salinity characterization work

In keeping with the prior salinity characterization work described in Chapters 3 through 6, water years 1991 through 2004 were selected as the primary analysis period based on data availability at key gauging sites. This period covers normal, high-flow, and drought conditions within the basin. Periodic discharge measurements for point-sources were obtained from the Colorado Department of Public Health and Environment, Water Quality Control Division (CDPHE-WQCD). Daily records of river diversion outflows at headgates were obtained from Hydrobase. Daily discharge records for the Denver Metropolitan Wastewater District (Denver Metro) outfalls were provided by Denver Metro.

Historical specific conductance (SC) and total dissolved solids (TDS) records for gauging sites were downloaded from the U.S. Geological Survey's National Water Information System (NWIS) (U.S. Geological Survey, 2006) as described in Chapter 3. TDS measurements for Denver Metro outfalls were obtained from the U.S. Environmental Protection Agency's (EPA) STORET water-quality database (U.S. Environmental Protection Agency, 2007b). Salinity measurements for other point sources were found in the data provided by CDPHE-WQCD or downloaded from the EPA's Permit Compliance System (PCS) online database (U.S. Environmental Protection Agency, 2007a).

7.2.3 Flow and Dissolved Solids Budget Approach

Figure 7-2 shows a conceptualization of the major inputs and outputs for a generalized reach. The residual term is defined as the difference between the sum of the outflows minus the sum of the inflows (Equations 7-1 and 7-2). The control volume for the discharge and dissolved solids budget analysis was defined as the river channel beginning at the Denver gauging site and ending at the Julesburg gauging site. This control volume was subdivided into six segments or reaches (Table 7-1) based on the location of selected mainstem streamflow gauging sites.

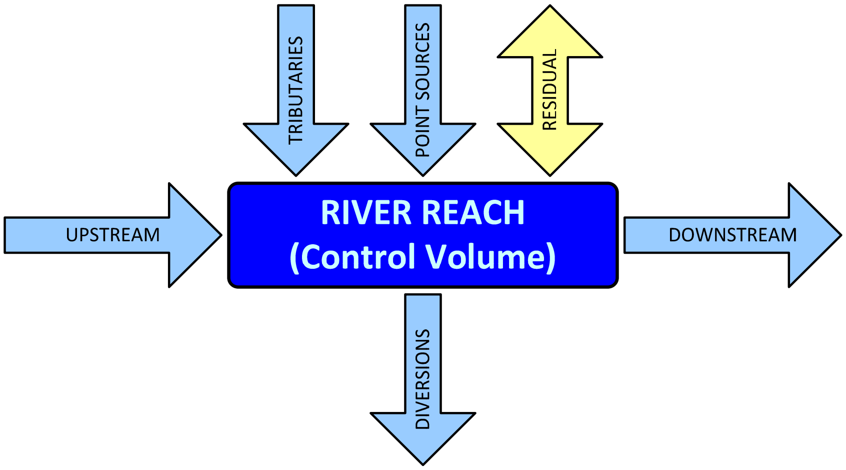


Figure 7-2. Conceptualization of a river reach with inputs and outputs as used in the mass-balance analysis.

$$Q_{\text{Residuals}} = Q_{\text{Downstream Outflow}} - Q_{\text{Upstream Inflow}} + \sum Q_{\text{Diversions}} - \sum Q_{\text{Tributaries}} - \sum Q_{\text{Point Sources}}$$

Equation 7-1

and

$$L_{\text{Residuals}} = L_{\text{Downstream Outflow}} - L_{\text{Upstream Inflow}} + \sum L_{\text{Diversions}} - \sum L_{\text{Tributaries}} - \sum L_{\text{Point Sources}}$$

Equation 7-2

Where:
Q = Flow Volume
L = Dissolved-solids load

Most of the flow inputs and outputs to a reach are measured at least periodically with the exception of evaporation from the river, surface-return flows, and ground-water return flows. Change in storage volume within the reach control volume is assumed to be negligible, however changes in storage outside the control volume due to changes in reservoir volume will likely dampen and time-shift the return response of the residual flow. Phreatophyte depletions from the river channel are accounted for in the residual term of the flow budget. The magnitude of these losses was assumed to be a fraction of the total flow in the river. Net free surface evaporation has been estimated to be a relatively insignificant loss of 54,000 m^3/d (Hurr *et al.*, 1975) and is therefore not included as a separate component in this analysis. Similarly, surface return flows to the river are not considered separately in this study because they are thought to be a relatively minor contribution to the total flow volumes (Gomez-Ferrer and Hendricks, 1983). Because of the small magnitude of free-surface evaporation and surface return flows, the residuals of the materials balance are assumed to primarily reflect net ground water inflow plus the net error of the various measurements.

7.2.4 Flow Budget

7.2.4.1 Tributary and Mainstem Flows

Historical flow data for tributary and mainstem gauging sites were obtained from the databases created for streamflow analysis as described in Chapter 4. Historical streamflow data for the South Platte River at Balzac which was not included in the earlier streamflow characterization was also obtained from Hydrobase for inclusion in this study.

7.2.4.2 Point-Source Discharges

The point-source discharge permit database obtained from CDPHE-WQCD contained historical discharge measurements which were was screened to select only major discharges (> 7,500 m^3/d) that discharge directly into the lower South Platte River. Of the nearly 1,900 discharge permits, five were deemed to be significant contributors to the river. These five discharge points are listed in Table 7-3 according to the reach in which they contribute. Flow rates for these outfalls were generally measured as instantaneous discharge and reported monthly or less frequently. Gaps in the records were filled in using monthly mean flow rates. Denver Metro provided daily flow rates for each of the three outfalls they operate. Because Denver Metro is a significant contributor of flow to the river and because treated effluent is sometimes discharged directly to the nearby Burlington irrigation canal instead of the river, it was important to use the daily flow values for each of the three outfalls rather than periodic measurements contained in the CDPHE-WQCD database in order to provide the best possible representation of Denver Metro's contribution to the total flow within this reach.

7.2.4.3 Diversions

Historical diversion outflow records for the period of study were compiled from records obtained from the Hydrobase database. Outflow volumes were totaled on a monthly basis according to the reach in which they are located. A summary of the number of diversions and the mean annual diversion outflow is shown in Table 7-4.

Table 7-3. Significant inflows included in the flow and dissolved solids budget.

Reach	Description	Tributary Inflows	Major Point Source Inflows
1	Denver to Commerce City	(insignificant)	(insignificant)
2	Commerce City to Henderson	Sand Creek Clear Creek	Denver Metro Wastewater Reclamation District Public Service Company of Colo. Cherokee Power Plant South Adams County Water and Sanitation District
3	Henderson to Kersey	Big Dry Creek Saint Vrain Creek Big Thompson River Cache la Poudre River	Public Service Company of Colo. Fort Saint Vrain Power Plant City of Brighton Wastewater Treatment Plant
4	Kersey to Weldona	(insignificant)	(insignificant)
5	Weldona to Balzac	(insignificant)	(insignificant)
6	Balzac to Julesburg	(insignificant)	(insignificant)

Table 7-4. Summary of diversion outflows included in the flow and dissolved solids budget.

[Num, Number; Irrig., Irrigation; ha, hectares]

Reach	Description	Num. of Irrig. Diversions	Mean Annual Diversion Volume (m^3 10^6)	Irrig. Area Served by Diversions (ha)
1	Denver to Commerce City	3	146.9	37,037
2	Commerce City to Henderson	2	63.6	5,735
3	Henderson to Kersey	15	307.5	25,731
4	Kersey to Weldona	6	448.8	35,278
5	Weldona to Balzac	6	244.9	27,678
6	Balzac to Julesburg	18	260.7	30,010

Figure 7-3 shows a reach-by-reach conceptual model of the river system as represented in this analysis. Individual tributary and point sources are shown at the reach in which they contribute.

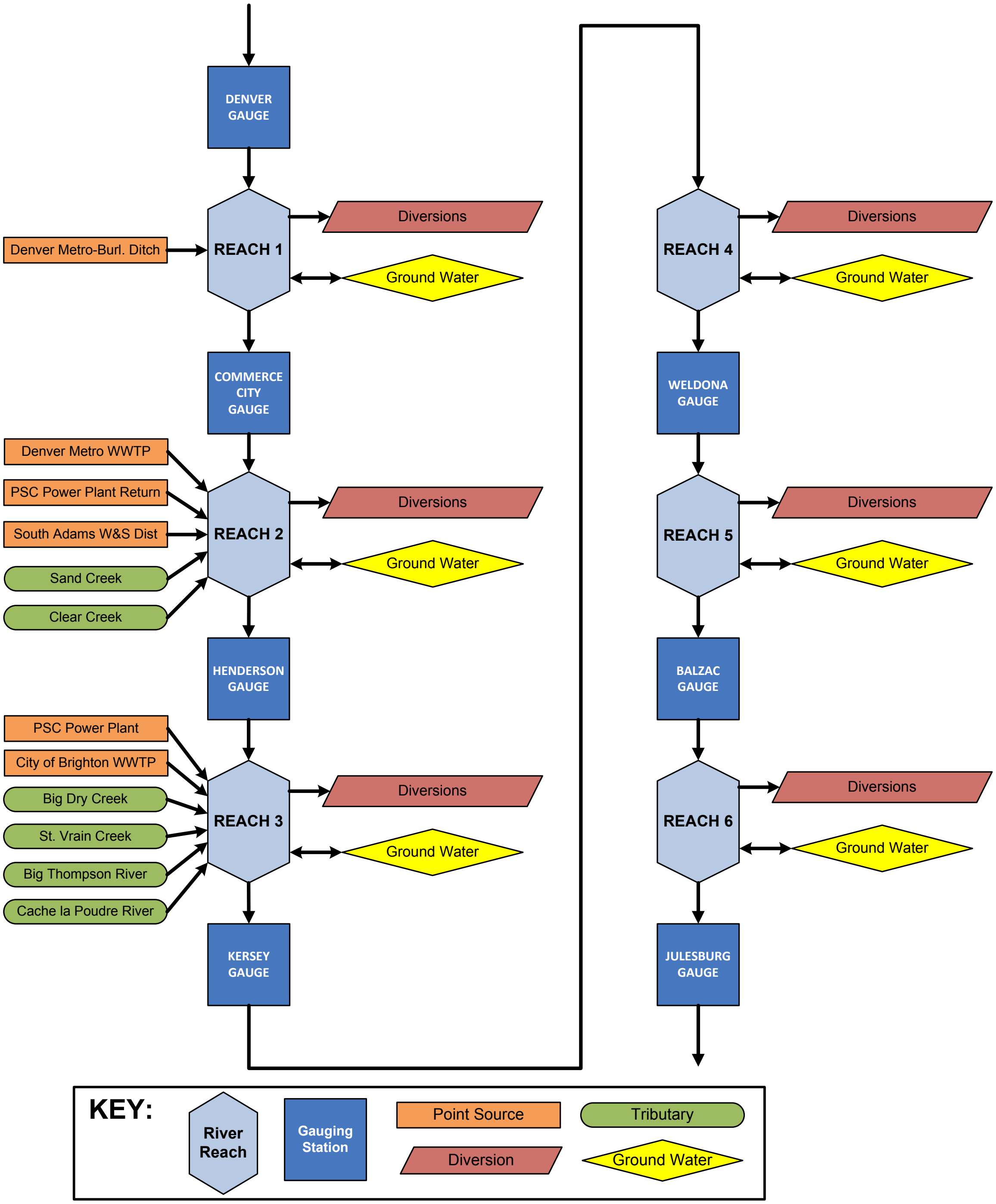


Figure 7-3. Conceptual river schematic showing components included in flow and dissolved solids budget analysis.

7.2.4.4 Calculation of Residual Flow

The difference in the sum of the measured outflows and inflows was computed to determine the estimated volume of residual flow on a monthly, annual, and period of study basis for each river reach as well as the length of the river from Denver to Julesburg and also from Kersey to Julesburg. These residual flow volumes were expressed as daily rates to represent the monthly, annual, and period of study mean daily residual flow rates for each reach. Incremental mean residual flow rates were determined by dividing the residual flow rates of the entire reach by the length of the respective reach in order to normalize flow rates for comparison to other reaches.

7.2.5 Dissolved Solids Budget

7.2.5.1 Load Estimation for Gauging Sites

The dissolved solids budget was developed using the results of the flow budget in conjunction with water-quality measurements to obtain the mass of dissolved solids in each component of the budget. Specific conductance measurements were converted to TDS concentrations through the use of site-specific SC-TDS regression equations as described in Section 3.2.3. Daily loads were then estimated through the use of the USGS LOADEST software package (Runkel *et al.*, 2004) through the procedures described in Chapter 6.

7.2.5.2 Load Estimation for Point Sources

Bi-monthly TDS measurements of Denver Metro effluent were obtained from EPA's STORET and combined with the daily effluent discharge values described above to obtain estimates of daily dissolved solids loads from Denver Metro. One-time TDS measurements for the City of Brighton WWTP (580 mg/L) and South Adams County Water and Sanitation District (1,050 mg/L) were found in STORET. These were assumed to represent the TDS of the effluent from these plants for the entire study period. Salinity in municipal effluent is generally relatively constant so this is a reasonable assumption. Salinity measurements for the two power plant discharges were not available so a value of 1,800 mg/L was assumed based on effluent data for similar plants found in STORET.

7.2.5.3 Load Estimation for Diversions

Because dissolved solids concentrations of diversion outflows are not measured, they were estimated on a reach-by-reach basis by multiplying the monthly mean TDS concentration of the upstream and downstream river gauges by the monthly diversion outflow of each reach to obtain monthly estimates of dissolved solids lost from the river due to diversions.

7.2.5.4 Calculation of Residual Dissolved Solids Loads

Using the same procedures as for the flow budget, the residual dissolved solids loading was determined on a monthly, annual, and period of study basis for each river reach. Incremental mean residual loading rates were determined by dividing the residual loading rates by the length of the respective river reach to normalize them for comparison to other reaches. Mean flow-weighted TDS concentrations were determined by dividing the respective residual load by the residual flow volume.

7.2.6 Salt Export Analysis

The long-term net salt balance of the region was examined by compiling historic water salinity records for the entire period of record at the major gauging sites along the river. The South Platte River at Kersey and the South Platte River at Julesburg had the longest and most complete records from the early 1950's. These also happen to be the two most important points in terms of evaluating the net gain or loss of salt in the lower South Platte. Monthly and annual dissolved solids loads were determined for the entire period of record using the daily flow values and the load estimation techniques described above. Net salt gain or loss for reaches 4 through 6 was evaluated by subtracting the monthly and annual dissolved solids load at Julesburg from the dissolved solids load at Kersey.

7.3 RESULTS AND DISCUSSION

7.3.1 Flow Balance

Results of the flow budget expressed on a mean daily basis (Table 7-5) indicate that each reach has a net gain in calculated residual flow. Expressed as a per-unit-length basis, mean values of residual flow ranged from nearly 4,400 m^3/d/km to over 16,000 m^3/d/km. Overall values for the study area (Denver to Julesburg and Kersey to Julesburg) were 7,200 m^3/d/km and 5,900 m^3/d/km respectively (final two columns in Table 7-5). Figure 7-4 expresses, on a percentage basis, the contribution of flow sources to the total inflow of each reach. Calculated residual flow accounts for a sizable amount of flow in each reach ranging from 5 percent (Reach 1) to 28 percent (Reach 6) of the total inflow. Figure 7-4 also shows the large contribution from tributary inflow to Reaches 2 and 3 and the significant contribution of point sources (primarily Denver Metro WWTP) to the total inflow of Reach 2.

Table 7-5. Reach-by-reach flow budget for the lower South Platte River, water years 1991–2004.

[km, kilometers; m, meters; d, day; %, percent]

	REACH 1	REACH 2	REACH 3	REACH 4	REACH 5	REACH 6	LOWER BASIN 1	LOWER BASIN 2
INPUTS (m^3 d^{-1})	DENVER TO COMMERCE CITY	COMMERCE CITY TO HENDERSON	HENDERSON TO KERSEY	KERSEY TO WELDONA	WELDONA TO BALZAC	BALZAC TO JULESBURG	DENVER TO JULESBURG	KERSEY TO JULESBURG
Flow at U/S Gauge	741,241	401,746	1,225,508	2,505,146	1,781,852	1,497,417	741,241	2,505,146
Tributary Inputs	*	375,237	1,285,141	*	*	*	1,660,378	*
Point Source Inputs	24,144	345,163	12,234	*	*	*	381,540	*
TOTAL INPUTS	765,385	1,122,145	2,522,882	2,505,146	1,781,852	1,497,417	2,783,159	2,505,146
OUTPUTS (m^3 d^{-1})								
Aggregate Diversions	402,022	174,037	841,771	1,228,605	670,426	713,554	4,030,414	2,612,586
Flow at D/S Gauge	401,746	1,225,508	2,505,146	1,781,852	1,497,417	1,374,490	1,374,490	1,374,490
TOTAL OUTPUTS	803,767	1,399,544	3,346,917	3,010,457	2,167,843	2,088,045	5,404,905	3,987,076
RESIDUALS								
Daily Residual Flow (m^3 d^{-1}) **	38,382	277,399	824,034	505,311	385,991	590,628	2,621,745	1,481,930
Fraction of Total Inputs (%)	5	20	25	17	18	28		
Reach Length (km)	7.4	17.2	88	66	50	135	364	251
Incremental Daily Residual Flow (m^3 d^{-1} km^{-1}) **	5,200	16,100	9,300	7,600	7,700	4,400	7,200	5,900

***** insignificant, ** positive value indicates reach is gaining flow*

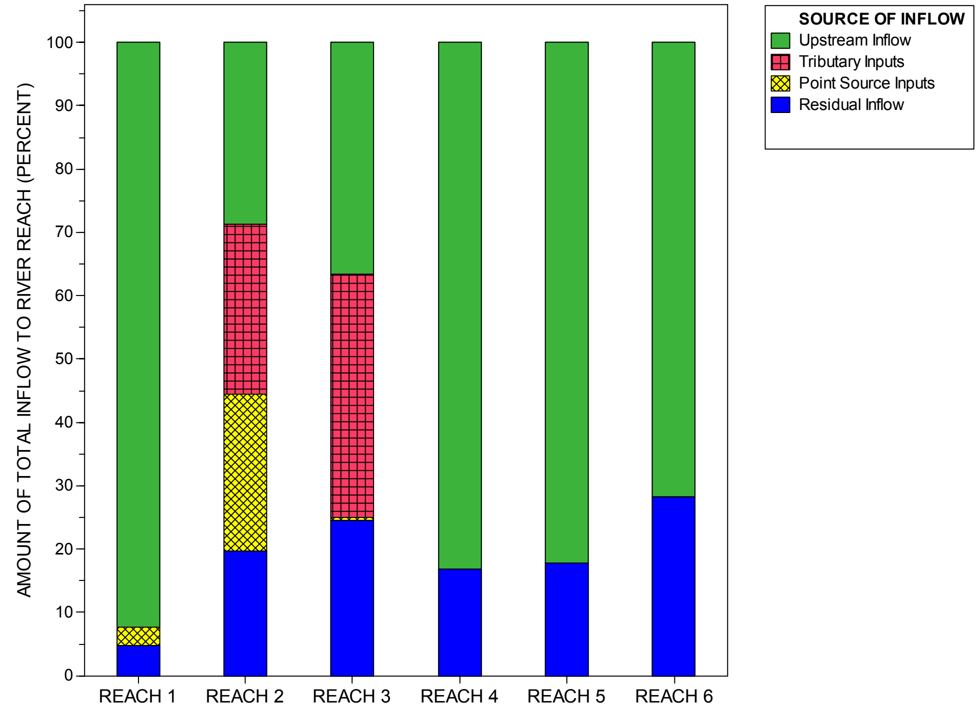


Figure 7-4. Relative contribution of inflow sources to each reach, water years 1991–2004.

Residual flow values computed in this study using mass balance analysis of historical values of gauged inflows and outflows generally compare favorably to past studies using similar methodology as well as to previous short-term, intensive field-based measurements of ground water inflow conducted for selected reaches of the river (Table 7-6). Values for Reach 2 are much larger than values for other reaches, but within the range of values (-41,000 to 26,000 m^3/d/km) reported in the field-based study by McMahon *et al.* (1995).

Table 7-6. Comparison of residual flow estimates by this study to previous ground water inflow and residual flow estimates.

[m, meters; d, day; km, kilometers]

Study	Period of Study	Method *	REACH 1 DENVER TO COMMERCE CITY (m^3 d^{-1} km^{-1})	REACH 2 COMMERCE CITY TO HENDERSON (m^3 d^{-1} km^{-1})	REACH 3 HENDERSON TO KERSEY (m^3 d^{-1} km^{-1})	REACH 4 KERSEY TO WELDONA (m^3 d^{-1} km^{-1})	REACH 5 WELDONA TO BALZAC (m^3 d^{-1} km^{-1})	REACH 6 BALZAC TO JULESBURG (m^3 d^{-1} km^{-1})	LOWER BASIN 1 DENVER TO JULESBURG (m^3 d^{-1} km^{-1})	LOWER BASIN 2 KERSEY TO JULESBURG (m^3 d^{-1} km^{-1})
This Study	Water Years 1991 - 2004	1	5,190	16,110	9,330	7,640	7,710	4,380	7,200	5,900
Hurr, *et.al*, 1975	March, 1968	2			2,940	10,900	6,610	4,440		
	November, 1968	2			4,820	11,710	2,430	3,040		
	1947 - 1970	1								5,040
	1967 - 1969	1								5,660
McMahon, *et.al*, 1995	August, 1992 - July, 1993	2	median:	6,995						
			low:	-41,055						
			high:	25,850						
Minges, 1983	Water Years 1977 - 1979	2				8,428				
Ruddy, 1984	May - October, 1982	2				8,840				
Gomez-Ferrer, *et.al*, 1983	Water Years 1965 - 1977	1			8,957	8,884	7,650	4,593		

*** 1: Analysis of historical inflow and outflow data, 2: Field-based, intensive measurement of known inflows and outflows**

Temporal patterns in monthly mean values of calculated residual flow are shown in Figure 7-5. Values are generally positive (net inflow to the river) with the exception of occasional observations in Reach 1 and a period in the late 1990's in Reach 6. The central tendency of the values as highlighted by the LOWESS smoothing line show that residual flows to the river remained relatively constant during the study period. There is some evidence of a reduction in residual flow seen in Reaches 1, 2, and 5 during water years 2000 – 2004. This might be a reflection of the drought conditions experienced in the basin during this time period. Reach 1 exhibits an upward trend in residual flow during the early 1990’s. Seasonal patterns in the residual flow within some reaches are also apparent in the plots. These patterns are highlighted in the boxplots of Figure 7-6. Reach 1 appears to regularly have net losses from the river and more variability during the summer months. Reach 2 has larger gains to the river during the middle of the summer. Reach 3 through 6 appear to have larger gains to the river later in the summer and early fall. This is probably a reflection of return flows from irrigation earlier in the summer.

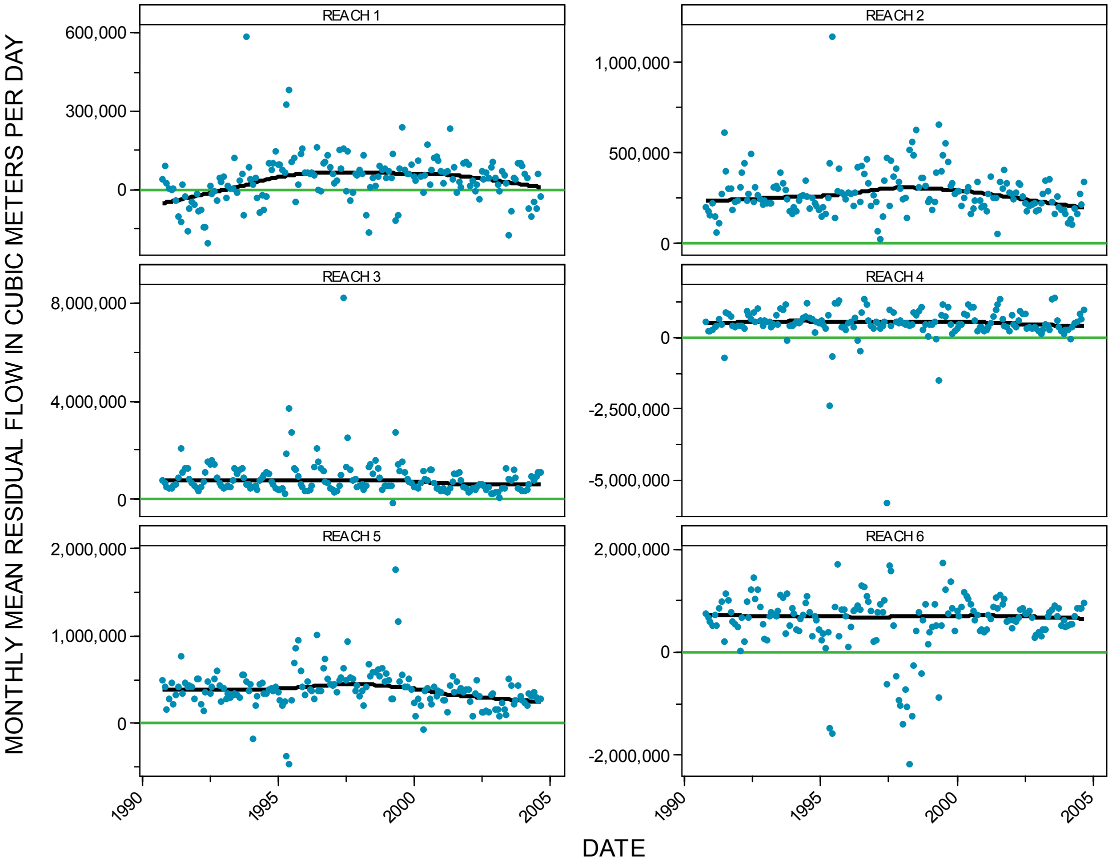


Figure 7-5. Temporal patterns in calculated residual flow, water years 1991–2004.

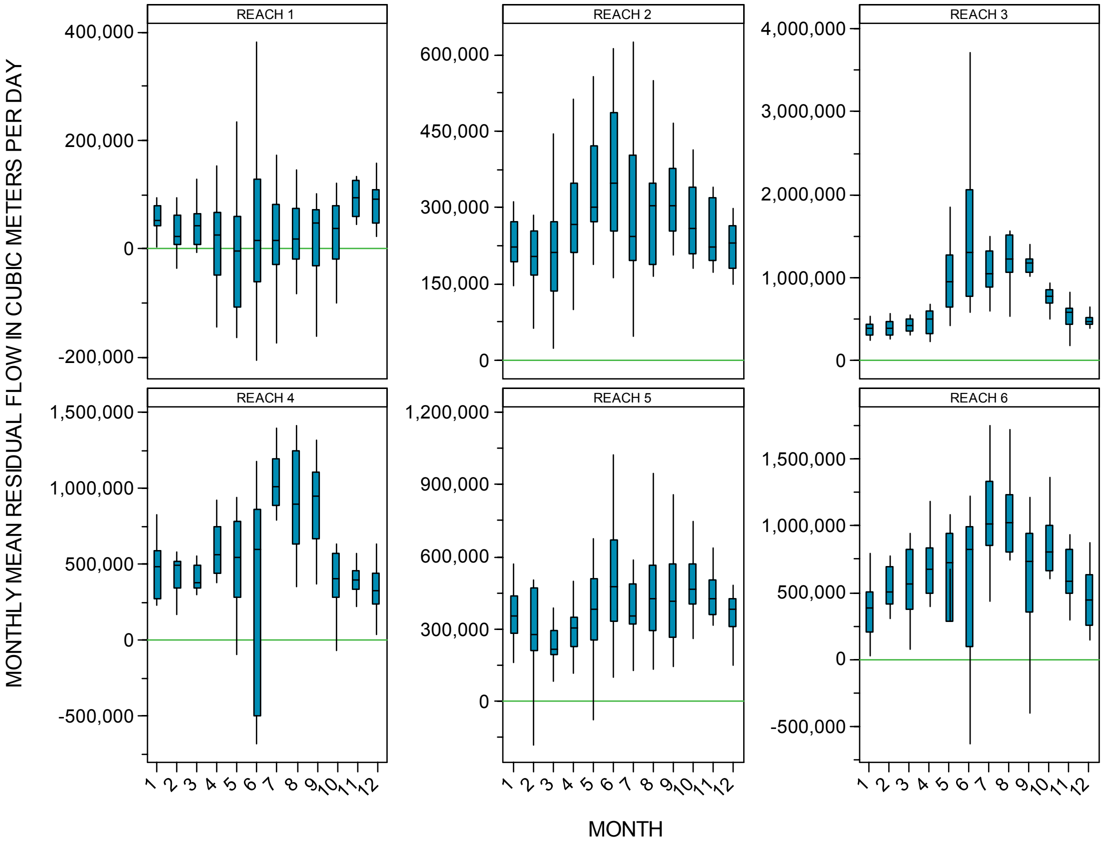


Figure 7-6. Seasonality in calculated residual flow, water years 1991–2004.

7.3.2 Dissolved Solids Budget

Mean results of the dissolved solids budget for water years 1991 through 2004 are reported in Table 7-7 for each reach. Also reported are larger-scale dissolved solids budgets for the entire study area from Denver to Julesburg and from the Kersey, the point of highest dissolved solids loads in the river, to Julesburg. Every reach had a net influx of dissolved solids load meaning more salt left the reach than can be accounted for by the known inputs. On a load gain per unit length basis, the values for each reach do not exhibit a large amount of variability between reaches. The range is 8.5 metric tons per day per km for Reach 2 to 14.9 metric tons per day per km for Reach 1 with the overall mean residual loading to the river close to 11 metric tons per day per km of dissolved solids.

Table 7-7. Reach-by-reach dissolved solids load budget for the lower South Platte River, water years 1991–2004.

[mt, metric ton; km, kilometer; d, day; %, percent] all units in metric tons per day unless otherwise noted

	REACH 1	**REACH 2**	**REACH 3**	**REACH 4**	**REACH 5**	**REACH 6**	**LOWER BASIN 1**	**LOWER BASIN 2**
INPUTS (mt d^{-1})	**DENVER TO COMMERCE CITY**	**COMMERCE CITY TO HENDERSON**	**HENDERSON TO KERSEY**	**KERSEY TO WELDONA**	**WELDONA TO BALZAC**	**BALZAC TO JULESBURG**	**DENVER TO JULESBURG**	**KERSEY TO JULESBURG**
Load at Upstream Gage	263	161	528	1,756	1,326	1,301	263	1,756
Load in Tributary Inputs	*	116	920	*	*	*	1,037	*
Load in Point Source Inputs	12	197	14	*	*	*	222	*
TOTAL LOAD INPUTS	275	474	1,462	1,756	1,326	1,301	1,522	1,756
OUTPUTS (mt d^{-1})								
Load Lost to Diversions	224	92	561	1,163	745	953	3,739	2,861
Load at Downstream Gage	161	528	1,756	1,326	1,301	1,669	1,669	1,669
TOTAL LOAD OUTPUTS	385	620	2,318	2,489	2,046	2,622	5,407	4,530
RESIDUALS (mt d^{-1})								
Residual Load **	110	146	856	732	720	1,321	3,885	2,774
Fraction of Total Inputs (%)	29	24	37	29	35	50		
Reach Length (km)	7.4	17.2	88	66	50	135	364	251
Incremental Residual Load (mt d^{-1} km^{-1}) **	15	8	10	11	14	10	11	11

***** insignificant, ** positive values indicate reach is gaining residual dissolved solids***

Temporal patterns in residual dissolved solids loads are shown in Figure 7-7. Just as with residual flow, Reach 1 increases during the first half of the study period. Reach 2 has a slightly upward shift in the later years unlike flow which appeared to be decreasing during the same time. Reach 4 remains fairly consistent while Reaches 3, 5, and 6 decrease in the later portions of the study period.

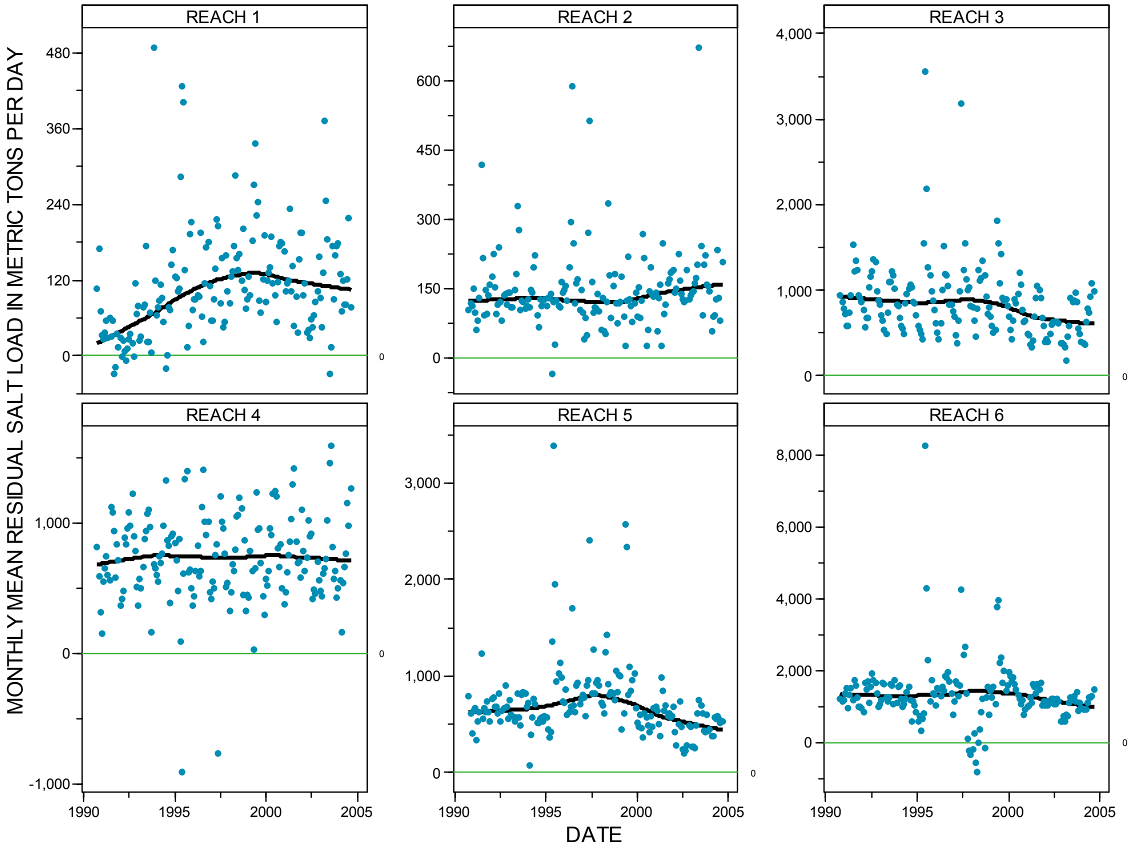


Figure 7-7. Temporal patterns in calculated residual dissolved solids load, water years 1991–2004.

Figure 7-8 shows on a reach-by-reach basis the relative composition of dissolved solids contributions from each of the measured and calculated sources. Compared to the relative composition of flow (Figure 7-4), residual salt load makes up a larger percentage of the total load contribution to each reach. Residual salt load comprises from 23% to 50% of the total salt load of a given reach. Figure 7-9 illustrates seasonal patterns in residual dissolved solids loads. As would be expected, seasonal patterns in residual loads are generally similar to seasonal patterns in residual flows as far as magnitude and changes in variability.

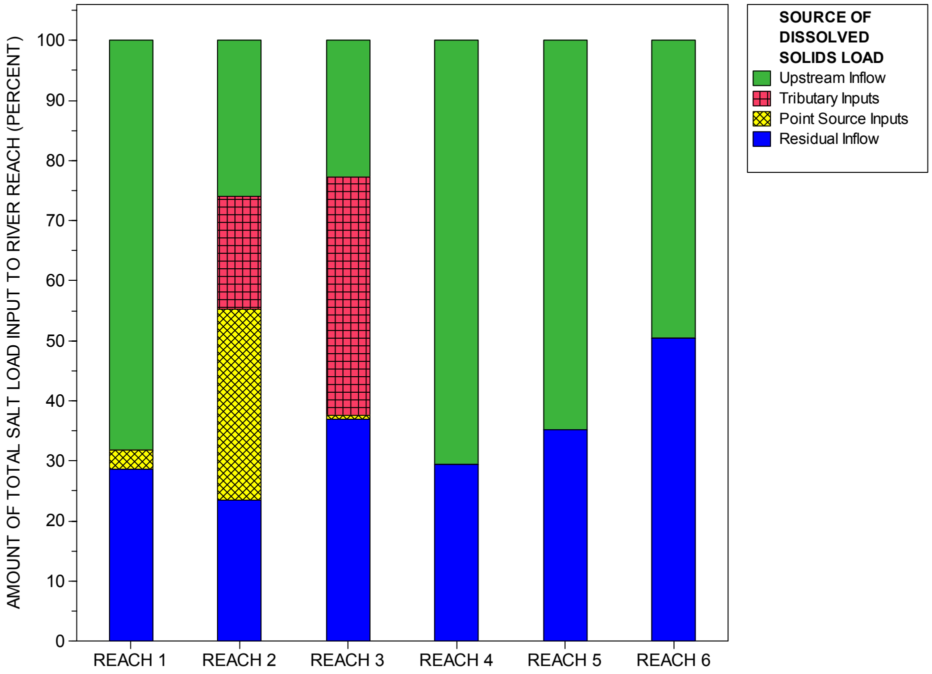


Figure 7-8. Relative contribution of dissolved solids sources, water years 1991–2004.

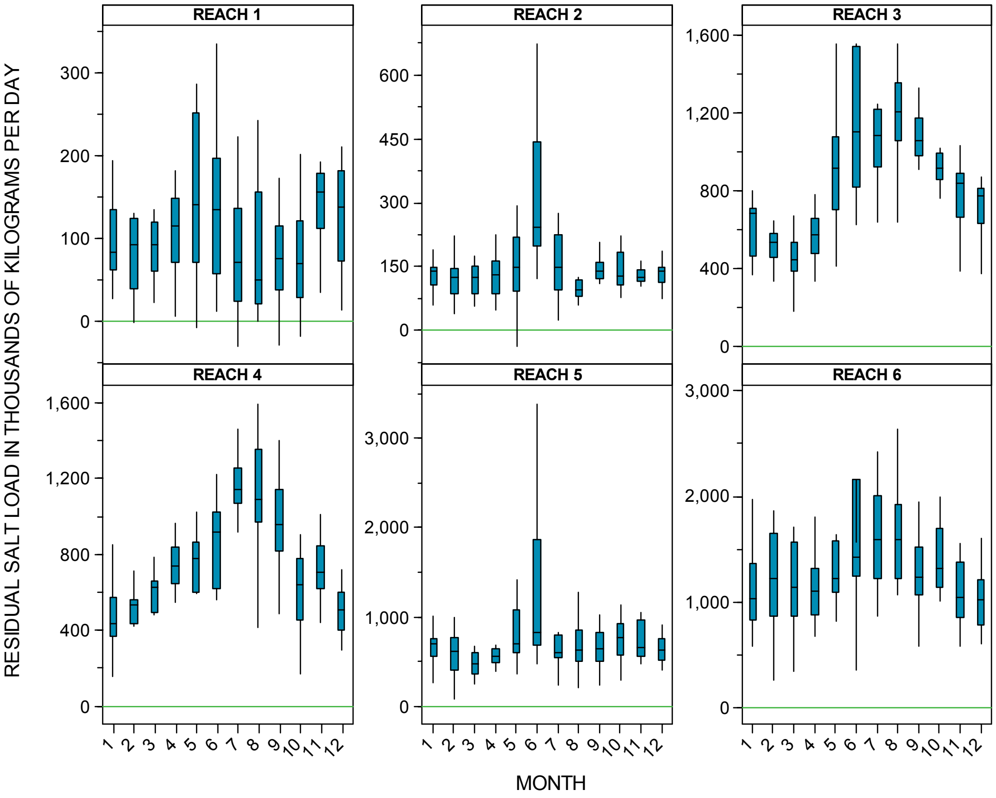


Figure 7-9. Seasonal patterns in residual dissolved solids loads, water years 1991–2004.

7.3.3 TDS Concentrations of Residual Flows

Calculated mean TDS concentrations of each component of the flow budget are shown in Table 7-8. These values were calculated by dividing the total salt mass of each budget component by the corresponding flow total. This results in a flow-weighted mean TDS concentration which is generally lower than an instantaneous TDS measurement due to the influence of high-flow periods. With the exception of Reach 1, the TDS concentrations of residuals appear to compare favorably with alluvial aquifer TDS concentrations (Figure 7-10).

Table 7-8. Flow-weighted TDS concentrations of various components of the dissolved solids budget.

[F.W., flow-weighted; TDS, total dissolved solids; (na), not applicable; mg, milligrams; l, liter] all units in milligrams per liter

	REACH 1	REACH 2	REACH 3	REACH 4	REACH 5	REACH 6	LOWER BASIN 1	LOWER BASIN 2
INPUTS (mg l^{-1})	DENVER TO COMMERCE CITY	COMMERCE CITY TO HENDERSON	HENDERSON TO KERSEY	KERSEY TO WELDONA	WELDONA TO BALZAC	BALZAC TO JULESBURG	DENVER TO JULESBURG	KERSEY TO JULESBURG
F.W Mean TDS at Upstream Gage	355	401	431	701	744	869	355	701
F.W. Mean TDS of Tributary Inputs	(na)	310	716	(na)	(na)	(na)	624	(na)
F.W. Mean TDS of Point Source Inputs	495	570	1,126	(na)	(na)	(na)	583	(na)
F.W. Mean TDS of All Inputs	359	422	579	701	744	869	547	701
OUTPUTS (mg l^{-1})								
F.W. Mean TDS of Diversions	557	529	667	946	1,112	1,336	928	1,095
F.W. Mean TDS of Downstream Gage	401	431	701	744	869	1,214	1,214	1,214
F.W. Mean TDS of All Outputs	479	443	692	827	944	1,256	1,000	1,136
RESIDUALS (mg l^{-1})								
F.W. Mean TDS of Residual Inflow	**2,900**	**500**	**1,000**	**1,400**	**1,900**	**2,200**	**1,500**	**1,900**

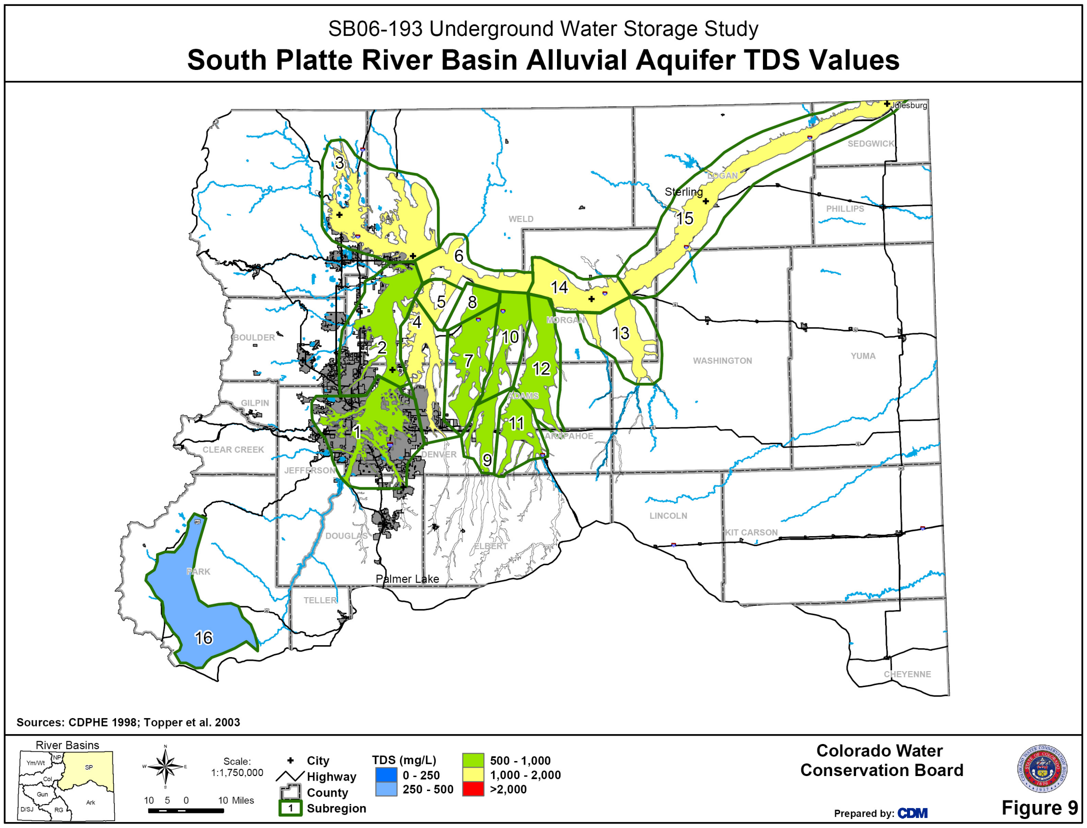


Figure 7-10. South Platte River Basin alluvial aquifer TDS values (Colorado Water Conservation Board, 2007).

Time series plots of mean flow-weighted TDS concentrations of residuals are shown in Figure 7-11. Reaches 2 and 4 appear to have increasing TDS concentrations in residual flow during the second half of the study period. Other reaches have indeterminate TDS patterns (Reach 1) or fairly constant TDS concentrations (Reaches 3, 5, and 6). The difference between the flow-weighted, mean TDS concentration of Reach 1 (Table 7-8) and typical alluvial aquifer TDS values (Figure 7-10) combined with the highly variable calculated TDS concentrations during the period of study suggest that the flow and dissolved solids budget for Reach 1 does not properly account for one or more significant sources of water and dissolved solids to the river not related to ground water return flow. Because they are not included as an input in the mass balance, the unknown source or sources are by default included in the residual term. Future refinement of the flow and dissolved solids mass balance should be conducted for this reach in order to identify additional sources of streamflow and dissolved solids.

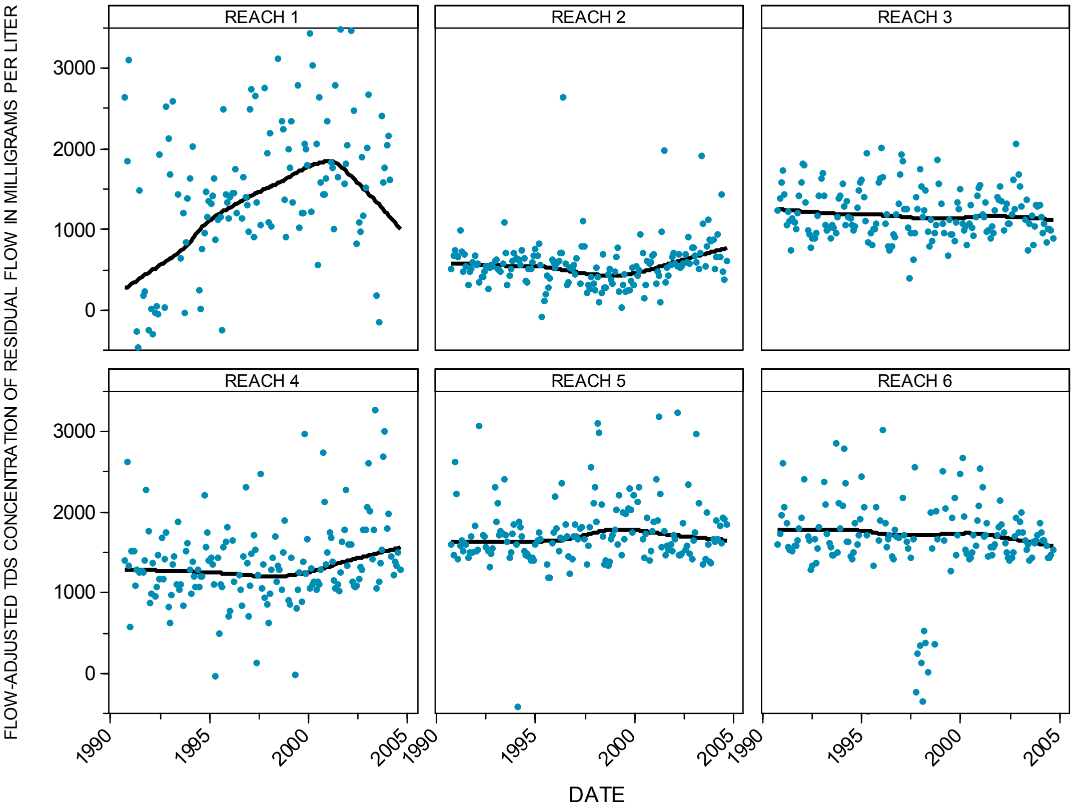


Figure 7-11. Temporal patterns in calculated TDS concentrations of residual flows, water years 1991–2004.

7.3.4 Salt Export Analysis

Recent and long-term cumulative dissolved solids loads at Kersey and Julesburg were compared to quantify the flux of dissolved solids into and out of the lower basin. The salt balance within the basin can serve as an indicator of the long-term sustainability of irrigation in the region. Figure 7-12 plots the cumulative dissolved solids load at Kersey and Julesburg for water years 1991 through 2004. During this period a relatively close balance was achieved. From water year 1998 through water year 2003, a net negative balance was observed meaning more salt mass was exported from the region than the amount of salt mass that had entered the region at Kersey.

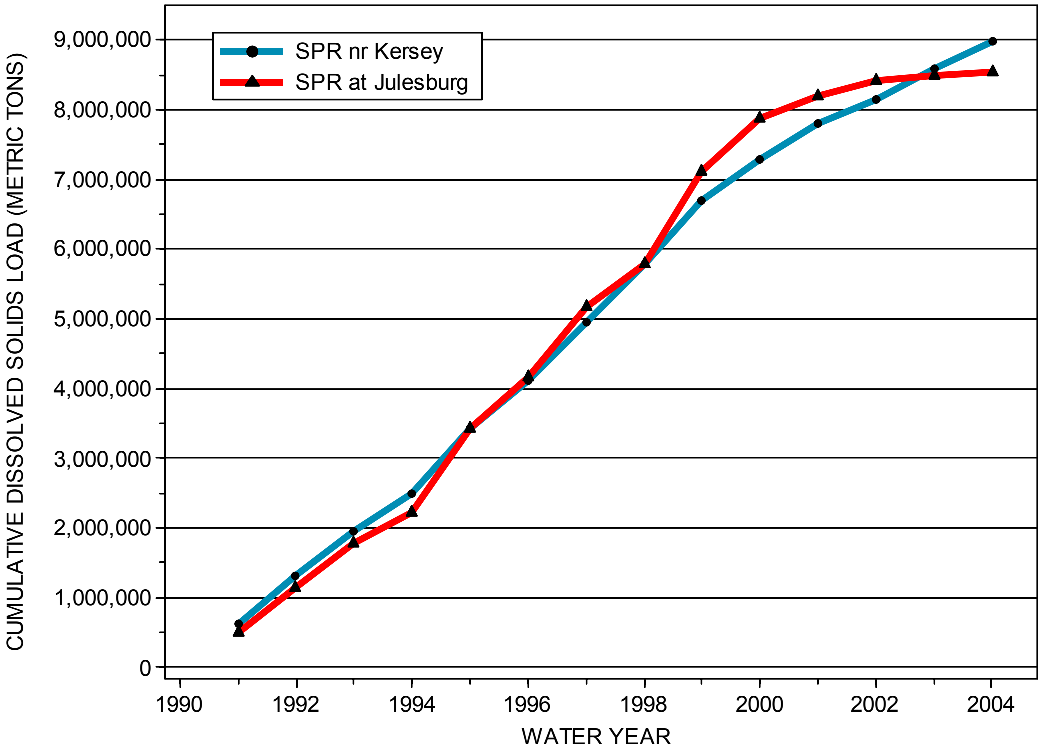


Figure 7-12. Cumulative dissolved solids loads at Kersey and Julesburg, water years 1991–2004.

Through analysis of the long-term period of water years 1951 through water year 2004 (Figure 7-13), it becomes clear that the salt balance has not been as positive. More salt mass has entered the region than been exported from it. It does appear that the salt balance status within the region became better during the 1980’s and has maintained that status until the last several years of the analysis.

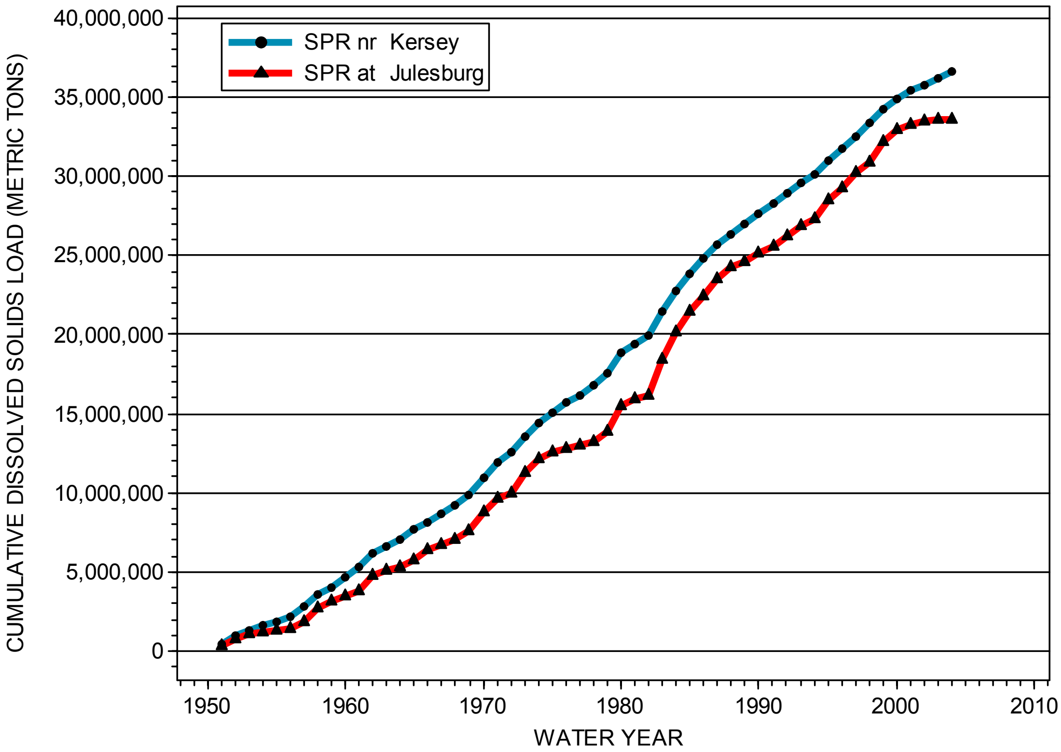


Figure 7-13. Cumulative dissolved solids loads at Kersey and Julesburg, water years 1951–2004.

Table 7-9 compares the overall salt balance between Kersey and Julesburg for the recent and long-term analysis period. For water years 1951 to 2004, an average of 149 metric tons of salts per day were retained in the region. If evenly distributed on the 93,000 hectares of irrigated land, the mean accumulation would be 0.59 metric tons per hectare per year or 32 metric tons per hectare during the study period. For the more recent period of water years 1991 to 2004, the retention rate was lower with a mean accumulation rate of 88 metric tons per day or 0.35 metric tons per hectare per year. On a yearly basis, the rate of net accumulation was found to be highly variable and inversely correlated with streamflow at Julesburg (i.e. high streamflow years result in more salt mass exported from the region).

Table 7-9. Recent and long-term estimates of salt retained in the irrigated area between Kersey and Julesburg.

[ha, hectare]

	Period of Analysis (water years)	
	1951 - 2004	1991 - 2004
Cumulative Load at Kersey (metric tons)	36,561,538	8,982,548
Cumulative Load at Julesburg (metric tons)	33,619,545	8,533,111
Cumulative Load Retained in Basin (metric tons)	2,941,993	449,437
Cumulative Load Retained in Basin (metric tons per day)	149	88
Irrigated Land Between Kersey and Julesburg (ha)	93,000	93,000
Salt Accumulation during Period of Analysis (metric tons per ha)	32	4.8
Annual Salt Accumulation (metric tons per ha per year)	0.59	0.35

7.4 CONCLUSIONS

This study updates and advances the body of knowledge regarding the occurrence, transport, and fate of dissolved solids in the lower South Platte River Basin through the development of a reach-based mass budget for water and dissolved solids. This mass budget tracks the measured gains and losses via streamflow, tributaries, point sources, and diversions on a monthly basis for key monitoring sites on the mainstem of the South Platte River from Denver to Julesburg. The residuals of this mass budget provide estimates of the water and dissolved solids movement to or from the river via groundwater.

Results indicate that in each of the six study segments the river gains both water and dissolved solids from ground water inflow on an annual basis. Residual flow contributes from 5 to 28 percent of the total flow depending on the reach. Some changes in residual flow values over time were observed for some reaches. Residual flows were also shown to vary seasonally to some degree. Calculated residual flow values compared favorably with previously published values in studies that used either mass balance techniques or intensive field-based measurement. This study is the first to present residual flow estimates for the entire mainstem from Denver to Julesburg in a single study. The fact that the residual flow values established in this study compare favorably to past studies indicates that these values provide a solid foundation for the development of a dissolved solids mass balance.

Results of the dissolved solids mass balance show the residual salt load to be fairly consistent between reaches. The average contribution for the region is 11 metric tons per day per km. Evidence of changes in the residual salt contribution over time in some reaches was seen in the time series plots; however formal trend analysis was beyond the scope of this work. Residual salt loading was shown to be a significant contributor to the total dissolved solids load in each reach. Depending on the reach, residual salt loads comprised between 23 to 50 percent of the total salt load. As with residual flow, residual loads exhibited some degree of seasonality. Calculated TDS concentrations of residual flows ranged from 500 mg/L to nearly 3000 mg/L and were found to compare favorably with measured ground water TDS concentrations. Calculated TDS concentrations showed evidence of time trends during the study period.

A recent and long-term analysis of the salt balance status of the lower South Platte River Basin was performed in order to quantify the flux of dissolved solids within and out of the basin and provide an indicator of the long-term sustainability of irrigated agriculture in the region. Dissolved solids loads in the river were generally highest in the upper study area at the Kersey, CO gaging site and slightly lower at the downstream gaging site at Julesburg. This indicates a net accumulation of dissolved solids on the irrigated lands between these two gaging sites.

For water years 1951 to 2004, the mean accumulation in the region was 0.59 metric tons per hectare per year. The more recent period of water years 1991 through 2004 had a lower mean accumulation rate of 0.35 metric tons per hectare per year. Although the rate of salt accumulation is lower than in the past, the salt balance status should continue to be monitored in the future to make sure the rate of salt accumulation in the region does not increase. Because salt accumulation is inversely correlated with streamflow at Julesburg, a reduction in streamflow at Julesburg could lead to even greater rates of salt accumulation in the region.

Overall, the results of this work demonstrate that a reach-based, mass-balance analysis is a functional method for the estimation of mass loading of water and salt via ground water in the absence of intensive field-based studies. This quantification of gains and losses of water and salt mass via ground water provides a critical component in the overall effort to create a process-based understanding of salinity behavior in the basin. Results of this work provide a basis for the development of a modeling system (described in the following chapter) which can be used for the evaluation of potential impacts to river salinity resulting from changes in water management, water use, and hydrologic regime.

CHAPTER 8: DEVELOPMENT AND DEMONSTRATION OF A DYNAMIC MASS BALANCE MODEL FOR EVALUATION OF FUTURE STREAMFLOW REGIMES AND DISSOLVED SOLIDS CONCENTRATIONS IN THE SOUTH PLATTE RIVER BASIN

8.1 INTRODUCTION

Increased competition for the limited water resources of the South Platte River Basin are causing changes in historical water uses and spurring the proposal and development of new water supply management schemes and structural projects. Many of these changes have the potential for reducing instream flows both through increased diversions and reduced return flows. A need exists for a user-friendly system that allows for the prediction of future downstream water quantity and quality conditions resulting from reduced upstream inflows.

Utilizing the flow and dissolved solids budget developed in the previous chapter, this chapter details the development and application of a modular decision-support system for prediction of streamflow, dissolved-solids concentrations, and dissolved-solids loads along a defined stream network. The resulting model uses simple conceptual and mass-balance concepts rather than process-based concepts in order to provide dynamic simulations of flow and water quality within a river system. The central hypothesis of this effort is that a dynamic system model can be developed to encapsulate historic flow and water-quality conditions, river gains and losses via tributaries and diversions, and mass-balance residuals in order to provide a user-friendly model for the prediction of impacts to downstream water quality resulting from modification of upstream flow and water quality.

8.1.1 Objectives

The primary objective of this work was to integrate the results of the previously completed lower South Platte River water and salt budget into a dynamic simulation and analysis tool that will allow the user to predict the downstream effects on water quantity and dissolved solids concentrations resulting from proposed changes in the hydrologic and salt loading regime in a highly-managed, over-appropriated river basin. The secondary objective of this work was to demonstrate the utility of the resulting simulation and analysis tool by using it to analyze the possible downstream impacts resulting from several approved or proposed water development projects.

8.1.2 Scope

Using the results of the lower South Platte River Basin water and salt budget developed previously, this chapter details the incorporation of the budgets into a dynamic simulation and analysis tool with the capability of exploring downstream water-quality impacts resulting from reductions in upstream flow. Effects of proposed water-diversion and reuse projects are simulated along the mainstem of the South Platte River from the Denver gauge to the Julesburg gauge on a monthly basis for a hypothetical 14-year period using historical flow and dissolved solids loading data for the period from October 1990 through September 2004 as baseline conditions.

8.1.3 Benefits

This work provides the ability to simulate the movement of water and salt in the lower South Platte River system within the framework of a dynamic decision-support system. In addition to providing a tool for the prediction of dissolved-solids concentrations at river gauging sites where salinity is not normally monitored, it provides a tool to help understand and manage water quantity and salinity issues on a basin-wide scale and could serve as an important tool in the assessment of the potential downstream impacts to flow and dissolved solids concentrations arising from upstream water-management activities.

A key requirement in collaborative planning and decision making is to have the ability to easily generate and evaluate various alternatives. This facilitates an increased understanding of the dynamic interactions within the system under evaluation. The ability to estimate downstream impacts to water quantity and quality resulting from multiple diversion and reuse projects provides an important tool for use in long-term planning and policy decisions as well as for the evaluation and permitting of projects. The ability to preview possible future water quantity and quality conditions in the lower South Platte River through the evaluation of a variety of possible scenarios provides an early warning tool that will allow for the development and evaluation of appropriate response and mitigation plans. The model design allows for relatively easy spatial or temporal expansion as well as incorporation of additional river network objects such as additional in-channel or off-channel reservoirs, additional diversions, and additional return flows.

8.1.4 Background

8.1.4.1 Basin Issues

The lower South Platte River Basin, like many basins in the West, is currently undergoing a transformation from a generally sparsely populated basin with primarily irrigated agricultural water use to a basin with a much higher population density and a competing mix of urban and rural water uses. Water rights and water-quantity issues have long been at the forefront of the debate between competing water interests, however changes in historical water use combined with pressure for more water exchange agreements, increasing reuse of water, and increased loss of water due to consumptive use are likely to add water-quality issues to the debate in years to come.

The primary force driving changes to historical water use in the lower South Platte River Basin is the ever-increasing Front Range population. Historically, when more water was needed in northeastern Colorado it was imported across the Continental Divide from the wetter Western Slope river basins through a series of transcontinental tunnels and reservoirs. Today, however, due to a combination of water supply limitations, legal challenges, and economic barriers, there is limited potential for additional supplementation of Front Range water supplies through increased transcontinental diversions. This situation is leading to increased competition for the already over-appropriated existing water supplies within the basin as well as providing additional incentive for increased water efficiency and water reuse.

Because the economic value of water is higher when used for municipal purposes than when used for irrigated agriculture, the increased competition for limited water supplies has led to increased transfer of agricultural water rights to municipal use. Not only does this have the effect of decreasing the number of irrigated acres, but it also has the potential to change the timing, location, volume, and quality of return flows to the stream.

In addition to acquiring larger volumes of water, cities are also turning to conservation and water reuse. Although generally thought of as a positive goal, water conservation can have the effect of reducing return flows to the stream. Increased water conservation can allow urban areas to grow larger without a subsequent increase in water supply. This has the effect of increasing the consumptive-use percentage and negatively impacting water quality of the return flows.

Colorado water law allows for water imported from other water basins to be used to extinction. The water supplies of many urban areas along the Front Range contain a significant fraction of imported water. Reuse is being pursued by most Front Range urban areas that own reusable supplies. Some of these plans involve direct reuse via downstream recapture and treatment while others use indirect reuse through water exchanges. Water reuse helps to reduce or postpone the demand for new water supplies. Just as with increased water conservation, water reuse will likely lead to reduced return flows to the river. Previously, these return flows were used by downstream agricultural users; however, agricultural shortages are expected to increase as conservation and reuse by municipal users increases (CDM, 2004). Reduced volumes of return flows and multiple use of water by municipalities will likely result in diminished water quality as well.

Urban areas are not the only forces leading to reduced flow in the lower South Platte River. There are a variety of infrastructure and management issues which are also likely to reduce or change the timing of flows. The shift from surface irrigation methods to sprinkler irrigation and lining of irrigation ditches reduces deep percolation to the aquifer and subsequent return flows to the river. The diversion of available river water to lined and unlined gravel pits for water storage and aquifer recharge directly impacts river flow and timing and can also increase evaporation losses. The increased number of aquifer-recharge projects used for well augmentation and environmental flows for endangered species will cause a shift in the timing of return flows. Changes in the volume of water available and in the timing of flows may cause normal agricultural water rights calls on the river to become more senior; thus causing an increase in the number of junior water rights that are our of priority (CDM, 2004).

The work presented in previous chapters has documented that the majority of the dissolved-solids load entering the South Platte River does so on the Front Range segments of the river from Denver to Kersey. Although the river carries a large dissolved-solids load, dissolved-solids concentrations are not excessively high due to the large volume of water present in the river between Denver and Kersey. Downstream from Kersey, dissolved-solids concentrations begin to rise as a result of consumptive use of the water which causes a subsequent concentration of the existing dissolved solids.

Many of the current and proposed changes in water use and river management discussed above are likely to result in lower instream flows and less return flow to the river. The loss of streamflow in the river, especially the loss of low salinity upstream contributions, has the potential to cause an increase in downstream salinity if the sources and contributions of dissolved-solids load remain relatively constant. The magnitude of the likely increase in downstream salinity is unknown and has not been previously considered in published reports.

8.1.4.2 Previous South Platte River Basin Modeling Efforts

The need for innovative modeling tools and decision-support systems (DSS) to aid in the understanding and evaluation of the South Platte River system is well recognized. Kunhardt and Fontane (1995) noted that partial solutions to competing water resources-demands in the South Platte River Basin might lie in better coordination of reservoir operations, additional conjunctive-use development, and innovative water-trading schemes; all of which could be developed and evaluated with the aid of a basin-wide DSS. The Statewide Water Supply Initiative Report (CDM, 2004) laments the lack of availability of a DSS to analyze all of the potential interactions and implications resulting from additional municipal and industrial development of conditional storage rights and the resulting reduction in return flows. The many interacting and competing hydrologic processes in the basin, in conjunction with the degree of water regulation and control, have been a major impediment in the development of a basin-wide DSS. Raymond *et al.* (1996) state that even though the South Platte River Basin has a smaller geographic area than the Colorado River Basin, modeling the South Platte River Basin will be more complex because of the amount of groundwater use and the competition for water which causes demand to often exceed supply.

In the past, most of the South Platte River Basin modeling efforts have focused primarily on water quantity and water rights. One of the earliest attempts at a basin-wide hydrologic model was the *Stream Aquifer Model for management by Simulation and OptimizatioN* (SAMSON) model (Morel-Seytoux and Restrepo, 1987) developed in the 1980s specifically for the South Platte River Basin. Designed as a tool to help deal with the complexity of the interactions between hydrologic components of the South Platte system, SAMSON was intended to be a tool for daily operations management as well as long-term strategic planning and optimization. SAMSON attempted to simulate the entire stream-aquifer system including reservoirs, ground-water return flow, evapotranspiration, and consumptive use. It did not include any water-quality modeling components. Although deemed successful in its objectives, it never achieved widespread use due to its complexity, changes in modeling philosophy, and development on what is now an obsolete and unavailable computing platform (Raymond *et al.*, 1996).

Previous salinity characterization efforts by Lord (1997) in conjunction with the work of Hendricks and associates (Gomez-Ferrer *et al.*, 1983; Gomez-Ferrer and Hendricks, 1983; Turner and Hendricks, 1983) provided a fundamental basis for the understanding of historical salinity conditions and dissolved solids flux in the basin. Both of these studies recognized the need to incorporate the fundamental groundwork into a basin-scale flow and salinity model; however that task was left for future researchers.

Paschal and Mueller (1991) calibrated the U.S. Environmental Protection Agency's (EPA's) QUAL2E model (Brown and Barnwell, 1987) for a short section of the South Platte River from Chatfield Reservoir through Denver in order to model the effects of wastewater effluent on selected water-quality constituents during steady-state, simulated low-streamflow conditions in 1989 as well as projected river and effluent volumes and constituent concentrations in 2010. The location and small geographic size of the modeled areas, lack of inclusion of non-point sources, and the fact that measures of salinity were used in the calibration of the model but not included in predictions of water quality during low-flow conditions limit the contribution of this effort to the overall understanding of salinity in the basin.

Chiang and Gates (2004) used a combination of empirical and physically-based stochastic modeling techniques to predict distributions of possible constituent concentrations in agricultural diversions resulting from various upstream pollution control strategies that could be implemented along the South Platte River. The study simulated water-quality conditions for a 190-km segment of the South Platte River that extends from Chatfield Reservoir to Weldona. Results suggested that some improvements in downstream irrigation water quality could be achieved through a combination of pollution control measures including reducing nonpoint source loadings and increasing the level of wastewater treatment. Increasing upstream reservoir releases was predicted to result in the least impact on downstream water quality. The authors caution that the moderate to high level of uncertainty associated with the model predictions should be taken into account in the evaluation of the predicted impacts of the pollution control strategies. They also state the need for additional data on nonpoint source constituent loading along the river.

An integrated surface and ground-water hydrology and water-rights analysis system is currently under development under the direction of the Colorado Water Conservation Board and the Colorado Division of Water Resources. Encompassing the South Platte and North Platte River Basins within the borders of Colorado, the South Platte Decision Support System (SPDSS) will consist of data sets that characterize the hydrologic and hydrogeologic features of the basin and will also include analysis tools that provide enhanced water administration and water-resource planning capabilities but will not include any water-quality components. Envisioned to be both a planning analysis tool as well as a water-rights administration system, the overall purpose of the SPDSS is to provide a system for accessing and organizing a wide range of basin information along with a framework for using the basin information for making decisions about the management, development, and preservation of water resources of the South Platte River Basin. This is expected to help develop optimal responses to the many water-resource issues in the basin, including population increases, changing water uses, competing demands and droughts (Colorado Water Conservation Board and Colorado

Division of Water Resources, 2001). There is clearly a need for an integrated water-resource information and analysis system such as the SPDSS; however, no provision has been made to integrate water-quality analyses into the system so that water-quality issues and impacts can be evaluated as part of the management and planning functionality provided by the SPDSS.

Past modeling projects have advanced the state of knowledge regarding water-quality and water-resource issues in the basin; however there is a clear need for new, coupled modeling systems that provide the ability to simultaneously evaluate streamflow and water-quality issues related to current and future water-resource development scenarios.

8.1.4.3 System Dynamics Modeling

System dynamics is an approach to evaluating the interrelationships of components and activities within complex systems and how they change over time. Initially developed through the work on industrial dynamics by Forrester (1961), this approach is built around the concept of stocks and flows. It uses information feedback and mutual or recursive causality to capture the dynamics of complex physical, biological, social, and other systems that have cause and effect separated by time and space (Sehlke and Jacobson, 2005). Systems models can help provide an understanding of the underlying mechanisms dictating how a system works and can also be used to predict future performance or conditions of a system (Deaton and Winebrake, 1999).

System dynamics modeling typically employs a visual modeling approach in which system components and linkages between system components are represented. Governing equations control the flow between components. A system dynamics approach is helpful for learning about interactions between system elements and to provide information for decision-making and is often the methodology employed in the development of decision support systems (DSS). Emphasis is placed on creating user-friendly assessment tools that are accessible to the typical user and allow for easy modification of input values and operational constraints to allow the user to conduct multi-scenario, multi-attribute comparisons of alternative management strategies. The ability to explore management scenarios in a simulation environment allows the user to better understand the complexity, dynamics, and constraints of a system and can help guide decision makers toward optimal policy decisions (Ford, 1999).

8.1.4.4 System Dynamics Modeling of Hydrological Systems

The benefits of a system-dynamics modeling approach make it an ideal tool for the evaluation of complex hydrological systems. In addition to the possibility of being used as the basis for traditional hydrologic surface-water or ground-water models, system-dynamics models are ideal platforms for the evaluation of trends and cause-effect relationships in large-scale hydrological systems. They are also ideal tools for integration of disparate data, for incorporation and analysis of output from traditional models, and for the integration of interdisciplinary data, management practices, and operational constraints in order to support better management decisions (Sehlke and Jacobson, 2005).

Although there are many publications detailing the application of a system dynamics approach to hydrological systems, most of the reports focus on simulating the quantity of flow in reservoir and river systems. However, the same attributes that make a system dynamics approach well suited to the simulation of water flow also make this approach ideal for the simulation of water quality throughout a system. The dynamic complexity of both water quantity and quality processes in the lower South Platte River Basin provides an ideal system for the application of system dynamics modeling in the development of a basin DSS to help guide future water supply and water-quality management decisions.

8.2 METHODOLOGY

8.2.1 Modeling Approach

The model uses mass-balance techniques to track the flow of water and dissolved-solids loads into and out of a defined stream network on a reach-by-reach basis. Historical streamflow and salinity conditions are used as a baseline condition for comparison against user-defined alternative scenarios. The model utilizes the results of the flow and dissolved solids residuals developed in Chapter 7 in order to evaluate deviations from baseline conditions with regard to monthly streamflow, dissolved-solids loads, and dissolved solids concentrations along the mainstem of the South Platte River in response to a variety of simulated changes to the historical baseline conditions. Cumulative effects from multiple projects resulting in changes to the historic flow regime can be simulated in order to provide a more realistic analysis of proposed projects compared to the evaluation of impacts from each project in isolation. The systems-analysis approach inherent in this methodology provides for the possibility of feedback loops so that limits on downstream impacts can trigger regulation of upstream processes causing those impacts.

8.2.2 Model Development

8.2.2.1 Modeling Platform

The DSS was created using the commercially-available dynamic-systems modeling environment STELLA version 9.0 (ISEE Systems, Inc., Lebanon, NH). This development environment provides a visual model building interface for the creation and linkage of objects or nodes. Logic statements provide rules for flows between the nodes via the linkages. Flows between objects are automatically translated into a set of sequential finite difference equations. A graphical user interface (GUI) development tool allows for the creation of a user-friendly interface containing provisions for data input, simulation control devices, and graphical and tabular model output. A consistent, modular design with model objects and logic replicated for each river reach allows for future expansion of the model to additional portions of the river, addition of reach modules within the current study area to increase spatial resolution of the simulation, and for use of this modeling approach on other river systems.

8.2.2.2 Data Sources

The model uses the historical and calculated lower South Platte River data for streamflow, TDS concentrations, and dissolved solids loads that were compiled and processed as described in Chapters 3 through 6. Additional data on diversions outflow and point-source inflows were compiled and processed as part of the development of the streamflow and dissolved-solids budget analysis described in Chapter 7.

8.2.2.3 Time Step

The model was configured to operate on a monthly time step, however it was designed to be easily modified to operate on a daily time step should that level of temporal resolution be desired.

8.2.2.4 Baseline Scenario

A baseline scenario was established using historical monthly flow and dissolved-solids loads for water year 1991 through water year 2004 (October 1990 through September 2004). As described in Chapter 3, this period was chosen based on the availability of historical flow monitoring data for the major gauging sites on the mainstem South Platte River and at the mouths of the major tributaries.

In order to gauge the potential impact resulting from proposed water-resource projects, model-predicted outputs under alternative scenarios are compared to the values of the historical baseline scenario. In other words, this approach evaluates what the impact on the river would have been if the alternate scenario had been in place at this time. Although this method superimposes future river scenarios on historical river conditions, the utilization of a historical baseline scenario eliminates the uncertainty associated with creating future time series for each model variable. This methodology provides an easy way to assess potential impacts through the comparison to baseline conditions.

8.2.2.5 River Reach Modeling Units

The study area consists of the same region and six river reaches used in the mass-balance analysis reported in Section 7.2.1. Figure 8-1 illustrates a conceptual river reach as implemented in the model. Unlike the conceptual river reach shown in Chapter 7 (Figure 7-2) in which the objective was to quantify the flow and dissolved solids residuals as an indicator of groundwater return flows, the conceptual river reach now includes the flow and dissolved solids residuals as known quantities. With all inputs and outputs known for the historical baseline scenario, the model is used to subject the system to deviations from the baseline scenario and then track the changes to inputs and outputs on a reach-by-reach basis as they occur along the river system. All inputs and outputs contain both a flow and dissolved-solids mass component which are tracked simultaneously within the model. Each of the input and output components are discussed in further detail in the following sections.

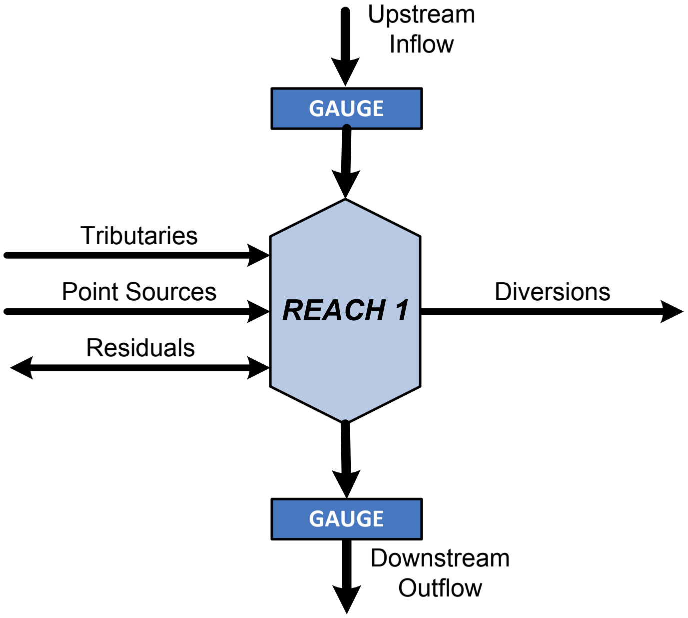


Figure 8-1. Conceptual river reach showing inflows and outflows tracked within the model.

8.2.2.6 Upstream Inflow

Upstream inflows into Reach 1 consist of monthly historical baseline flow and load values as measured at the Denver gauge plus any user-defined modifications to the historical baseline values to reflect a particular scenario. Subsequent reaches receive the computed outflows from the upstream reach. Under the baseline scenario, the inflow values to each reach will match the historical values. If upstream conditions are modified by the user as part of an alternative scenario evaluation, the inflow values to each reach will deviate from baseline conditions in response to the changes.

8.2.2.7 Tributaries

Major tributaries of the South Platte River join the mainstem in Reaches 2 and 3 (Table 7-3). The model adds the historical tributary flow and load time series compiled in Chapter 7 to the respective reaches on a monthly basis. In addition, the model provides the user the ability to increase or decrease the historical tributary mass loadings for each reach on a percentage basis in order to simulate scenarios which might impact the flow and/or load contributions from tributaries.

8.2.2.8 Point Sources

Major point sources (> 7500 m^3 d^{-1}) contribute to the South Platte River in Reaches 2 and 3 (Table 7-3). As with tributaries, the model utilizes the historical point source flow and load time series developed in the previous chapter. Tools are provided to allow modification of the mass loadings to any of the reaches. Unlike the modification capability for tributaries which is based on percentages, modifications to point source contributions for alternative scenario evaluation are based on absolute values of flow (m^3) and load (kg). This difference allows for the simulation of new point source contributions in reaches that historically did not have major point source contributions.

8.2.2.9 Diversions

Historical diversion records compiled in Chapter 7 were used to represent the volume of water lost via diversions under the historical baseline scenario. Diversion volume under alternate scenarios is assumed to remain unchanged from historical baseline conditions unless specifically modified by the user for analysis of a particular scenario or if an alternate scenario causes the total inflow volume to be less than the historical diversion volume for a given month. In the later case, diversion volume is reduced to match inflow volume so that the mass balance is maintained.

The mass of dissolved solids leaving a reach via diversions is determined within the model by first calculating the flow-weighted, monthly dissolved-solids concentration within the reach according to the following expression:

$$C_{\text{Reach}} = \frac{(L_{\text{Upstream Inflow}} + L_{\text{Tributaries}} + L_{\text{Residuals}} + L_{\text{Point Sources}})}{(Q_{\text{Upstream Inflow}} + Q_{\text{Tributaries}} + Q_{\text{Residuals}} + Q_{\text{Point Sources}})} \qquad \textbf{(8-1)}$$

Where:
C = Flow-Weighted Monthly Dissolved-solids concentration
L = Dissolved-solids load
Q = Flow Volume

The dissolved-solids concentration of the water lost via diversions is then assumed to be equal to the flow-weighted monthly dissolved-solids concentration of the entire reach:

$$C_{\mathrm{Diversion}} = C_{\mathrm{Reach}} \tag{8-2}$$

The mass of dissolved solids lost from the reach via diversions is then calculated as the product of the diversion volume and the calculated diversion concentration:

$$L_{\mathrm{Diversion}} = Q_{\mathrm{Diversion}} \times C_{\mathrm{Diversion}} \tag{8-3}$$

This method for determination of the salt load lost via diversions is slightly different than the method used for the mass budget analysis presented in the Chapter 7. That method assumed the total dissolved-solids concentration of diversion outflow was equal to the mean of the total dissolved-solids concentrations at the upstream and downstream gauges. That method could not be used in the model because water quality at the downstream gauge is being predicted by the model. Figure 8-2 compares the method used in the previous chapter (Method 1) to the method used by the model (Method 2) under the historical baseline scenario. The methods are generally comparable in both central tendencies and ranges. Method 2 results in slightly higher values; however, that is expected given that dissolved-solids concentrations generally increase in a downstream direction. Method 1 provides diversion concentrations between the upstream and downstream gauge concentrations; whereas, Method 2 used in this model results in diversion concentrations equal to the downstream gauge concentration.

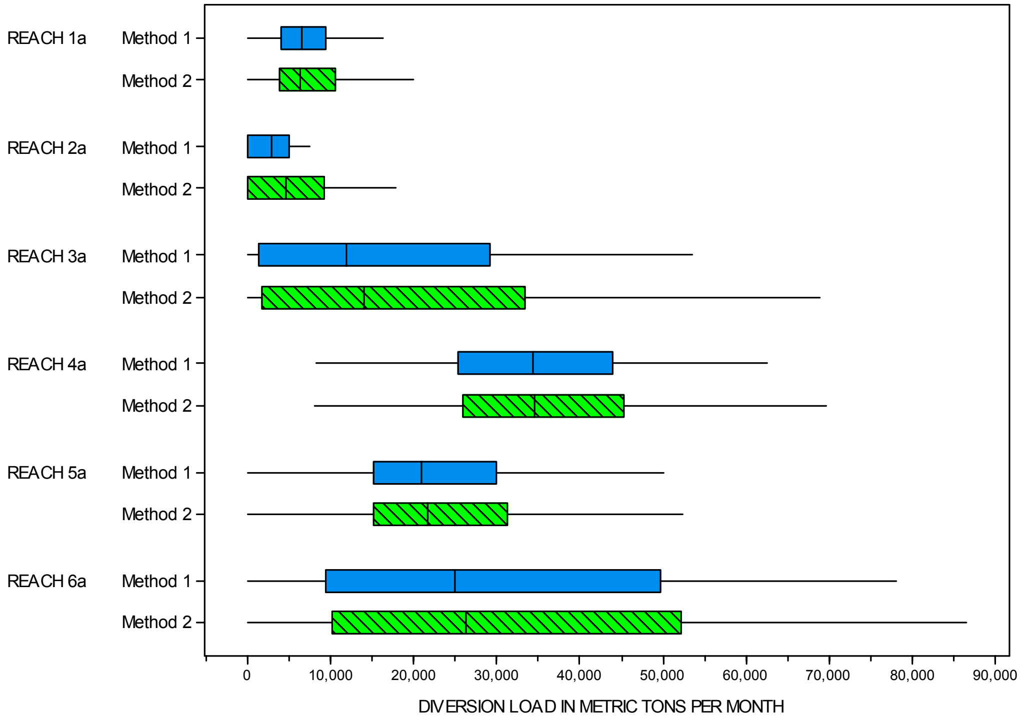


Figure 8-2. Comparison of methods for prediction of dissolved-solids load in diversion outflows.

8.2.2.10 Mass Balance Residuals

Flow residuals calculated in Chapter 7 are used in the model to represent groundwater inflows and outflows plus any other ungauged inflows or outflows and the mass balance error term. Load residuals were recalculated for the model using the revised method (Method 2) for calculating dissolved-solids loads lost to diversions. The revised load residuals are used in the model to represent dissolved-solids load inflow and outflow via groundwater.

8.2.2.11 Adjustments to Residuals

Much of the residual flows and loads contributing to the river are subsurface irrigation return flows resulting from upstream irrigation diversions. The residual flow and load are calculated based on the historical baseline conditions, therefore adjustments to the residuals are required for alternate scenarios that result in a change in the water volume and mass of dissolved solids lost via diversions. An example of this situation occurs under scenarios that result in increased dissolved-solids concentrations in a reach. Assuming diversion volumes remain the same as historical baseline values, higher dissolved-solids concentrations in the reach result in larger dissolved-solids loads lost via diversions. The adjustment to residuals is performed in an attempt to maintain mass balance and adequately capture the system response resulting from deviations from the historical baseline scenario.

Adjustments to the residuals are made by comparing the diversion flow and load under the current alternate scenario to the diversion flow and load under the historical baseline scenario. The difference between these sets of values is added back into the system at the next downstream reach during the next time step. An illustration of the adjustment process for residual loads is shown in Figure 8-3. The same process is used for adjustment of residual flow for alternate scenarios in which diversion volumes differ from historical baseline values.

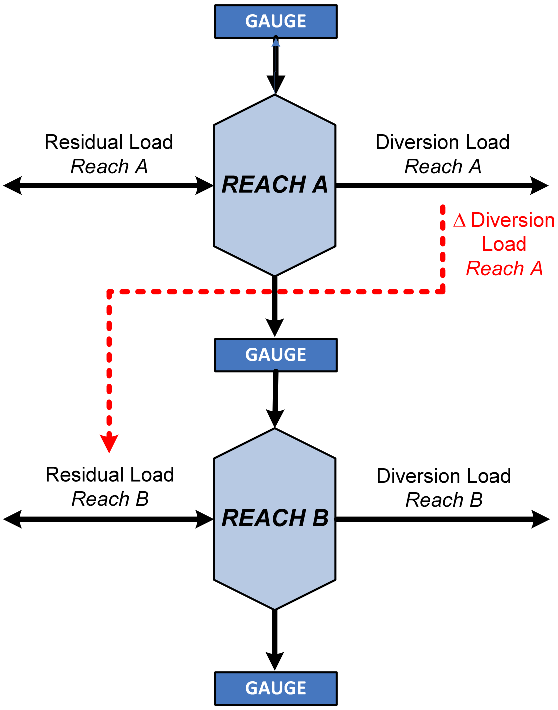


Figure 8-3. Illustration of adjustment to residual load values under alternate scenarios to account for deviations from historical baseline diversion loads.

Because it is likely that not all of the difference in diversion flow and load under alternate scenarios will impact the downstream residuals, the model interface has provisions to allow the user to specify the percentage of the difference of flow and load that returns as residuals downstream. Examples of processes that could impact the percentage of flow and salt load returning to the river would be consumptive use of diversion flow and precipitation of salts present in the diversion water into less soluble forms that remain in the soil after the water has been used for irrigation.

8.2.2.12 Downstream Outflow

After subtracting the water volume and salt mass of the agricultural diversions from the reach subtotals, the remaining water volume and salt mass is passed downstream and becomes the input to the next reach. Because the reaches were defined based on the location of stream gauging sites, a gauging site exists between each of the reaches. As the remaining water volume and salt mass is passed from one reach to the next, the water volume, salt mass, and concentration are reported by the model for comparison with historical baseline values at the respective gauges.

8.2.2.13 Assumptions

As with most models that attempt to simulate physical systems, a number of simplifying assumptions were made during the development of this model in order to create a decision-analysis tool that provides a reasonable representation of potential future river conditions without the need for an overwhelming array of input variables. The following is a list of the major assumptions inherent in this model:

- Unless specifically modified by the user or predicted by the model, all other hydrologic and water-quality conditions and management operations that comprise the historical baseline scenario remain fixed and are unaffected during evaluation of alternate scenarios. This includes the assumption that agricultural ditch diversions will remain the same as in the baseline scenario. In reality, the reduced flow conditions under alternate scenarios would likely result in reduction and redistribution of agricultural diversions depending on water-right seniority.

- Within the internal calculations for each reach, instantaneous and complete mixing of all water and salt is assumed.

- All of the components of the dissolved solids are assumed to be conservative within the river.

- The calculated flow and dissolved-solids residuals primarily represent the inflow of water and dissolved solids to the river via groundwater; however they could also represent overland return flows, ungauged tributary or canal inflows, and measurement errors.

- During evaluation of alternate scenarios, long-term averages are assumed to have reestablished themselves to the new conditions at the beginning of the simulation period.

- Changes in the amount of dissolved-solids load diverted in a given segment under alternate scenarios are assumed to be reflected in residual inputs of the downstream reach during the next time step. Depending on how and where the diversion water is used, these changes could take months or years to be reflected in return flows to the river and the impacts might be observed in multiple reaches.

8.2.3 Scenario Analysis

In order to illustrate the utility and flexibility of the model in the predictions of future downstream water flow and quality conditions, the model was used to evaluate impacts resulting from several water resource projects in the middle portion of the basin that are either in the proposal or development stages. These projects have the potential to reduce flow in the river through direct withdrawals, indirect withdrawals, or a reduction of return flows. Three scenarios are presented: the first of these scenarios, or case studies, models the impact of the River resulting from two large metropolitan water recapture and reuse projects that are currently being implemented (Case 1). The second case study simulates the impact to the river from an additional diversion of previously unclaimed flow for a proposed reservoir near Greeley (Case 2). After separate examination of these case studies, the combined downstream effects are evaluated (Case 3). These case studies are presented as examples of how the model can be applied. The flexibility inherent in the design of the model will easily allow for the development and evaluation of other scenarios as desired by the user.

8.2.3.1 Case 1: Urban Water Recapture and Reuse

As discussed above, the recapture and reuse of transbasin water by municipalities is becoming more common as cities strive to maximize their limited water supplies. Two of the largest recapture and reuse projects planned for the South Platte River Basin are currently being implemented by Denver Water and the City of Aurora. Although the water will be transported to other locations within the urban areas, these will both impact the river within Reach 2 (Figure 8-4). Both projects will be evaluated together as Case 1 in order to investigate potential impacts from large water recapture and reuse projects such as these.

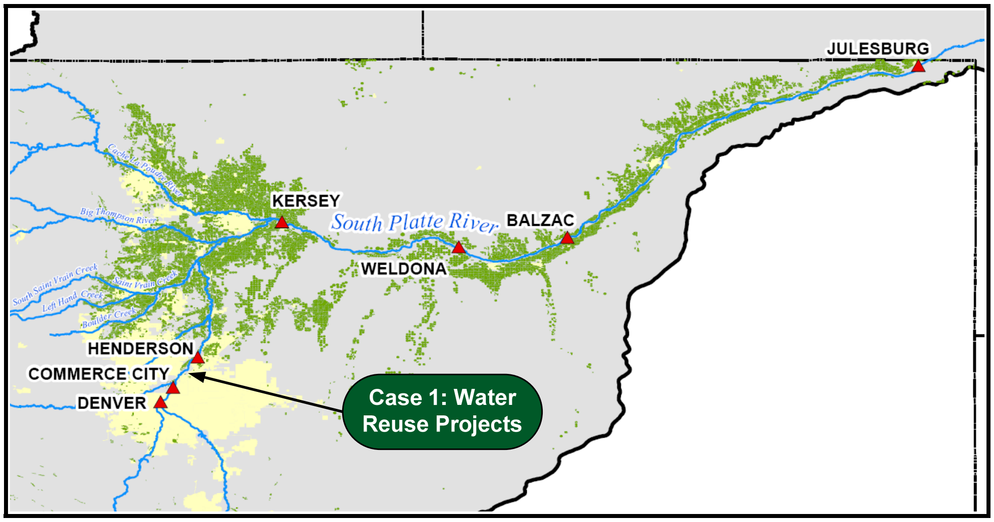


Figure 8-4. Location of potential streamflow reduction resulting from water projects simulated under Case 1.

Denver Water's Recycling Project takes secondary treated wastewater from the Denver Metropolitan Reclamation District (Denver Metro) wastewater treatment plant (WWTP) and performs a further treatment for use in lieu of potable water for turf irrigation, cooling water, industrial process water, and use at the Denver Zoo. Phase 1 of this project has been in operation since 2004. When developed to full capacity (Phase 3) in the year 2017, the project will recycle 17,000 acre-feet (21 million m^3) of potable water a year and will be the largest potable water recycling project in the state (Denver Water, 2002).

The Denver Water Recycling Project was incorporated into the model as a user-selectable option that reduces the monthly discharge of treated wastewater from Denver Metro's WWTP to Reach 2 of the river. Records for monthly volumes of water diverted from the Denver Metro WWTP to the Denver Water Recycling Project treatment plant during the operation of Phase 1 were obtained from Denver Metro (Nealey, 2008) for the period 2004 – 2007. During this time period, the project intercepted a mean annual volume of 6,000 ac-ft (7.4 million m^3) from Denver Metro WWTP discharge to the river. Using the monthly historical data, a monthly distribution of annual volume was calculated. This monthly distribution was applied to the planned Phase 3 project volume of 17,000 ac-ft (21 million m^3) per year to obtain the estimated monthly flow reduction when the full project capacity is implemented (Figure 8-5).

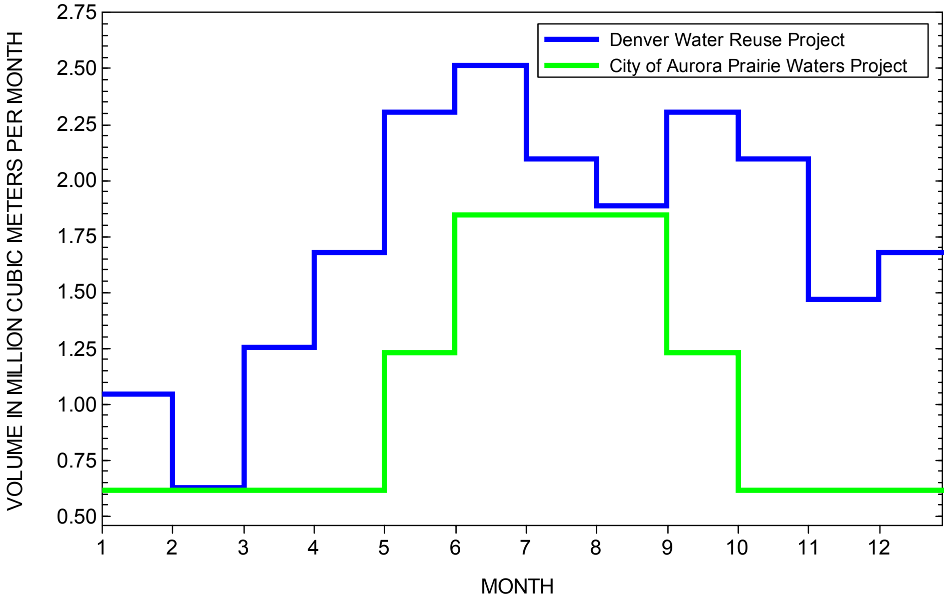


Figure 8-5. Projected monthly streamflow reduction resulting from water reuse projects under Case 1.

The second urban recapture and reuse project modeled as part of Case 1 is the City of Aurora's Prairie Waters Project (PWP). The PWP will allow the City of Aurora to recapture some of the city's reusable return flow from the South Platte River for use as a supplemental source to the city's potable water supply. Recapture takes place via a series of alluvial wells located along the riverbank just north of Brighton, Colorado and downstream from Denver Metro's WWTP discharge. The use of alluvial wells allows for riverbank filtration of the river water captured by the wells. This is followed by an aquifer storage and recovery process for reduction of nutrients and organic contaminants followed by a variety of physical and chemical treatments at a water purification facility. The resulting water is then added to the existing potable water supply system.

Expected monthly or seasonal withdrawal volumes from the alluvial wells along the river were not available at the time of this evaluation; however, a consultant involved with the project (Ingvoldstad, 2008) stated the project is expected to take 10,000 ac-ft (12.3 million m^3) from the alluvial wells per year and that the withdrawal rate would likely be higher in the summer. Because further details were not available, a hypothetical monthly usage distribution (Figure 8-5) was created to match the annual value. This assumed distribution has three times the amount of water being withdrawn in the summer than in the winter to reflect the traditional seasonal pattern of higher water usage by municipalities during the summer due in large part to landscape irrigation.

Figure 8-6 presents a time series plot of the combined streamflow reduction expected under Case 1 and compares the volume lost from the river to the streamflow at the nearest downstream gauging site before implementation of Case 1. For both projects simulated under Case 1, it is assumed that the anticipated project capacity is equivalent to the net amount of streamflow reduction in the river. This means that within the model, no fraction of the project water returns to the river. This is a plausible assumption because the water is legally usable to extinction, so even when used for turf irrigation, the non-consumed portion returning to the river as subsurface flow will be claimed by the owner using flow accounting techniques. In the case of the Prairie Waters Project, it is further assumed that the volume of water collected in the alluvial wells will result in an equivalent volume reduction in the river.

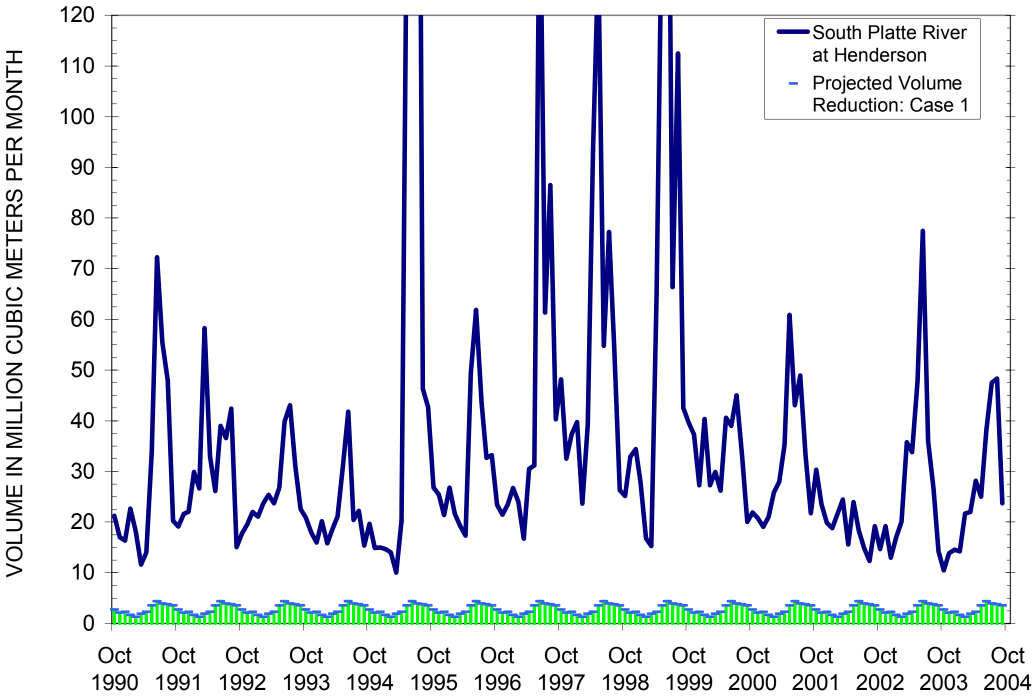


Figure 8-6. Streamflow reduction under Case 1 compared to historical baseline streamflow at Henderson.

8.2.3.2 Case 2: Additional Water Diversion near Kersey

The Northern Colorado Water Conservancy District (NCWCD or Northern Water) has proposed the Northern Integrated Supply Project (NISP) as a means for participating Front Range municipalities and water districts to increase their water supplies with an anticipated 40,000 acre-feet of new water yield. The project would utilize existing NCWCD water rights on the Cache la Poudre River combined with water exchange agreements on existing Poudre River irrigation diversions to supply the proposed Glade Reservoir, a 170,000 acre-feet off-channel reservoir north of Fort Collins, Colorado. In order to provide replacement water for the Cache la Poudre River diversion exchanges, a new river diversion and reservoir are proposed for the South Platte River near Greeley, Colorado (Figure 8-7). Termed the South Platte Water Conservation Project (SPWCP), this project would provide water to the lower segments of the Larimer-

Weld and New Cache irrigation canals to replace the water exchanged upstream into Glade Reservoir. Water diverted under NCWCD's junior water rights on the South Platte (December, 1992 and August, 1997 priority dates) would be stored in the proposed Galeton Reservoir near Greeley during winter and spring for delivery during the irrigation season (MWH Americas Inc. *et al.*, 2004).

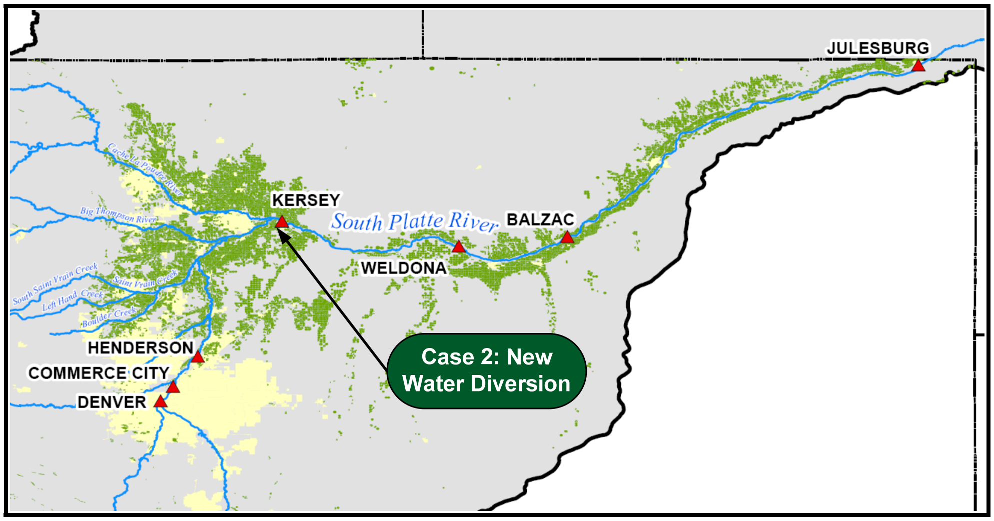


Figure 8-7. Location of new water diversion under Case 2.

Because of the many senior water rights holders downstream of the planned SPWCP diversion on the South Platte as well as diversion limitations imposed as part of the Colorado – Nebraska South Platte River Compact minimum flow requirements, the expected volume of water that can be diverted from the South Platte River to Galeton Reservoir will vary from year to year. Modeling performed by NCWCD (Brouwer, 2007) for the historical period 1950 to 1999 indicate an annual average of slightly less than 33,000 ac-ft per year (40.7 million m^3 per year) could have been diverted into Galeton Reservoir during this period.

Although the model presented in this chapter would be an ideal tool to predict the volume of water available for diversion to the proposed Galeton Reservoir, adding such logic would require details such as the downstream water-rights holders priority dates, anticipated delivery volumes out of Galeton Reservoir, and anticipated Cache la Poudre River to Glade Reservoir exchange volumes which are all beyond the scope of this analysis. Instead, results of NCWCD's modeling efforts (Brouwer, 2007) were used to provide projected monthly diversion volumes for the period October, 1990 through October, 1999. Projected diversion volumes beyond this time were not available. Drought conditions were experienced in the basin from 2000 through 2002. To provide a highly conservative estimate of diversions to Galeton Reservoir during these dry years, NCWCD's predicted monthly values for the drought year 1955 were used for as substitute values for the remainder of the baseline period stretching from November, 1999 through September, 2004. The substitute values from 1955 predict an annual diversion of slightly over 22,000 ac-ft (27.1 million m^3) and therefore reflect much lower annual diversions than expected for wetter years. Projected water volumes diverted from the river under Case 2 are plotted in Figure 8-8 along with historical baseline streamflow near the diversion point for comparison. Estimated values for the period November 1999 through September 2004 using values from 1955 are indicated.

Case 3 was incorporated into the model as an additional diversion from Reach 3 with a lower priority than the exiting historical baseline diversion volumes. Dissolved-solids concentrations and loads of the SPWCP diversions were calculated in the same manner as detailed above for historical baseline diversions. The volume of return flows resulting from irrigation with SPWCP water is assumed to remain constant if an equivalent volume of water is provided under the exchange agreement. The dissolved-solids concentration of the irrigation return flow is likely to be higher, however, because the water diverted from the South Platte River under the SPWCP will have a higher TDS concentration than historical irrigation water which was diverted from the Cache la Poudre near the river's departure from the mountains where the TDS concentration tends to be relatively low. As configured for these case studies, the model will not capture this difference in return flow. This could be incorporated into future analyses given information on historical TDS concentrations of irrigation water used on these lands and an estimate of how much TDS concentrations increase as a result of irrigation. It is likely much of the return flow from this region reports to the Cache la Poudre River, so some impact from increased dissolved solids in return flows might be observable at the mouth of the Cache la Poudre River before it joins the South Platte River.

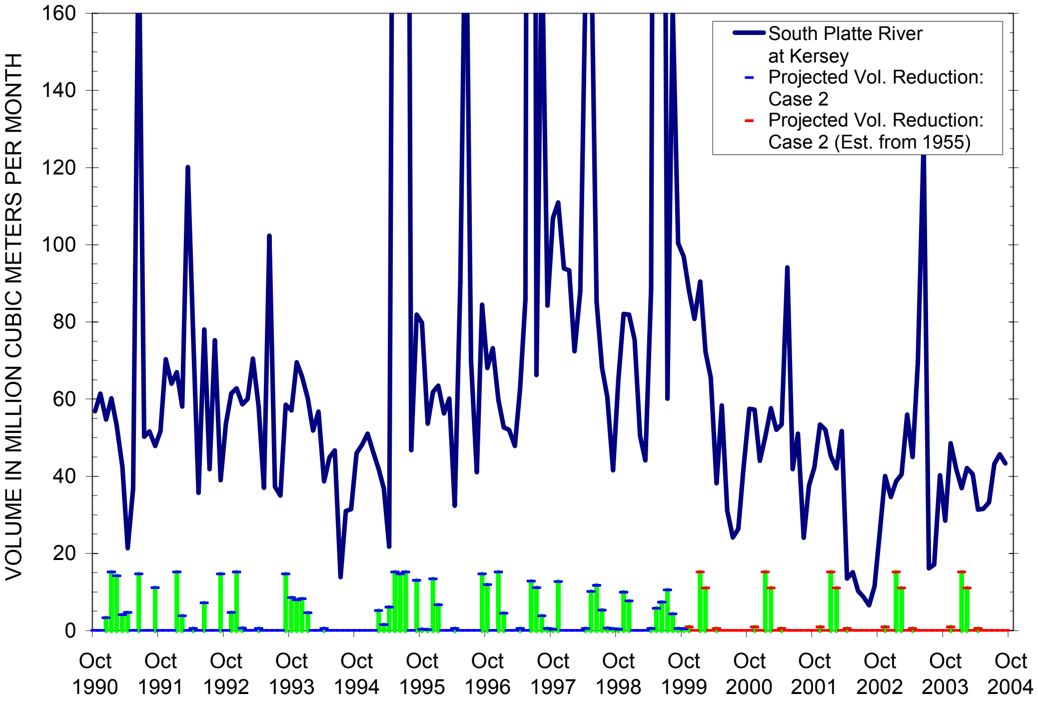


Figure 8-8. Streamflow reduction under Case 2 compared to historical baseline streamflow at Kersey.

8.2.3.3 Case 3: Combined Impacts

Case 3 examines the combined impacts to downstream flow and salinity resulting from the combination of Case 1's water reuse projects upstream from Henderson and

Case 2's proposed diversion near Kersey. Figure 8-9 shows the combined reduction in river volume expected under Case 3 compared to the historical baseline streamflow leaving Reach 3 at the Kersey gauging site. Because the reuse projects of Case 1 are likely to be developed to full capacity before the new water diversion of Case 2 is built, Case 3 allows for the evaluation of the proposed water diversion of Case 2 with the probable reduced streamflow conditions resulting from the reuse projects of Case 1 occurring upstream.

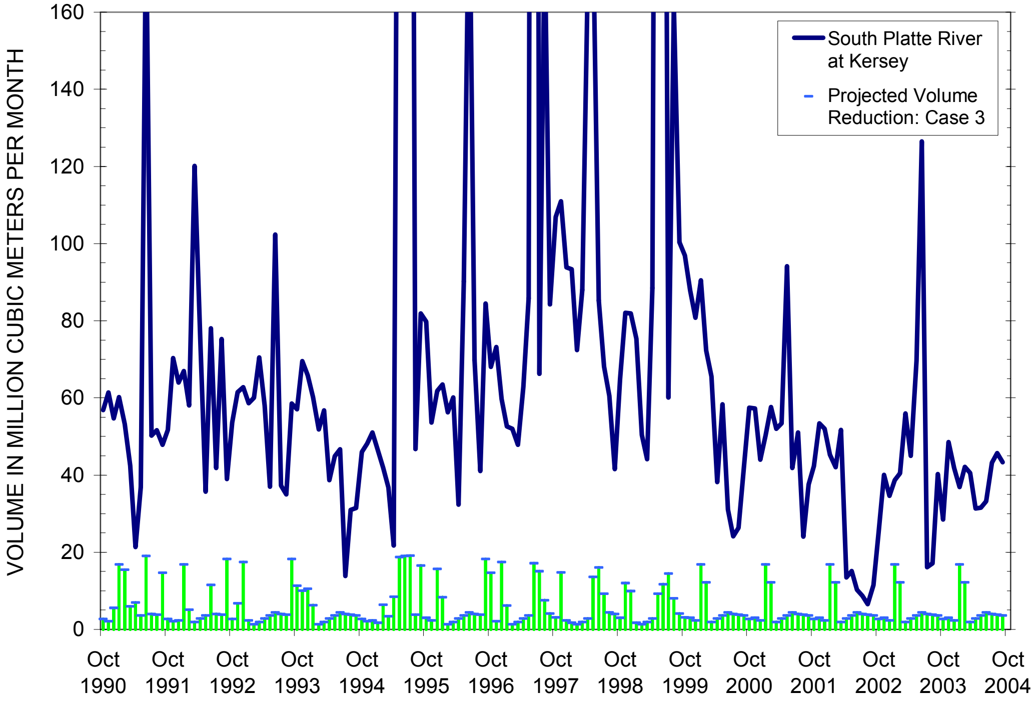


Figure 8-9. Streamflow reduction under Case 3 compared to historical baseline streamflow at Kersey.

8.2.4 Residual Load Adjustment for Case Studies

Under alternate scenarios which increase the historic baseline TDS concentrations of diversions, the mass of salt lost to diversions will also increase. Under steady state conditions, some of this difference in salt mass is likely to contribute to the salt mass returning to the river as residuals. Because the true value of the difference in residual salt load returning to the river is unknown, each scenario was analyzed two ways: 1) assume none of the additional load diverted under the alternate scenario returns to the river (0% Residual Load Adjustment or RLA) and 2) assume all of the additional load diverted under the alternate scenario returns to the river (100% RLA). The model can be set to simulate any amount of adjustment to load residuals, however the actual value is unknown and likely to be quite variable based on the use of diverted water, local geology, and other factors. By bounding the results between the extreme values, this approach provides a reasonable range of values that might be expected.

8.3 RESULTS AND DISCUSSION

8.3.1 Model Development

8.3.1.1 User Interface and Model Operation

A point-and-click graphical user interface (GUI) allows the user to easily navigate between various menus, control simulations, change model input data parameters, and visualize model output through a central integrated environment. The opening menu of the GUI (Figure 8-10) presents the main navigation menu that leads to sub-menus for running simulations, modifying model inputs and settings, and viewing or editing the model structure and logic.

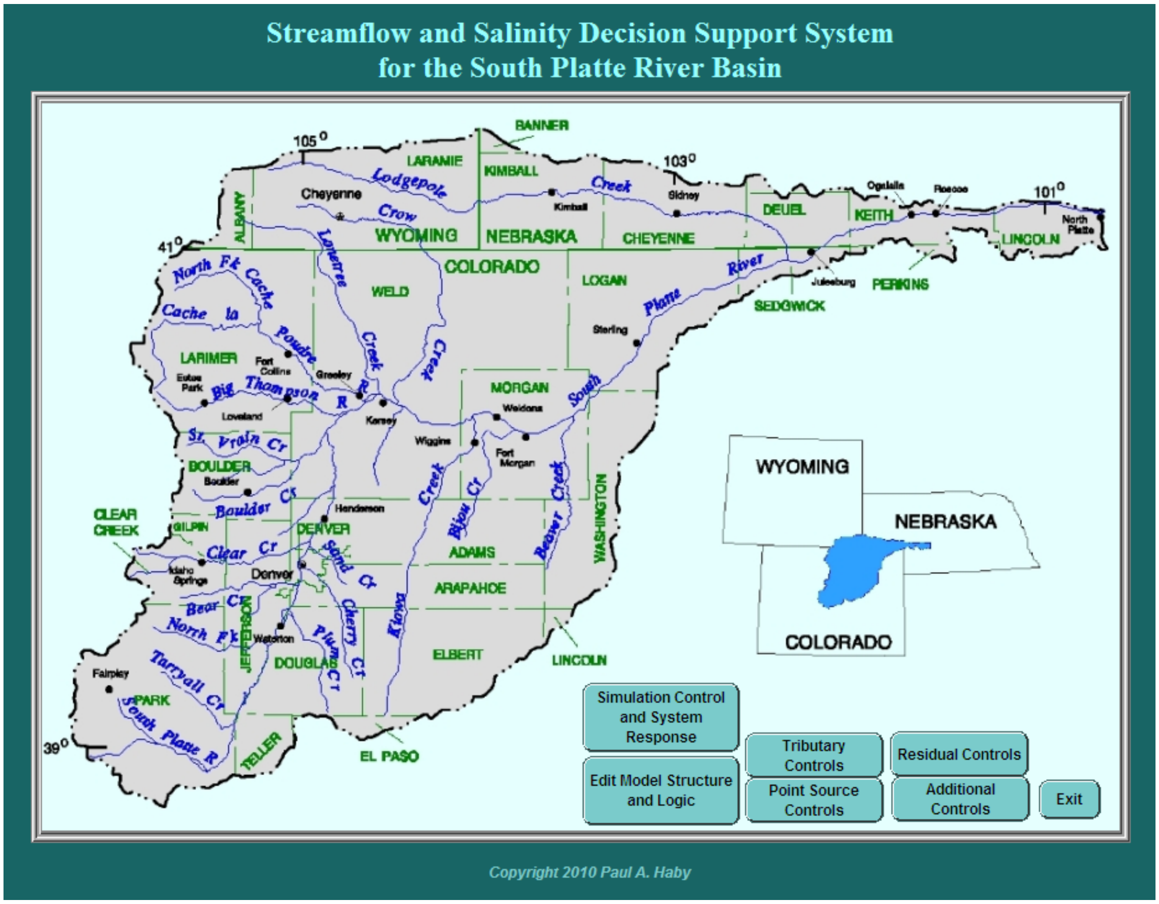
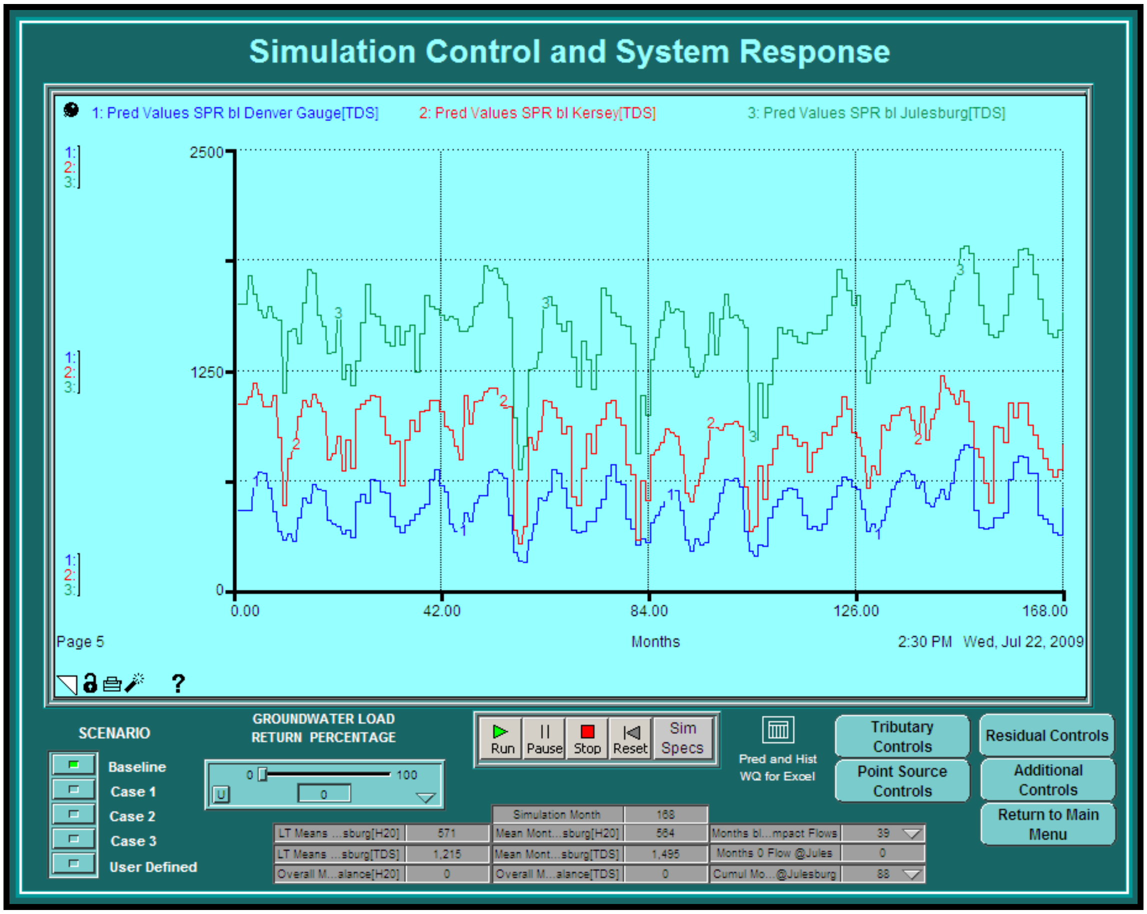


Figure 8-10. Screen image of the main menu with navigation buttons leading to all sub-menus.

The Simulation Control and System Response menu (Figure 8-11) serves as the control room for the model. It contains the operational controls for conducting simulations as well as selection buttons and a slider control to select and customize scenarios. More controls can be easily added as needed by the user when creating additional scenarios. Feedback on simulations is provided through tables, numeric display boxes, and a variety of pre-defined time-series plots that show the status of the system over time. Basic plots for any model variable can be added as needed. Model variables are exportable to external plotting software to produce more sophisticated plots if needed. Navigation buttons lead to additional menus for control of tributaries, point sources, residuals, and other miscellaneous simulation parameters.



GROUNDWATER LOAD RETURN PERCENTAGE: 0

		Simulation Month	168		
LT Means ...sburg[H20]	571	Mean Mont...sburg[H20]	564	Months bl...mpact Flows	39
LT Means ...sburg[TDS]	1,215	Mean Mont...sburg[TDS]	1,495	Months 0 Flow @Jules	0
Overall M...alance[H20]	0	Overall M...alance[TDS]	0	Cumul Mo...@Julesburg	88

Figure 8-11. Screen image of the operational control center for the model.

The input menu for setting historical flow and load contributions from tributaries is shown in Figure 8-12. These historical values will not need to be modified unless the time period for the historical baseline is adjusted. Controls on this menu allow the user to specify changes, on a monthly percentage basis, to the historical flow and load contributions. This provides the capacity for simulation of alternate scenarios involving reduced or increased contributions of flow and dissolved solids loads from tributaries. The monthly adjustments to the historical values are invoked by the model only for simulations in which the *User Defined* scenario button (Figure 8-11) is selected. Similar input for point source inputs, residuals, and diversion volumes are available via navigation buttons on both the *Main* and *Simulation Control and System Response* menus.

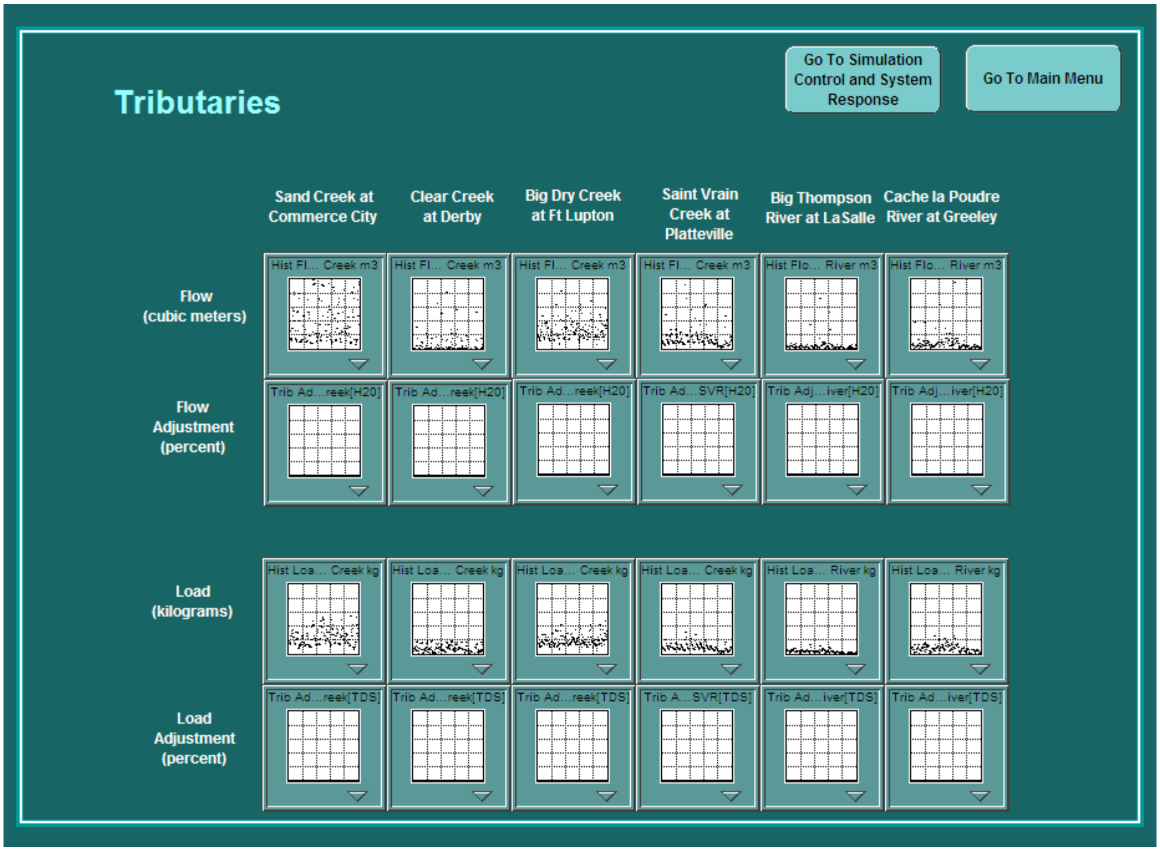


Figure 8-12. Screen image of input menu for control of flow and load contributions from tributaries.

8.3.1.2 Calibration and Baseline Simulation

The mass-balance methodology used to construct the modeling system does not require calibration in the traditional sense. The reason for this is that under historical baseline conditions, the model-predicted flow and load out of each reach will match the historical flow and historical load at the respective gauging site because of the use of the calculated residuals which are calculated based on the difference between the inputs and outputs. Comparison of model-predicted flow and loads under the historical baseline scenario were found to exactly match historical values for each reach (not shown). This verifies the model is properly accounting for all flow and load inputs and outputs.

Additional confirmation of model operation and the validity of the model-predicted dissolved solids concentrations can be seen by comparing the model-predicted dissolved solids values to historical field-measured values at three locations along the river (Figure 8-13). The model-predicted values represent flow-weighted monthly means and the field values represent instantaneous measurements so they would not be expected to match exactly because flow-weighted mean concentrations generally tend to be lower than instantaneous values. Overall, however, there is generally a good correlation between the two. This indicates that the model outputs provide a functional approximation of field-measured TDS concentrations for the baseline scenario.

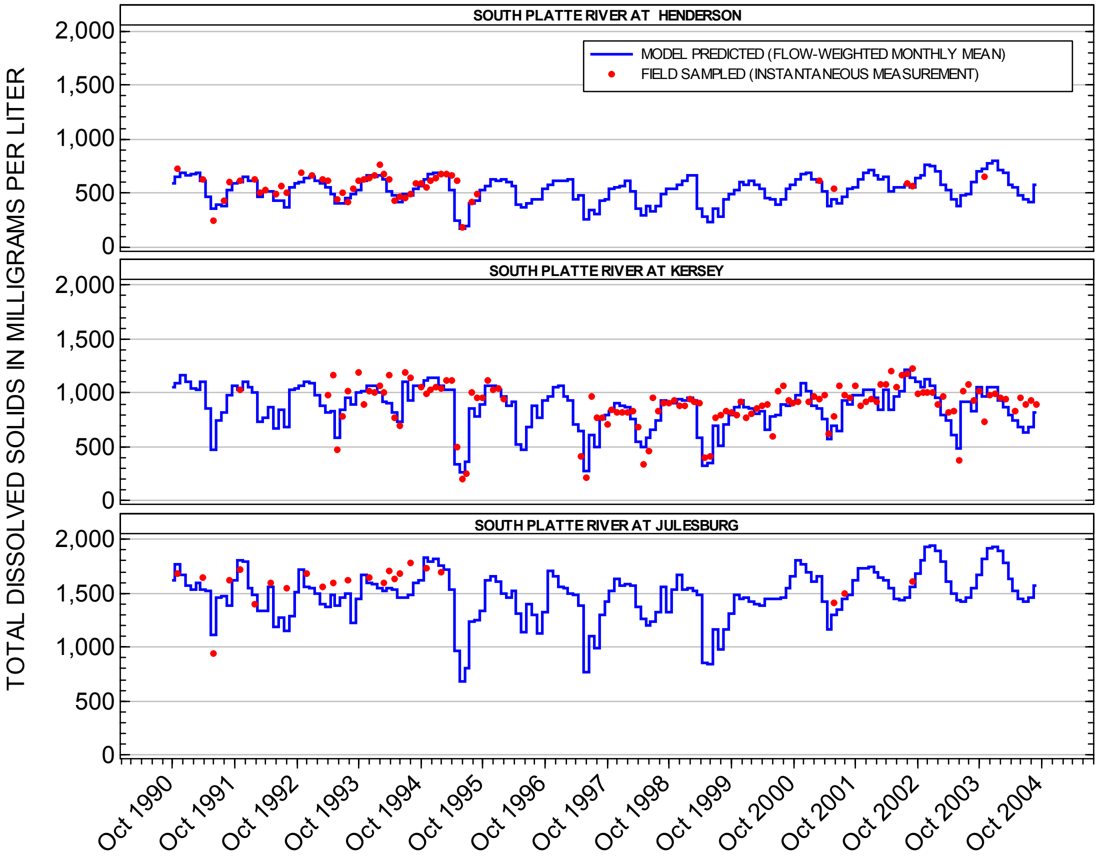


Figure 8-13. Comparison of model-predicted, flow-weighted monthly mean TDS with periodic instantaneous field measurements for three locations along the lower South Platte River.

An additional benefit of the model as illustrated in Figure 8-13 is the ability to provide monthly estimates of TDS concentration for all seven gauging sites along the mainstem South Platte River even when TDS was not measured at these gauging sites for extended periods of time. Examples of this can be seen in Figure 8-13 with the plots of the gauging sites at Henderson and Julesburg. Even after multi-year periods with no field measurements, there is close agreement between the predicted TDS concentration and the field-measured value when field monitoring resumed.

8.3.2 Scenario Analysis

The model was used to simulate the downstream effects of three scenarios involving potential water reuse and diversion projects that will reduce the upstream flow volume. Although deviations from historical baseline conditions could occur within all downstream reaches, this study focuses on impacts along Reach 6 and the gauging site at Julesburg. It is this region where the effects of upstream water reduction on irrigated agriculture are likely to be most pronounced due to the historically lower streamflow values and higher TDS concentrations resulting from consumptive use and subsequent concentration of salts.

8.3.2.1 Impacts on Flow

Figure 8-14 compares the model-predicted flow regime at Julesburg for each of the three case studies to the historical baseline flow at that location. The historical baseline flow has no periods where the total monthly flow past the gauge is equal to zero. Assuming no change in other historical conditions in the basin such as the volume of historical agricultural diversions, the upstream reduction in flow resulting from the water projects modeled in the three scenarios is predicted to result in multiple periods where there is no monthly flow past the gauge at Julesburg.

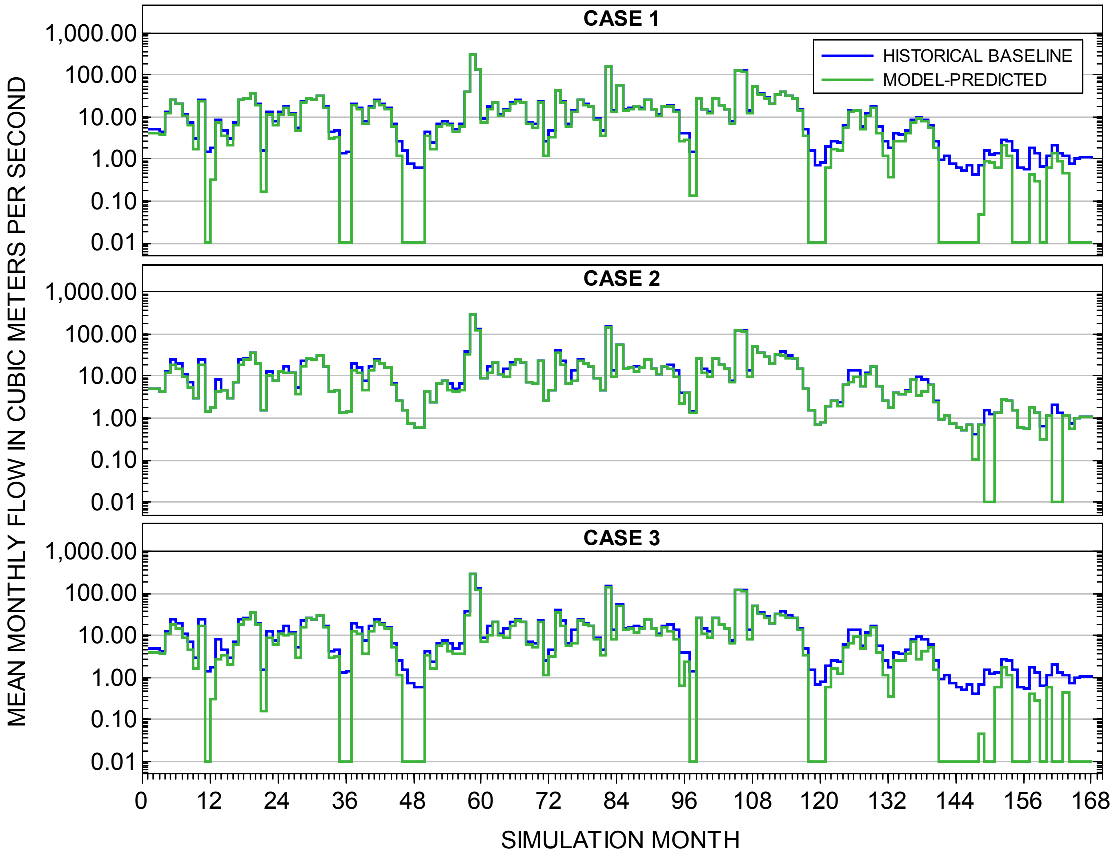


Figure 8-14. Historical-baseline and model-predicted mean monthly flow at Julesburg for each of the three case studies.

Table 8-1 quantifies changes to the flow regime at Julesburg under each of the scenarios. Case 1 causes a 1.0 m^3/s (6.1%) reduction in monthly mean flow at Julesburg and a 0.9 m^3/s (12.0%) reduction in monthly median flow. Impacts under Case 2 are within the same range with monthly mean flow reduced by 1.2 m^3/s (8.0%) and monthly median flow reduced by 0.7 m^3/s (11.1%). The combined impacts under Case 3 result in a 2.1 m^3/s (14.6%) reduction in monthly mean flow and a 1.5 m^3/s (21.9%) reduction in monthly median flow. Cumulative flow at Julesburg is reduced by 6.1%, 7.5%, and 13.5% by Case 1, Case 2, and Case 3 respectively over the 168 month simulation period.

Table 8-1. Changes in flow at Julesburg for each of the case studies.

[Num., Number; Min, Minimum; m^3, cubic meter; s, second; %, percent; n/a, not applicable]

		South Platte River at Julesburg			
	UNITS	HISTORICAL BASELINE	CASE 1	CASE 2	CASE 3
Monthly Mean Flow	m^3/s	16.0	15.0	14.8	13.8
Monthly Median Flow	m^3/s	7.5	6.6	6.8	6.1
Change in Cumulative Flow	%	n/a	-6.1	-7.5	-13.5
Num. of Months Flow = 0	months	0	26	4	31
Num. of Months Flow <= South Platte Compact Min. Flow	months	38	48	43	53

Even though Case 2 results in a slightly greater reduction in monthly mean flow and cumulative flow, only 4 months with no net flow past Julesburg are predicted compared to 26 months of no net flow under Case 1. Table 8-1 also shows the impact of the scenarios on the number of months the South Platte Compact minimum flows are not met. As implemented in the model, minimum flow requirements under baseline conditions were not met for 38 out of the 168 months of the simulation. The conditions of Case 1 cause the South Platte Compact minimum flows to be exceeded for an additional 10 months while Case 2 adds an additional 5 months to the baseline value and Case 3 conditions add 15 months to the 38 months under historical baseline conditions for a total of 53 months of not meeting the minimum flow requirements. The greater impact under the Case 1 scenario is caused by flow reductions resulting from water reuse or recapture of trans-basin water rather than river diversions subject to the priority system. As a result, the reduction in river flow under Case 1 is not subject to rules limiting operations during low flows at Julesburg or diversion limitations arising from senior water rights holders when there is a call on the river. Water diversion under Case 2 would be subject to South Platte Compact minimum flow restrictions as well as to the many senior water rights downstream and under the proposed operating rules would not be allowed to divert water when it would cause the South Platte Compact minimum flows to not be met. Four of the five additional months of not meeting South Platte Compact minimum flows under Case 2 occur during the period where NCWCD's modeled SPWCP diversion flows were not available and modeled diversion flows from the 1955 drought period were used as a surrogate. This indicates that the 1955 drought surrogate data do not provide a good description of the diversion volumes or diversion timing that would be available to the SPWCP during the period of water years 1999 through 2004 and suggests that water volumes available to the SPWCP during this period might even be less than what would have been available during the drought period of water year 1955. Updated SPWCP diversion volume modeling by NCWCD beyond 1998 would help to clarify this issue and provide better input data to this model.

These modeled results of the impacts on flow at Julesburg illustrate how historical water uses and demands may not continue to be met. In actual future river conditions, flow at Julesburg is unlikely to be reduced to zero. Instead, the impacts of reduced upstream flows will be felt by junior water rights holders along the river that will be forced to divert less water than they would have been able to without the upstream flow reductions. This includes the junior water rights of the SPWCP modeled in Case 2 which would be forced to curtail diversions in response to these restrictions and competing demands.

8.3.2.2 Impacts on Dissolved Solids Concentrations

The model-predicted impacts to TDS concentration resulting from reduced upstream streamflow under each of the three case studies assuming one-hundred percent RLA are shown in Figure 8-15. Impacts to TDS concentrations for the case studies with zero percent RLA are shown in Figure 8-16. As previously detailed in the Methodology section, 100% RLA assumes all additional load lost via diversions as a result of higher TDS concentrations in the river reach compared to baseline conditions returns to the river in the next reach as residuals input. As a result of this adjustment, predicted concentrations using 100% RLA will always be equal to or greater than predicted concentrations assuming 0% RLA which assumes none of the additional load lost to diversions compared to baseline conditions is returned to the river. Because the true value for RLA is unknown and is likely different for each reach, these two scenarios result in extreme values that serve as boundary values that define the range of likely values. Examination of Figure 8-15 and Figure 8-16 shows the range of predicted TDS increases that would occur under all three case studies which reduce or remove upstream water with lower TDS concentrations.

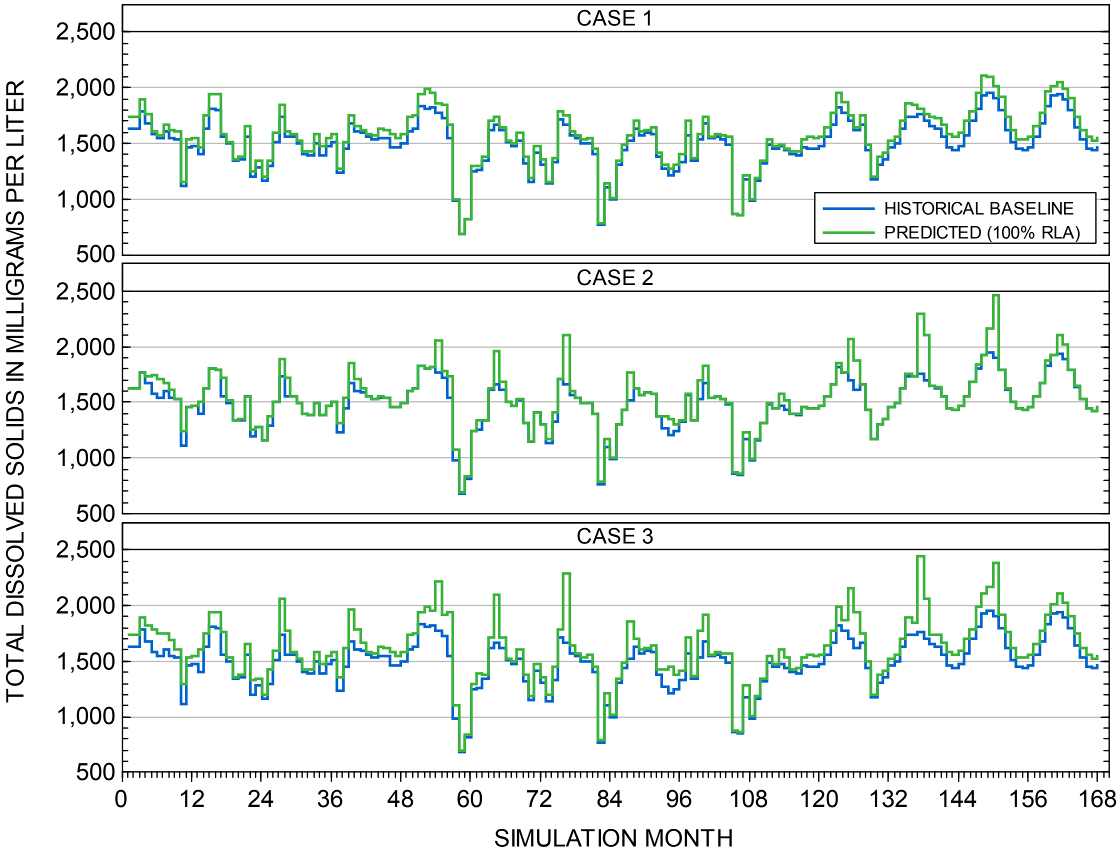


Figure 8-15. Historical baseline and predicted TDS concentrations under the 100% residual load adjustment option for the three case studies.

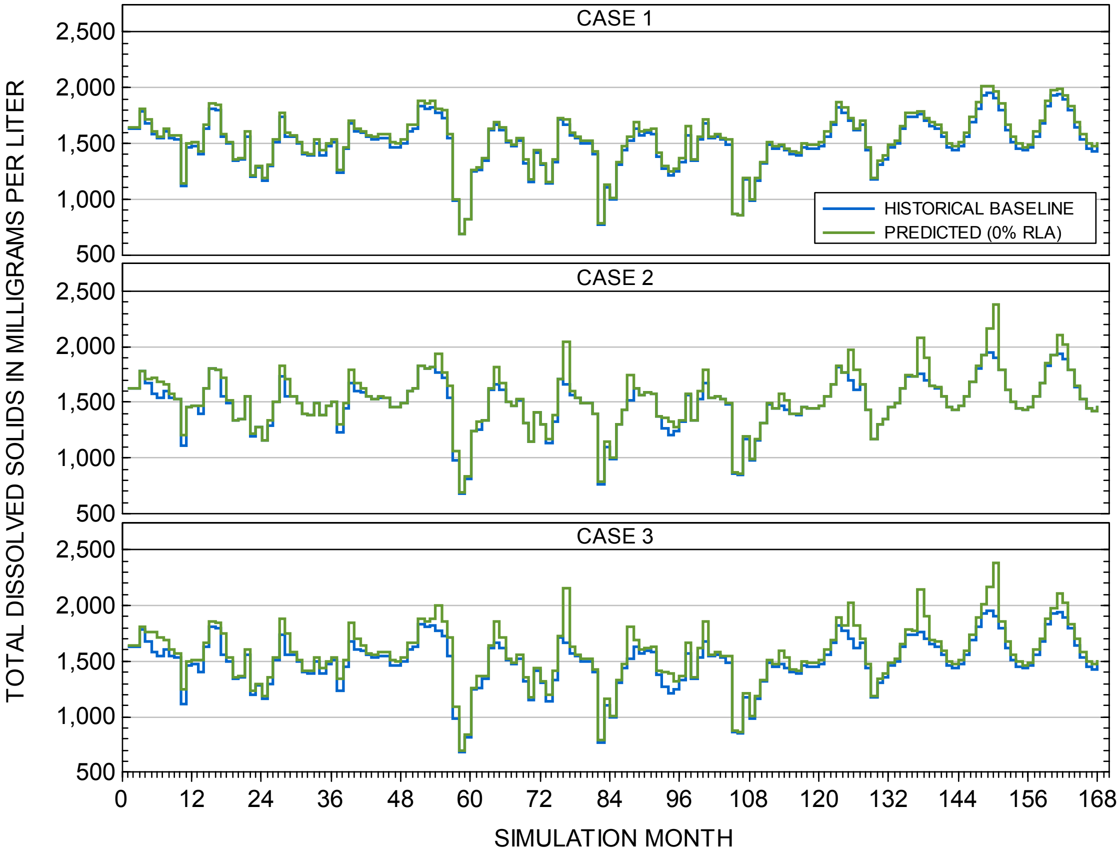


Figure 8-16. Historical baseline and predicted TDS concentrations under the 0% residual load adjustment option for the three case studies.

The impacts of the three case studies on TDS concentrations are quantified in Table 8-2. The water recapture and reuse projects of Case 1 are predicted to increase the mean monthly flow-weighted dissolved solids concentration at Julesburg by 30 mg/L (2.0%) under the 0% RLA assumption to 68 mg/L (4.5%) assuming 100% RLA. Median monthly TDS concentrations increased by a similar range under Case 1. The additional water diversion near Kersey modeled as Case 2 increase downstream TDS by a range of 35 mg/L (2.4%) to 47 mg/L (3.2%) for the 0 and 100% RLA setting respectively, however the number of months in which no diversions occur mask the true magnitude of the impact on mean TDS concentrations. Figure 8-15 and Figure 8-16 show that at times Case 2 results in a higher TDS concentration than Case 1. If only months in which diversions take place are examined, the mean TDS concentration under baseline conditions is 1,455 mg/L and model-predicted mean values for Case 2 range from 1,529 mg/L to 1,554 mg/L for the 0 and 100% RLA setting respectively. This represents an increase in mean TDS concentration at Julesburg during the study period of 74 mg/L (5.1%) to 99 mg/L (6.9%) depending on the RLA option. The combined impacts of Case 1 and Case 2 are predicted to cause mean monthly TDS to increase between 66 mg/L (4.4%) and 117 mg/L (7.8%) depending on the RLA setting.

Table 8-2. Summary statistics for historical baseline and case study TDS concentrations.

[TDS, total dissolved solids; mg/L, milligrams per liter; Num., Number, >, greater than; %, percent, RLA, Residual Load Adjustment]

MEASURE	UNITS	HISTORICAL BASELINE	CASE 1		CASE 2		CASE 3	
			0% RLA	*100% RLA*	*0% RLA*	*100% RLA*	*0% RLA*	*100% RLA*
Mean Monthly TDS	mg/L	1,495	1,525	1,563	1,530	1,542	1,561	1,611
Median Monthly TDS	mg/L	1,511	1,543	1,577	1,524	1,530	1,550	1,583
Num. of Months Mean TDS > 1500 mg/L	months	88	103	116	91	95	107	119

Impacts on the suitability for irrigation caused by the scenarios were evaluated by comparing the number of months that TDS concentrations at Julesburg exceeded an agriculturally significant reference value. A value of 1,500 mg/L was chosen as the reference value based on the irrigation water classification scheme developed by the U.S. Salinity Laboratory (U.S. Salinity Laboratory Staff, 1952). Under this system, irrigation water with a TDS concentration of 1,500 mg/L falls into the upper range of class C3 which is defined as high-salinity water which must be used on soils with adequate drainage and with careful management for salinity control. No attempt was made to include only months in which diversions from Reach 6 occur because diversions take place nearly year-round and can impact agriculture even if they are stored for use during the irrigation season or used in recharge projects.

Under the historical baseline, the monthly mean TDS concentration exceeded the reference value 88 out of the 168 month simulation period (Table 8-2). Case 1 is predicted to cause the 88 months to be increased by a range of 15 months (17.0%) to 28 months (31.8%). Case 2 has less impact than Case 1. It only increases the number of months exceeding the reference value by 3 months (3.4%) to 7 months (8.0%). The combination of water projects examined under Case 3 cause the reference TDS concentration to be exceeded by an additional 19 months (21.6%) to 31 months (35.2%) for a total of 107 to 119 months out of the 168 month simulation. All three alternate scenarios cause the number of months with a mean TDS concentration exceeding 1,500 mg/L to increase, however Case 1 has a much larger impact on this statistic. This is likely a result of the fact that unlike Case 2, the water reuse and recapture modeled in Case 1 occurs year-round even during low river flows.

8.3.2.3 Prediction of Water Quality for Future Water Projects

The ability to integrate various dynamic processes within this modeling framework in conjunction with the model's simulation of flow, dissolved solids loads, and dissolved solids concentrations within each reach provides the means for predicting dissolved solids concentrations of the additional water removed from the river as part of the case studies. Figure 8-17 shows the dynamic nature of both TDS concentrations and the projected Case 2 diversions and highlights why a dynamic-modeling approach such as presented herein is useful in predicting likely TDS concentrations of the diversions used to fill the proposed reservoir. Although the actual TDS concentrations of the proposed reservoir will also depend on the outflow schedule, subsurface inflow of water and dissolved solids, geologic contributions and evaporation rates, the TDS concentration of the water used to supply the reservoir provides a good indication of the expected lower range of TDS concentration in the reservoir and resulting quality of irrigation water supplied from the reservoir under proposed water exchange agreements.

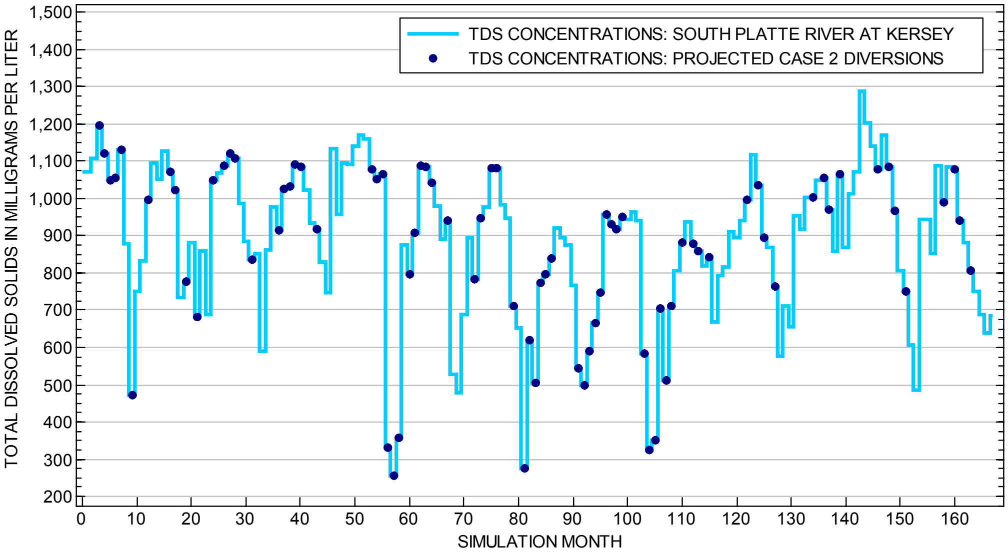


Figure 8-17. Plot showing predicted TDS concentration and timing of diversions for the proposed diversion simulated under Case 2.

Based on the model-predicted water quality of Reach 3 during months when reservoir diversions are expected to occur, the monthly mean TDS concentrations of these diversions are projected to be 853 mg/L under Case 2 and 865 mg/L under Case 3 (Table 8-3). Median concentrations are projected to be higher than the mean values. Case 2 is projected to have a median concentration of 921 mg/L and Case 3 a median concentration of 936 mg/L. Less than 1 mg/L difference was found between the 0% and 100% RLA options for all predictions of water quality. Mean values are lower than the median values because the mean values reflect the larger influence of the three periods of extremely low TDS concentrations occurring during large flow events. Overall flow-weighed mean TDS concentrations for the entire simulation period are projected to be 843 mg/L for Case 2 and 854 mg/L for Case 3. These values are lower than the mean of monthly TDS concentrations because more water tends to be diverted during periods of higher flow in the South Platte which correspond to lower TDS concentrations in the river.

Table 8-3. Predicted TDS concentration of water that would be diverted from the South Platte River near Kersey for the proposed SPWCP reservoir during the hypothetical modeling period.

[TDS, total dissolved solids; mg/L, milligrams per liter;]

MEASURE	UNITS	CASE 1	CASE 2	CASE 3
Median Monthly TDS	mg/L	N/A	921	936
Mean Monthly TDS	mg/L	N/A	853	865
Flow-Weighted Mean TDS	mg/L	N/A	843	854

Due to the reservoir's relatively small volume and large outflow rates, it will have a smaller residence time and therefore less carryover and mixing of water from year-to-year. Because of that, the median monthly values are believed to be a more useful predictor of typical TDS concentrations in the reservoir. The higher values for Case 3 (Table 8-3) reflect the impact of Case 1's upstream water reuse and recapture projects which are included as part of Case 3. The water reuse and recapture projects are predicted to cause a measureable increase in TDS concentrations even near Kersey at the proposed SPWCP reservoir diversion point. This demonstrates the importance of examining the impacts of proposed water resource projects in conjunction with other future water projects and likely future river conditions in order to get a better estimate of the true available water volume and likely water quality of the water project being evaluated.

As described above, the function of the proposed SPWCP reservoir is to provide water to the lower portions of the Larimer-Weld and New Cache canals in exchange for water diverted upstream from the Cache la Poudre River. Because the model provides a tool for the prediction of likely TDS concentrations of water comprising the proposed

SPWCP reservoir, these values can then be compared to TDS concentrations currently found in the lower portions of these canals to get an estimate of the difference in water quality should this water exchange occur. Surveys of stream and canal salinity were conducted by NCWCD from 2001 through 2005. Sites on the Larimer-Weld and New Cache canals were included during the irrigation seasons of 2004 and 2005. Mean specific conductance (SC) values from the most recent report (Wilson *et al.*, 2006), are shown in Table 8-4. Using the guidance suggested by Tanji (1996a), the EC values were converted to approximate TDS values. Comparison of the approximate TDS values of Table 8-4 to the predicted mean and median values of the water diverted for the SPWCP reservoir indicated the potential for significantly higher TDS concentrations in irrigation water supplied from the reservoir than the TDS concentrations found historically in the lower portions of the canals.

Table 8-4. Field-measured specific conductance and approximate TDS concentrations for lower portions of the Larimer-Weld and New Cache Canals (from Wilson *et al.*, 2006).

[SC, specific conductivity; μS/cm, microsiemens per centimeter; TDS, total dissolved solids; mg/L, milligrams per liter]

CANAL	SAMPLING SITE	2005 MEAN SC * (μS/cm)	APPROXIMATE TDS ** (mg/L)
Larimer-Weld Canal	West of Eaton	330	211
	Owl Creek Extension	280	179
New Cache Canal	East of Lucerne	650	416
	South of Galeton	630	403
	North of Barnsville	650	416

* from Wilson *et al.* (2006)

** Generally accepted rule of thumb estimate for most waters: TDS (mg/L) = SC (μS/cm) * 0.64 (Tanji, 1996)

8.4 CONCLUSIONS

8.4.1 Benefits

The primary objective of this work was the development of an object-oriented, system dynamics-based model that provides the ability to simulate the movement of water and salt in the lower South Platte River system within the consistent framework of a decision support system. The secondary objective demonstrated the model's utility in the evaluation of possible changes to downstream streamflow and water quality resulting from individual or multiple upstream water resource projects. The ability to track water quality of intermittent processes was also shown. These case studies demonstrate the capabilities of the model, however it was designed to allow for the development and evaluation of additional scenarios. Although designed for the South Platte River Basin, this modeling approach could easily be adapted to other basins.

This model provides a tool to aid in the understanding of water and salinity issues on a basin-wide scale and can serve as a tool for the assessment of streamflow and water-quality responses to changes imposed upon the system. The resulting model is a transparent, easy-to-use tool that is easily modified and provides the user the ability to run an unlimited variety of scenarios within a short time frame. It also serves as an ideal way to integrate disparate data, regulations, and operational rules into a single modeling application. These features allow decision makers and stakeholders direct access to the model in order to gain insights into system behavior and test management alternatives, both of which are crucial in long-term planning and development of policy decisions.

8.4.2 Future Work and Applications

This work provides the framework not only for further evaluation of combined impacts of currently proposed water resource projects, but also provides a tool that could be adapted to explore streamflow and salinity impacts from new inter-basin transfers, additional conversion of agricultural water to municipal and industrial usage, changes in reservoir operating policies, changes in river salinity due to recharge projects, droughts, and new reservoirs.

Additional work could help provide a more detailed analysis of the SPWCP diversions, reservoir volume and water quality, and downstream impacts given the likely upstream changes in flow and water quality due to other water resource projects. If SPWCP diversion rules and logic to account for senior water rights calls and South Platte Compact minimum flow requirements were added, the model could be used to evaluate the actual volume of water that could be diverted as well as the expected water quality under the projected upstream changes in flow and water quality instead of relying on results modeled using past conditions. Addition of the proposed SPWCP reservoir to the model in conjunction with operating logic for irrigation outflows, ground water gains and losses, and evaporation losses could provide a better estimate of reservoir volume and water quality over time.

Future work could also incorporate impulse-response functions derived from groundwater modeling of alluvial aquifers to provide greater refinement in prediction of irrigation return flows. Similarly, stream depletion factors could be added to provide the ability to evaluate the impacts to the river from ground water pumping. Other conservative water-quality constituents in addition to TDS could easily be added and even non-conservative water-quality constituents could be added along with appropriate reach-specific loss and conversion coefficients. Spatial resolution could be increased beyond the reach scale to even track individual diversion points and associated water right priorities which would allow the model to highlight the diversions that would be impacted when there is insufficient streamflow. Finally, additional components and logic could be added to address economic or ecological impacts related to water resources and water quality in the basin.

CHAPTER 9: SUMMARY AND CONCLUSIONS

9.1 OVERVIEW

The primary motivation for this research was the need to develop an understanding of the threats to the long-term sustainability of irrigated agriculture in the South Platte River Basin resulting from elevated salinity levels in irrigation water and an unfavorable salt balance in the lower basin. This study addressed the critical need for a comprehensive understanding of salinity status, past and present, in the South Platte River Basin and provided the foundation for a comprehensive understanding of the processes involved in the origin, flux, and ultimate destination of salts throughout the basin. The results of this fundamental characterization were incorporated into a dynamic decision support tool to evaluate future water quantity/quality conditions resulting from changes in historical water uses, impacts of water recycling efforts, and development of new water resource projects.

9.2 SIGNIFICANT CONCLUSIONS AND ACOMPLISHMENTS

The five most significant accomplishments of this research are summarized below:

1. Produced the most complete salinity characterization of the South Platte River Basin to date.
2. Quantified recent and long-term salt balance status of the middle and lower basin.
3. Developed estimates of water and dissolved solids contributions to the mainstem of the South Platte River occurring via ground water for a series of six reaches in the middle and lower basin.
4. Developed and demonstrated the utility of a dynamic streamflow and dissolved solids modeling system for evaluation of future river conditions.

5. Demonstrated the importance of simultaneous analysis of the combined impacts of multiple proposed water resource projects.

Each of these conclusions and accomplishments will be discussed in detail in the following sections.

9.2.1 Produced the Most Complete Salinity Characterization of the South Platte River Basin to Date

This work provides the most comprehensive analysis of dissolved solids in the South Platte River Basin to date. This study went beyond replicating and updating previous characterization efforts by enlarging the geographic scope of the area studied and through the employment of additional characterization techniques. By enlarging the study area from just sites along the mainstem to include sites along the entire length of the tributaries, a more detailed picture of the patterns of increases in TDS concentrations and loads along the tributaries emerged. This provided new insight into the geographic location of major salt-loading areas along the tributaries. The application of trend analysis to both recent and long-term data sets at a large number of sites provided a more detailed characterization of recent and historical changes in TDS concentrations.

Characterization of TDS concentrations found that dissolved solids concentrations vary substantially throughout the basin. In general, the lowest concentrations were found in headwater sites while the highest levels were found at the most downstream sites. As would be expected, monitoring sites located near the headwaters of stream originating in mountainous regions had lower TDS values than monitoring sites near the headwaters of streams originating in the plains along the Front Range. Strong seasonal patterns in dissolved solids concentrations were observed at many sites. Trend analysis found that salinity concentrations at the majority of study locations throughout the basin are changing. There were twice as many sites with increasing trends as sites with decreasing trends. Along the mainstem of the South Platte River, significant upward trends were found in the upstream portion of the study area for both the recent and longer-term trend analysis periods. With the exception of Julesburg, sites along the middle and lower portions of the study area have slight decreases in both short and long-term dissolved solids concentrations. Tributaries in the central portion of the basin were found to have mostly upward trends in both recent and long-term dissolved solids concentrations while sites along the three largest tributaries originating farther north in the basin generally had no trend or decreasing trends in both recent and long-term dissolved solids concentrations.

Analysis of dissolved solids loads at sites throughout the basin found that most of the load increase in the tributaries occurs along the Front Range region just east of the foothills, correlating with the location of major urban areas. Most of the dissolved solids are thought to result from shale formations in this area. Annual load values typically exhibited large inter-site variation and often had large intra-site variation from year-to-year as well. Median annual loads and variability in annual loads generally increased in a downstream direction. The largest dissolved solids loads generally occur along the mainstem at Kersey. A large portion of the load in the South Platte River at Kersey results from load contributions from three large tributaries that join the mainstem between Henderson and Kersey. Rather than increasing as might be expected, the dissolved solids loads between Kersey and Julesburg typically decreases slightly. This decrease is a cause for concern as it is indicative of dissolved solids being deposited in lower regions of the basin. Mean annual load values were found to be generally comparable to past studies at corresponding sites, however evidence suggests that loads at some sites might have decreased significantly compared to the period 1965–1979. Trend testing revealed no upward trends in annual dissolved solids loads but did detect four significant downward trends. These occurred mid-basin at Kersey and in the Saint Vrain and Big Thompson tributary systems.

A major benefit of this salinity characterization is that it documents recent salinity status and provides reference points for comparison with future salinity conditions. It also highlights trends in salinity status which provide an indication of potential future conditions. Finally, it establishes the basis for understanding the origins and transport of dissolved solids in the basin. A fundamental understanding of salinity status is a necessary requirement for the development of salinity management and mitigation strategies as well as for predicting the downstream impacts to water quality resulting from the development of additional water resource projects and changes in water management.

9.2.2 Quantified Recent and Long-Term Salt Balance Status of the Middle and Lower South Platte River Basin

Recent and long-term analyses of the salt balance status of the lower South Platte River Basin were performed in order to quantify the flux of dissolved solids throughout the basin and to provide an indicator of the long-term sustainability of irrigated agriculture in the region. Dissolved solids loads in the river were generally highest in the upper study area at the Kersey monitoring site while loads were slightly lower at the downstream monitoring site at Julesburg. This suggests a net accumulation of dissolved solids in the irrigated region between Kersey and Julesburg. For water years 1951 through 2004, the mean accumulation in the region was 0.59 metric tons per hectare per year and during the more recent period of water years 1991 through 2004 the mean accumulation rate was 0.35 metric tons per hectare per year. The ultimate destination of the dissolved solids in this irrigated region is unknown. If they are being deposited with the root zone of the irrigated soils in this region, an increase in soil salinity levels could occur over the long-term which could lead to reductions in crop yield. Continued monitoring of the salt balance of this region is advisable, as it will show the net effects of upstream water management decisions on salt accumulation. Soil-salinity mapping of representative irrigated fields in this region should be performed both as a check on current soil-salinity levels and for the establishment of baseline conditions which can be compared to future soil-salinity measurements for determination of trends in soil salinity throughout this region.

9.2.3 Developed Estimates of Water and Dissolved Solids Contributions to the Mainstem of the South Platte River Occurring Via Ground Water for a Series of Six Reaches in the Middle and Lower Basin.

This study updates and advances the body of knowledge regarding the occurrence, transport, and fate of dissolved solids in the lower South Platte River Basin through the development of a reach-based mass budget for water and dissolved solids. This mass budget tracks the measured gains and losses via streamflow, tributaries, point sources, and diversions on a monthly basis for key monitoring sites on the mainstem of the South Platte River from Denver to Julesburg. The residuals of this mass budget provide estimates of the contribution of water and dissolved solids to the river via ground water. Because these contributions cannot be measured directly, their quantification provides important insight into the role of ground water return flows as a source of water and dissolved solids to the mainstem of the river.

Results of the streamflow mass budget indicate that in each of the six study segments, the river gains water from ground-water inflow. Depending on the reach, this flow contributes from 5 to 28 percent of total flow. Temporal trends and seasonal variations in residual flow were observed at various reaches. Calculated residual flow values compared favorably with previously published studies that used either mass balance techniques or intensive field-based measurement. This study is the first to present residual flow estimates for the entire mainstem of the South Platte River from Denver to Julesburg. Results of the dissolved solids mass balance indicate that in each of the six study segments, the river gains dissolved solids through ground-water inflows. The contribution of residual dissolved solids varies by reach, but the overall mean contribution for the study area is 11 metric tons per day per km. Evidence of changes in the residual salt contribution over time in some reaches was seen in the time series plots and seasonal patterns in load contribution were observed for some reaches. Residual salt loading was shown to be a significant contributor to the mainstem total dissolved solids load in each reach. Calculated TDS concentrations of residual flows ranged from 500 mg/L to nearly 3000 mg/L and were found to compare favorably with previously-published ground-water TDS concentrations. Calculated TDS concentrations showed evidence of time trends in time series plots, however formal trend analysis was not performed.

Overall, the results of this work demonstrate that this mass balance approach is a valid method for the estimation of mass loading of water and salt via ground water. The quantification of gains and losses of water and salt mass via ground water provides a critical component in the overall effort to develop a process-based understanding of salinity behavior in the basin. It also provided the required input data sets for use in the later development of the streamflow and dissolved solids dynamic simulation model.

9.2.4 Developed and Demonstrated the Utility of a Dynamic Streamflow and Dissolved Solids Modeling System for Evaluation of Future River Conditions

The foundation provided by the salinity characterization and mass balance analysis performed for this study was incorporated into a dynamic, user-friendly streamflow and dissolved solids simulation system. Based on mass balance concepts, this dynamic modeling system allows for the simulation of possible impacts to streamflow, dissolved-solids loads, and dissolved-solids concentrations along the middle and lower portions of the South Platte River resulting from a combination of user-configurable upstream water development and water conservations scenarios. This model provides a tool to aid in understanding water and salinity issues on a basin-wide scale. It was designed to be a transparent, easy-to-use application that can be readily modified by the end-user to meet their specific needs. It provides the user the ability to simulate a wide-variety of scenarios with relatively short setup and computational time frames. It also serves as an ideal way to integrate disparate data, regulations, and operational rules into a single modeling application. These features allow decision makers and stakeholders direct access to the model in order to gain insights into system behavior and to test management alternatives, both of which are crucial in long-term planning and development of policy decisions. The ability to preview future water-quantity and quality conditions in the lower South Platte River provides a predictive tool that will allow for the development and evaluation of appropriate response and mitigation plans.

The utility of this modeling system for analysis of downstream impacts to streamflow and water quality was demonstrated through the simulation of several case studies. The first case study investigated impacts resulting from the implementation of water reuse projects by two large metropolitan water utilities. These projects have the net effect of reducing the amount of lower-salinity water returned to the river in the middle part of the basin. The second case study simulated the impacts from a proposed diversion from the river near Kersey. The third case study investigated the combined impacts of Case 1 and Case 2. In all three cases, the model successfully demonstrated potential impacts to downstream water quantity and dissolved solids concentrations. With each of the case studies, dissolved solids concentrations were shown to be higher than baseline conditions and the difference generally increased in a downstream direction.

A key requirement in collaborative planning and decision making is to have the ability to readily generate and evaluate various alternatives. This can foster an increased understanding of the dynamic interactions within the system under evaluation. The object-based model design allows for spatial or temporal expansion of the model, as well as the incorporation of additional river network objects such as additional in-channel or off-channel reservoirs, additional diversions, and additional return flows. In addition to the demonstrated use of the model in the evaluation of combined river impacts from proposed water resource projects, the modeling system provides a tool that could be adapted to explore streamflow and salinity impacts from new inter-basin transfers, additional conversion of agricultural water usage to municipal and industrial usage, alternative reservoir operating policies, recharge projects, pumping of alluvial aquifer wells, droughts, and simulation of new reservoirs. Although designed for the South Platte River Basin, this modeling approach could easily be adapted to other basins.

9.2.5 Demonstrated the Importance of Simultaneous Analysis of the Combined Impacts of Multiple Proposed Water Resource Projects

Upcoming changes in water use and river management within the South Platte River Basin are likely to result in reduced mid-basin streamflow and diminished return flows to the river. Because the return flow from one water user often becomes the water source for a downstream user, activities that change return flow quantity or quality will impact downstream users. This also applies in the case of water resource projects where the impact of one project might influence the quantity and quality of inflows to a second project. Due to the potential for interaction or a cascading effect among river impacts resulting from multiple water resource projects, it is important to evaluate potential water resource projects using projected future streamflow and water-quality conditions that include potential future water resource projects and management changes rather than simply using historic baseline conditions. In order to perform this type of analysis, it is necessary to analyze potential water resource projects simultaneously rather than evaluating each one singularly. Unfortunately, the complexity of the decision-making process increases dramatically when multiple projects are evaluated.

A dynamic simulation system such as the streamflow and dissolved solids modeling system developed herein provides an ideal tool for the evaluation of multiple impacts to a river system. One of the primary motivations for the development of the model was to facilitate the analysis of multiple water resource projects and/or changes in water management. In the analysis of the sample case studies, the model showed that the impacts resulting from the combination of the case studies were generally larger than the impacts resulting from a single case study. The model was also used to predict the initial water quality of a proposed reservoir that would be filled with periodic diversions from the South Platte River. This simulation was repeated with the addition of upstream water reuse projects which have the effect of reducing the return flows to the river from major metropolitan water treatment facilities. The inclusion of the upstream water reuse projects in the simulation resulted in the prediction of higher initial dissolved solids concentrations in the proposed reservoir. This demonstrates the importance of examining the impacts of proposed water resource projects in conjunction with other future water projects and likely future river conditions. The ability to estimate downstream impacts to water quantity and quality resulting from multiple diversion and reuse projects provides an important tool for use in long-term planning and policy decisions as well as for the evaluation and permitting of projects.

9.3 SUGGESTIONS FOR FUTURE WORK

9.3.1 Improvements in Monitoring Program

Unfortunately, many seemingly important water-quality monitoring sites in the basin had inconsistent monitoring programs. This problem was encountered for mainstem sites as well as monitoring sites at the mouths of major tributaries. Because of their locations, sites at the mouths of tributaries serve as integrator sites that reflect all processes occurring in the upstream sub-basin that have an impact on water quality. These sites are also important for determination of the relative water quality and constituent load contributions to the mainstem of the river by each of the tributaries.

Inconsistent monitoring at sites reduces the precision of statistical analyses and load estimation efforts. It may also preclude formal trend analysis if minimum data requirements are not met. Even if trend analysis can be performed, the results are less useful if they cannot be compared to other sites because of differences in the time periods in which regular monitoring was performed. In the evaluation of future monitoring priorities in the South Platte River Basin, consideration should be given to the importance of consistency in monitoring and the importance of monitoring sites located near the mouths of tributaries. The importance of systemic, long-term monitoring of salinity concentrations and salt balance status will increase in the future as water scarcity continues to drive changes in water use and management throughout the basin.

9.3.2 Analysis of Spatial Patterns and Trends in Ionic Constituents

One original objective of this work was to characterize spatial patterns and trends in the composition of major dissolved solids constituents. Unfortunately, due to inadequate availability of major ion analysis for many of the sites, it was decided that this work could not be accomplished in a suitable manner. Investigation of spatial patterns in ionic composition could reveal changes in dominant salinity sources while temporal trends in ionic composition might help explain reasons for trends in dissolved solids concentrations or possibly indicate changes in salinity sources over time. Analysis of specific constituents of heightened interest to agriculture such as boron, selenium, chloride and sodium would help provide better characterization of water used to support agricultural crops and animals. In the future, if monitoring programs in the basin are enhanced to include regular analysis of major ions, analysis of spatial patterns and trends in ionic composition would be a valuable addition to the overall understanding of salinity in the basin.

9.3.3 Further Development of the Dynamic Streamflow and Salinity Model

There are almost limitless possibilities for enhancement and expansion of the streamflow and salinity simulation model developed as part of this work. Perhaps the most useful improvement would be linkage of this model to a basin ground water model that could provide a better estimate of impacts to return flows resulting from changes in the volume of water diverted under alternate scenarios. A simpler and more computationally efficient way to accomplish this would be through the use of pre-calculated discrete kernel response coefficients (Fredericks *et al.*, 1998). These discrete coefficients, or impulse-response functions, would be derived from a calibrated groundwater model through repeated simulations under a variety of conditions. The resulting impulse-response functions would provide the resulting ground water response as predicted by the ground water model without the need to explicitly run the ground water model at each time step.

Simulation of objects and processes beyond the mainstem of the South Platte River could also extend the functionality of the model. Some of these additional components might include irrigation reservoirs, groundwater recharge projects such as the Tamarack Managed Groundwater Recharge Project (Altenhofen, 2000), and even simulation of impacts to the river resulting from the operation of alluvial wells. The model would serve as an ideal tool for prediction of the quantity and quality of water available for a proposed diversion at any point along the mainstem South Platte River. The addition of these types of additional components would allow for more sophisticated analysis and optimization of basin management strategies and provide insight into the resulting water-quality impacts. Rather than aggregating and simulating river diversions by reach, the model could be modified to track individual diversions and their associated water right priorities. This would allow the model to simulate the shutdown of diversions that are out of priority during periods of water scarcity. This important capability would provide a more realistic simulation of the impacts resulting from downstream water shortages instead of aggregating the impacts at the Julesburg site as the model does currently.

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APPENDIX A. DAILY FLOW TIME SERIES PLOTS – WATER YEARS 1991 - 2004

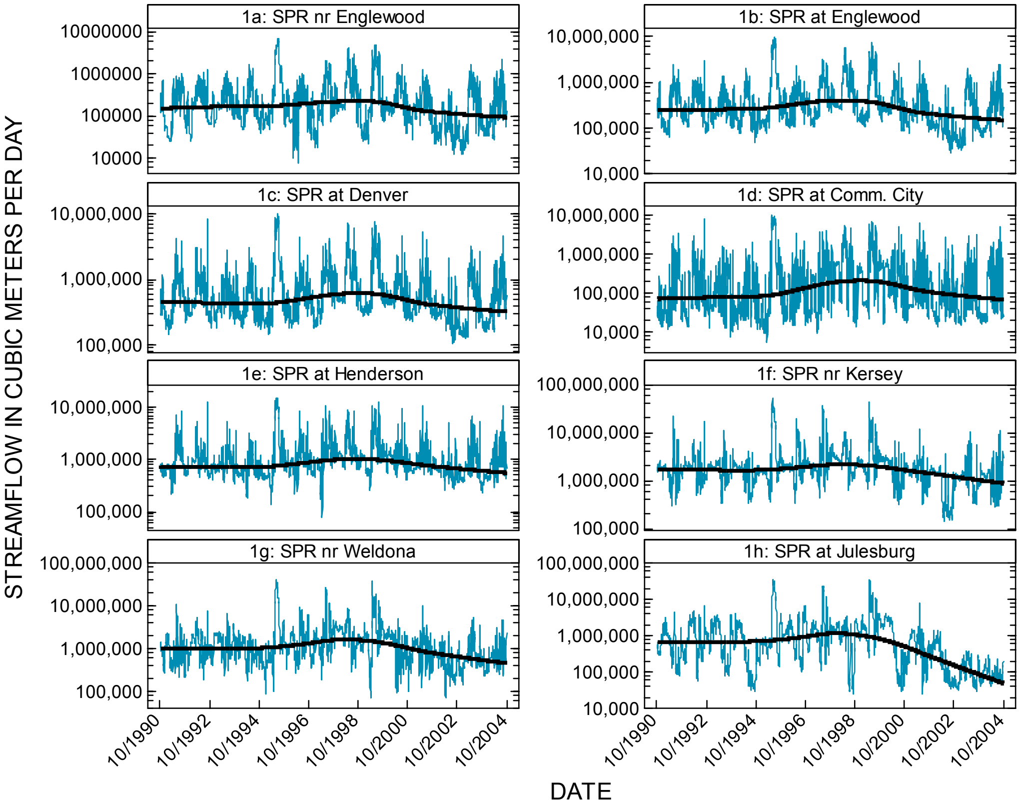

Figure A-1. **Time series plots of streamflow with LOWESS smoothing lines at selected monitoring sites along the mainstem of the South Platte River, water years 1991–2004.**

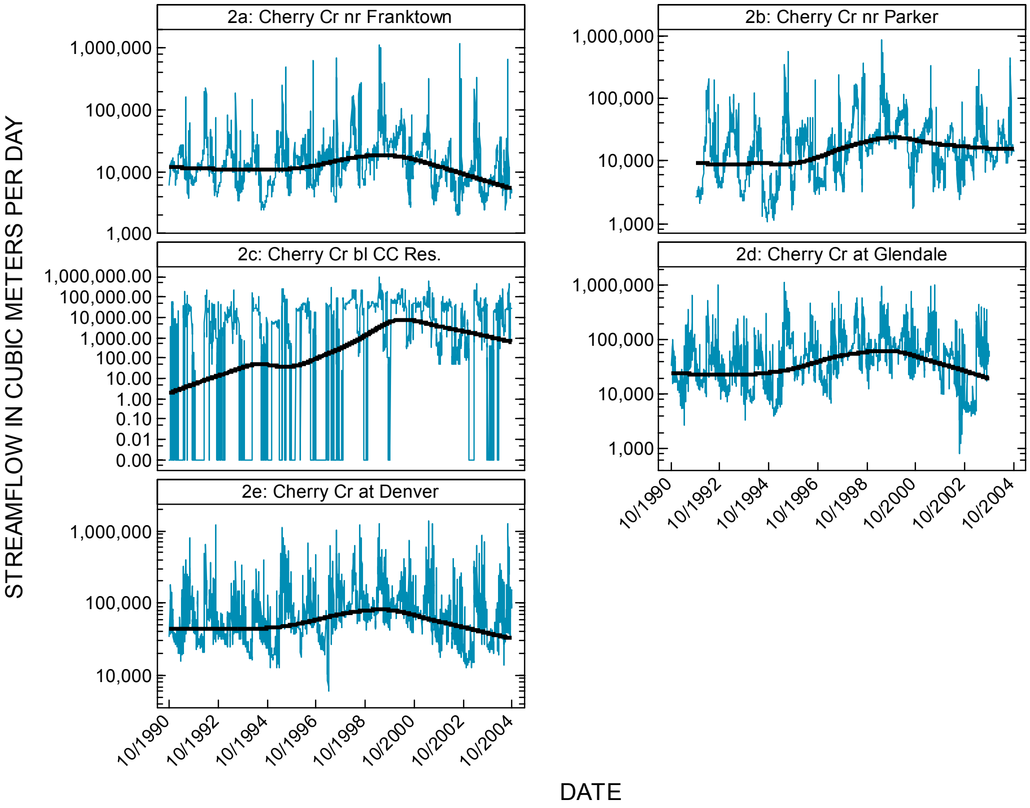

Figure A-2. Time series plots of streamflow with LOWESS smoothing lines at selected monitoring sites along Cherry Creek, water years 1991–2004.

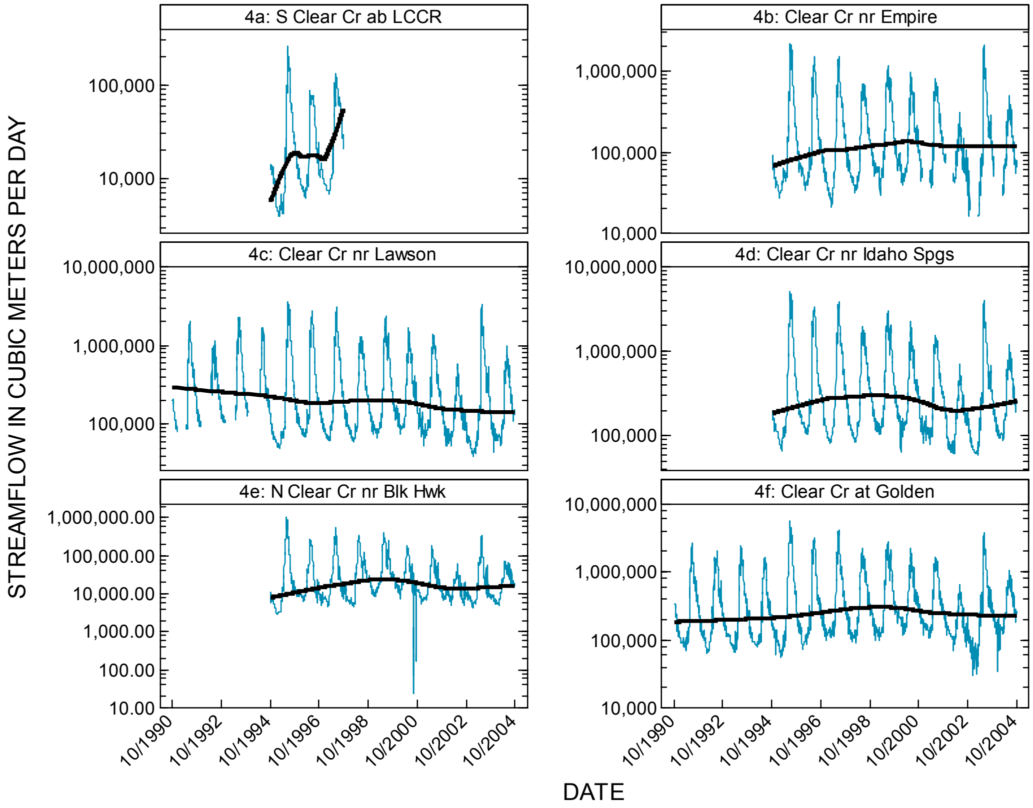

Figure A-3. **Time series plots of streamflow with LOWESS smoothing lines at selected monitoring sites along Clear Creek, water years 1991–2004.**

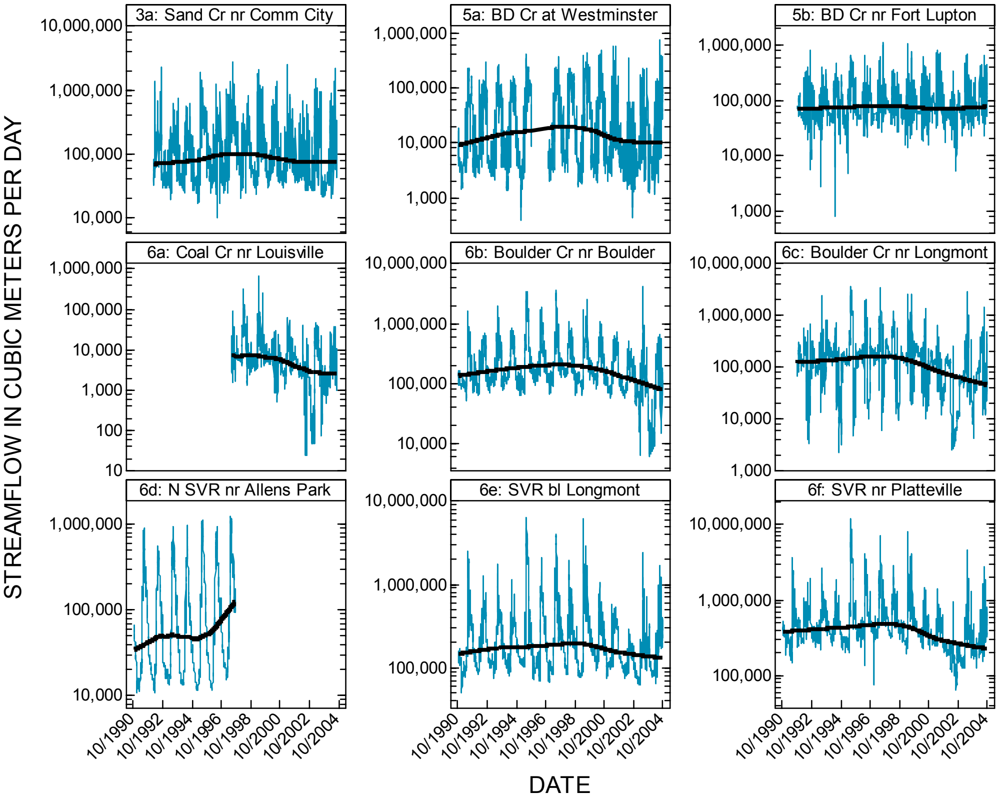

Figure A-4. Time series plots of streamflow with LOWESS smoothing lines at selected monitoring sites along Sand, Big Dry, Coal, Boulder Creeks and the Saint Vrain River, water years 1991–2004.

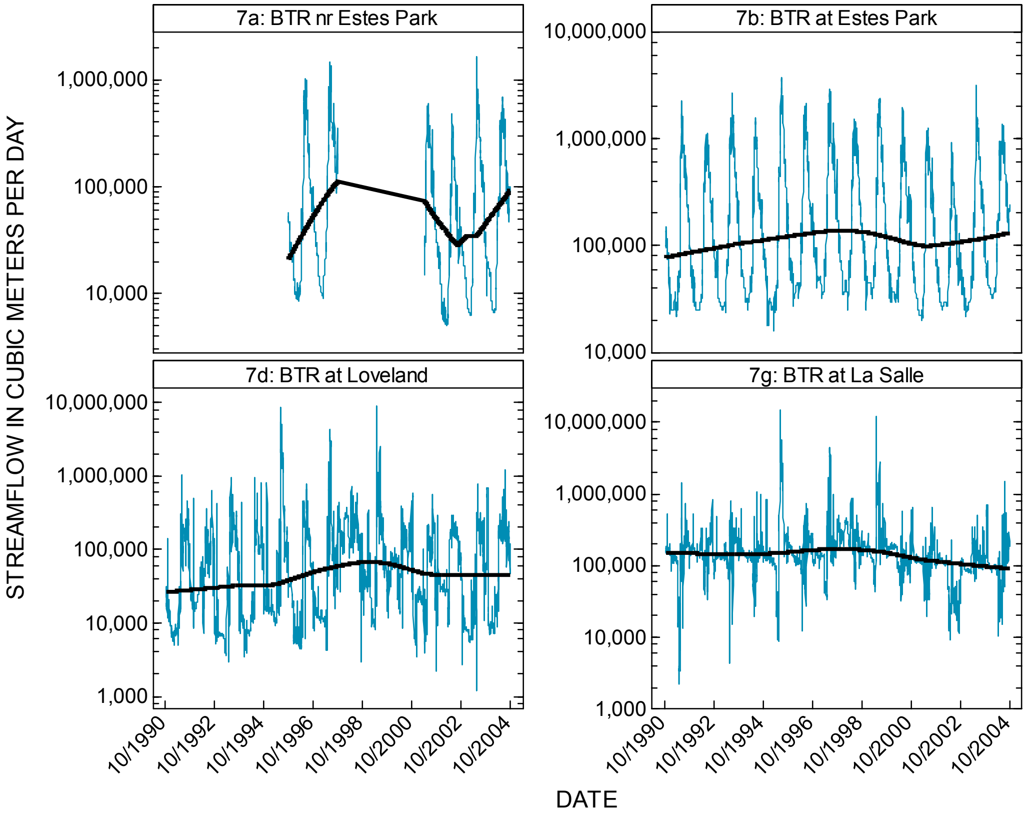

Figure A-5. Time series plots of streamflow with LOWESS smoothing lines at selected monitoring sites along the Big Thompson River, water years 1991–2004.

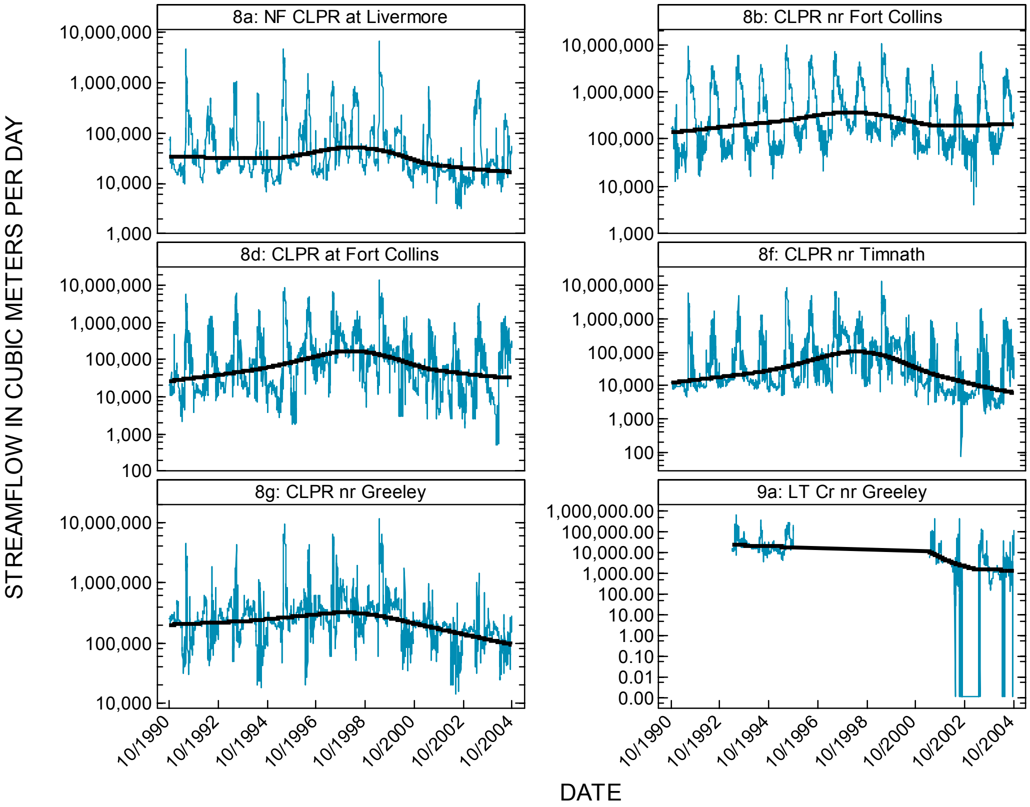

Figure A-6. **Time series plots of streamflow with LOWESS smoothing lines at selected monitoring sites along the Cache la Poudre River and Lone Tree Creek, water years 1991–2004.**

APPENDIX B. ADDITIONAL FIELD OBSERVATIONS

Due to the physical distances between active USGS water quality monitoring sites, additional field measurements of specific conductance were performed along tributaries of the South Platte River in order to discern the location and magnitude of salinity increases along these rivers in greater detail than the historical data from the fixed monitoring sites. This field monitoring project operated periodically from September through November, 2002 and January to April, 2003. Except for the generally small impact of direct surface evaporation from a river and evapotranspiration by phreatophytes, salinity increases in rivers are caused by inflow of higher-salinity water. Often, this higher-salinity water enters the river as ground water seepage, but contributions can also come from higher-salinity tributaries, overland return flow, or other point sources. This work was performed in the fall when flows were low in order to highlight the segments contributing to salinity increases without the confounding effects of high-volume, low-salinity flows that occur later in the spring and summer. The region was experiencing drought conditions during this time period which reduced flows more than normal and helped ensure the streams were dominated by return flows and point-source discharges. Field measurements were not performed if there had been measurable precipitation in the basin during the past seven days. Monitoring specific conductance of base flows also helps to reduce the variability introduced when measuring sites at different dates.

Measurements were made using a handheld specific conductance meter (YSI, Inc. Model 30, Yellow Springs, Ohio). The instrument's calibration was checked at the beginning of each sampling day using standard reference solutions of 100 and 1,413 µS/cm KCl. Measurements were automatically temperature compensated and reported as µS/cm at 25 degrees Celsius. When flow velocities were high, water samples were obtained using a plastic beaker attached to a rope. After sample retrieval, the specific conductance probe was inserted in the beaker and a reading recorded once the meter achieved a stable reading. When flow velocities were lower, the probe was lowered directly into the river until a stable reading was achieved. Tests comparing results obtained using both methods on the same river location showed no significant differences between the methods as long as flow velocity was low enough to allow the probe to remain submerged. With both sampling methods, attempts were made to obtain the sample from the upper half of the water column to reduce anomalous effects from localized groundwater seepage into the river. When possible, measurements were taken from at least three points across the width of the river and the results averaged.

Preliminary surveys at widely-spaced measuring points were performed in the Saint Vrain, Big Thompson, and Cache la Poudre basins. Follow-up measurements at more closely-spaced intervals were performed for river segments exhibiting large changes in SC between the initial measurement points. Many of the original sites were re-sampled during these follow-up visits. Follow-up measurements at the same locations one or two months later generally recorded slightly higher SC values; however several locations had small decreases. Results were averaged at sites having multiple measurements. Ideally all measurements would have been made within a shorter timeframe; however that was precluded by resource limitations. Resource limitations also did not allow for flow measurement at each of the sampling locations. Visual descriptions of the flow were recorded. Flow was generally very low at all locations during the field sampling period.

Results of field measurement of SC at more finely-spaced intervals than were available in the historical USGS data for the Saint Vrain, Big Thompson, and Cache la Poudre basins are shown in Figure B-1. Specific conductance generally increased in a downstream direction with the exception of the Cache la Poudre River downstream from Fort Collins and a section of Boulder Creek on the eastern edge of the city of Boulder. Increases in SC occur in each of the three tributaries included in this sampling program occur as they flow through urban areas west of Interstate 25, however it is unknown whether the increase is a result of urban impacts or similar geology in the north-south plane where these cities developed. Evidence for the later explanation is provided by observations along Left Hand Creek which shows similar increases in SC in this region even though it is not flowing through an urbanized area. Other notable increases in SC observed as a result of this field sampling occur on both the Big Thompson River and the Saint Vrain River between Interstate 25 and their confluence with the South Platte River.

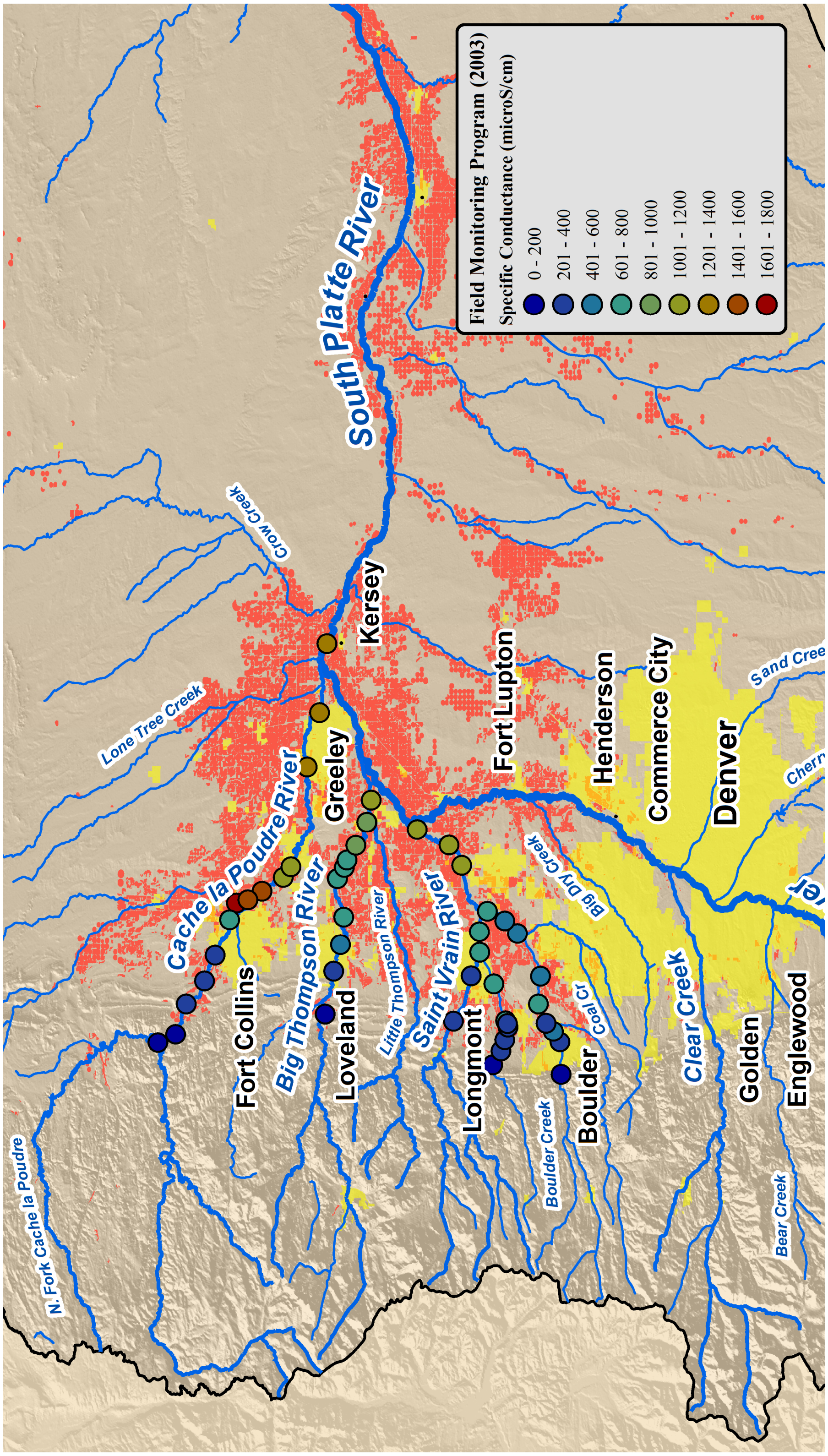

Figure 9-1. Results of additional field measurements of specific conductance, September through November, 2002.

In the case of the Cache la Poudre River, SC doubled from near 700 µS/cm to 1,400 µS/cm in the region between Fort Collins and Interstate 25. Just downstream of this zone and east of Interstate 25, specific conductance decreased to around 1,000 µS/cm before slowly increasing to 1,200 µS/cm just west of Greeley and then to 1,400 µS/cm east of Greeley near the junction with the South Platte River. An additional sampling event conducted January 13, 2003 between Fort Collins and Greeley showed a similar magnitude and pattern of SC values. A more detailed, late-winter 2006 investigation of the region with the sharp increase in SC between Fort Collins and Interstate 25 found the river flowed through a reclaimed aggregate quarry with many ponds and wetland areas. This area is now two natural areas for the city of Fort Collins: Cottonwood Hollow and Running Dear Natural Areas. Several groundwater seeps and drainage canals in these areas were found to have SC of 1,500 µS/cm to 2,600 µS/cm. A channel of the Cache la Poudre River flows through a large wetland area and is joined by water from the seeps and canals. Farther downstream, Boxelder Creek empties into the Cache la Poudre just west of Interstate 25 near the western edge of the natural areas. Boxelder Creek originates north of Fort Collins near Wellington, Colorado and flows south. Water near the mouth of Boxelder Creek had a SC of 2,300 µS/cm. Upstream of these natural areas the Cache la Poudre River is diverted in several places resulting in low flow through these natural areas for much of the year. It appears that the low river flow allows the small flow contributions from the higher salinity seeps, canals, and Boxelder Creek to have a significant impact on river salinity within this region.

APPENDIX C. DISSOLVED SOLIDS CONCENTRATION TIME SERIES PLOTS - PERIOD OF RECORD

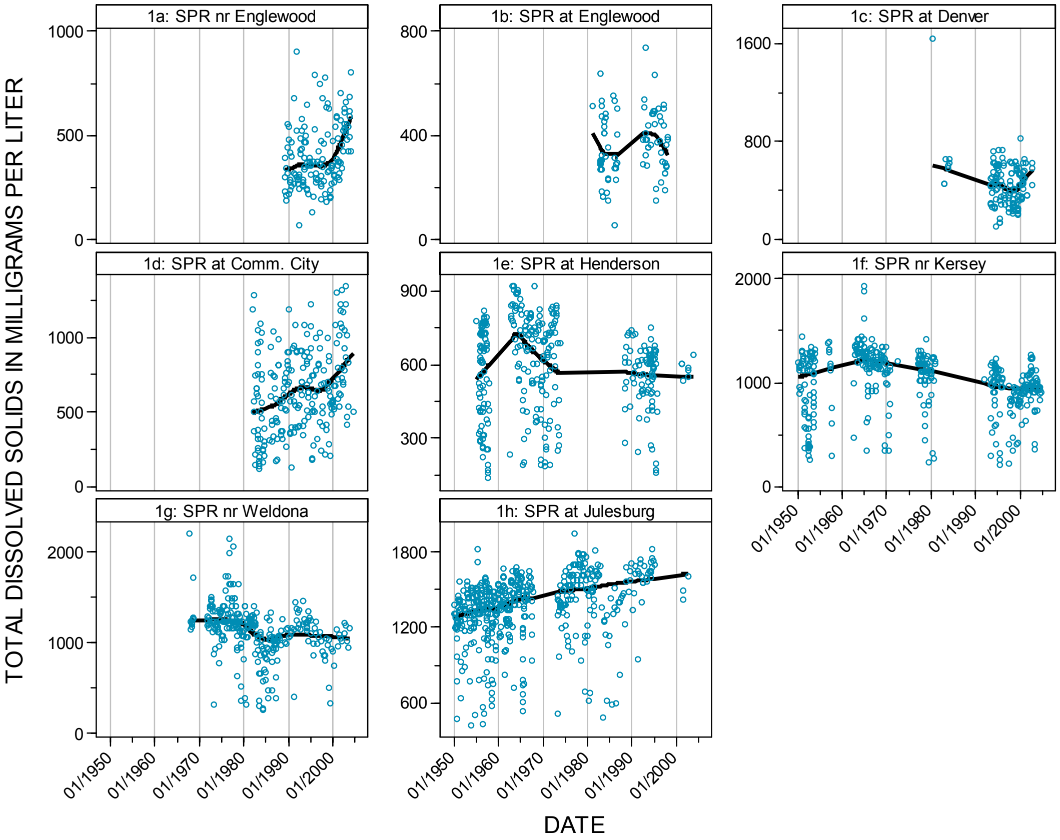

Figure C-1. Time series plots of TDS concentration with LOWESS smoothing lines at selected monitoring sites along the mainstem of the South Platte River, January 1950–October 2004.

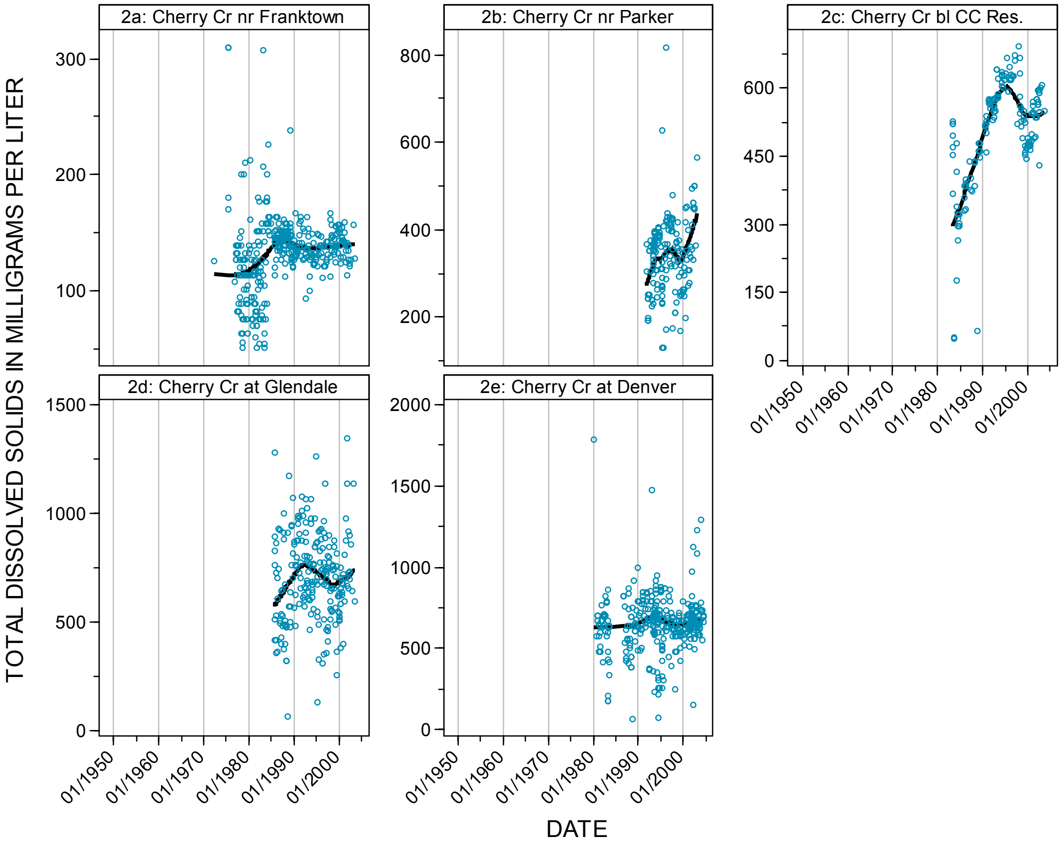

Figure C-2. Time series plots of TDS concentration with LOWESS smoothing lines at selected monitoring sites along Cherry Creek, January 1950–October 2004.

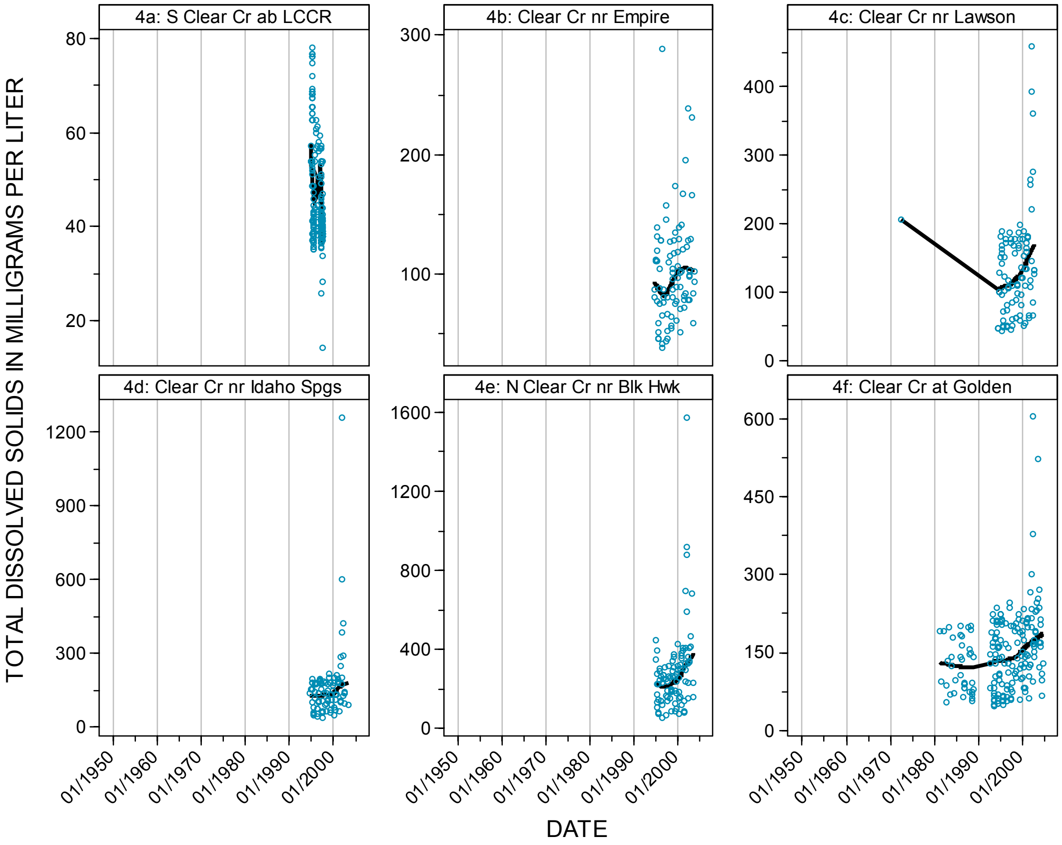

Figure C-3. Time series plots of TDS concentration with LOWESS smoothing lines at selected monitoring sites along Clear Creek, January 1950–October 2004.

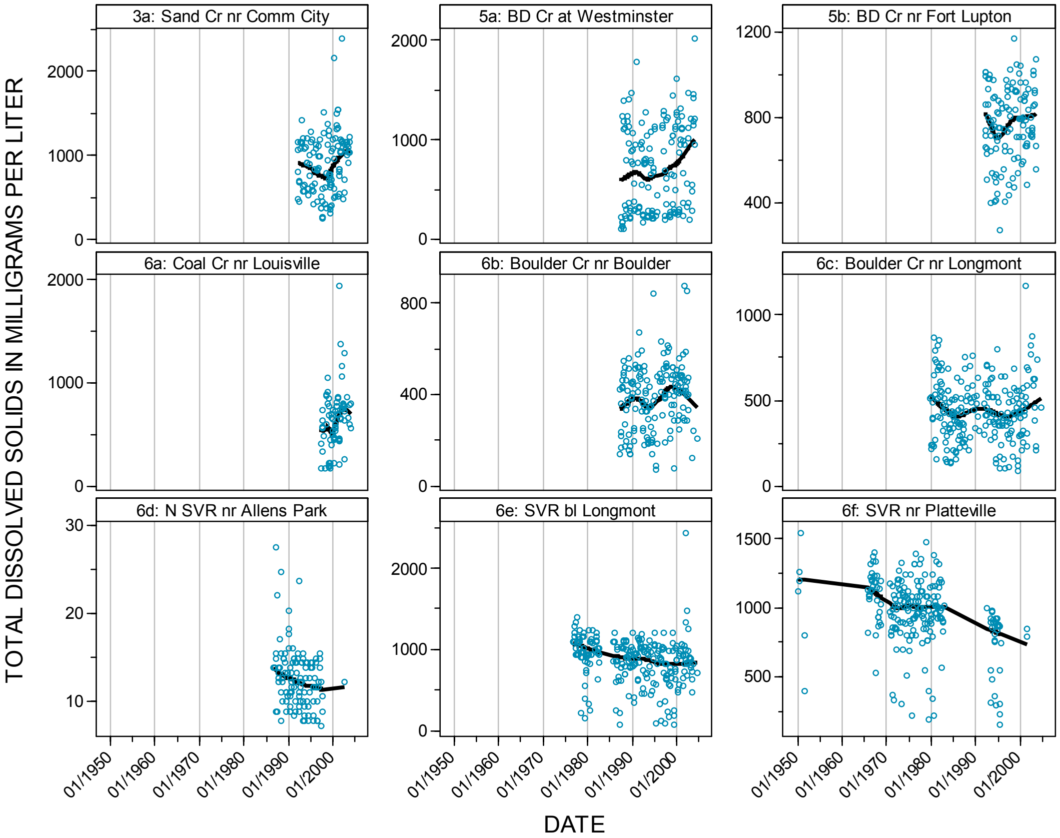

Figure C-4. Time series plots of TDS concentration with LOWESS smoothing lines at selected monitoring sites along Sand, Big Dry, Coal, and Boulder Creeks, and the Saint Vrain River, January 1950–October 2004.

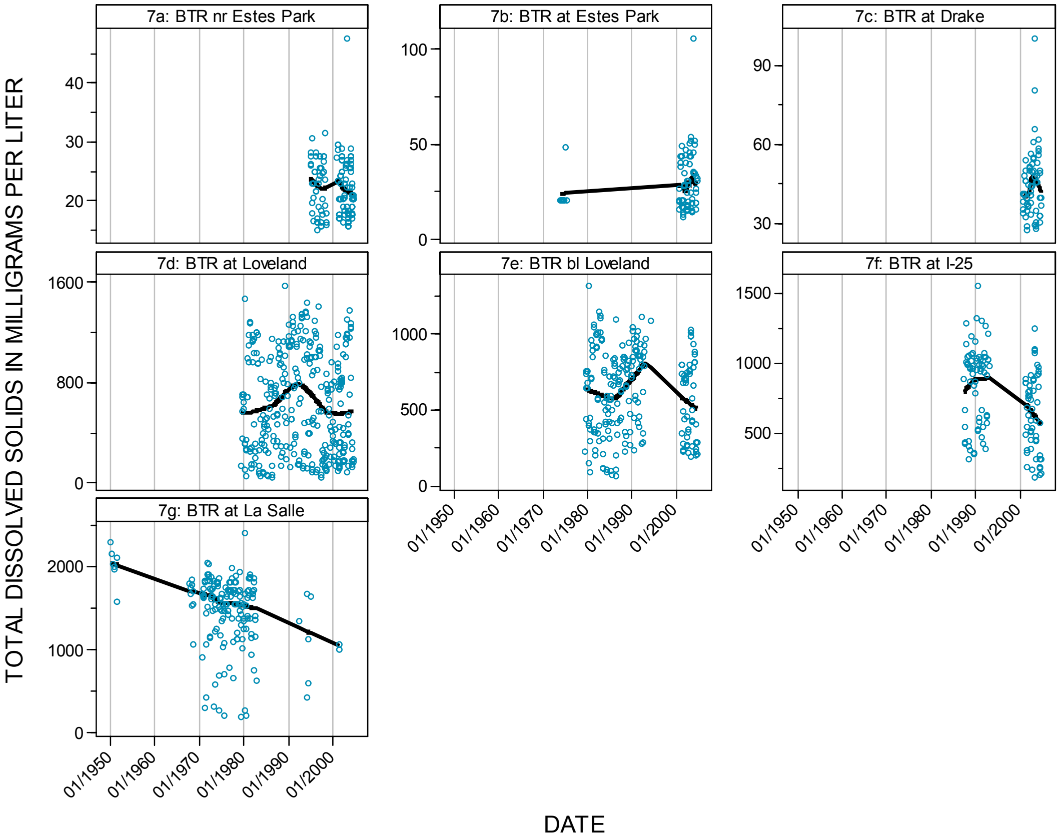

Figure C-5. Time series plots of TDS concentration with LOWESS smoothing lines at selected monitoring sites along the Big Thompson River, January 1950–October 2004.

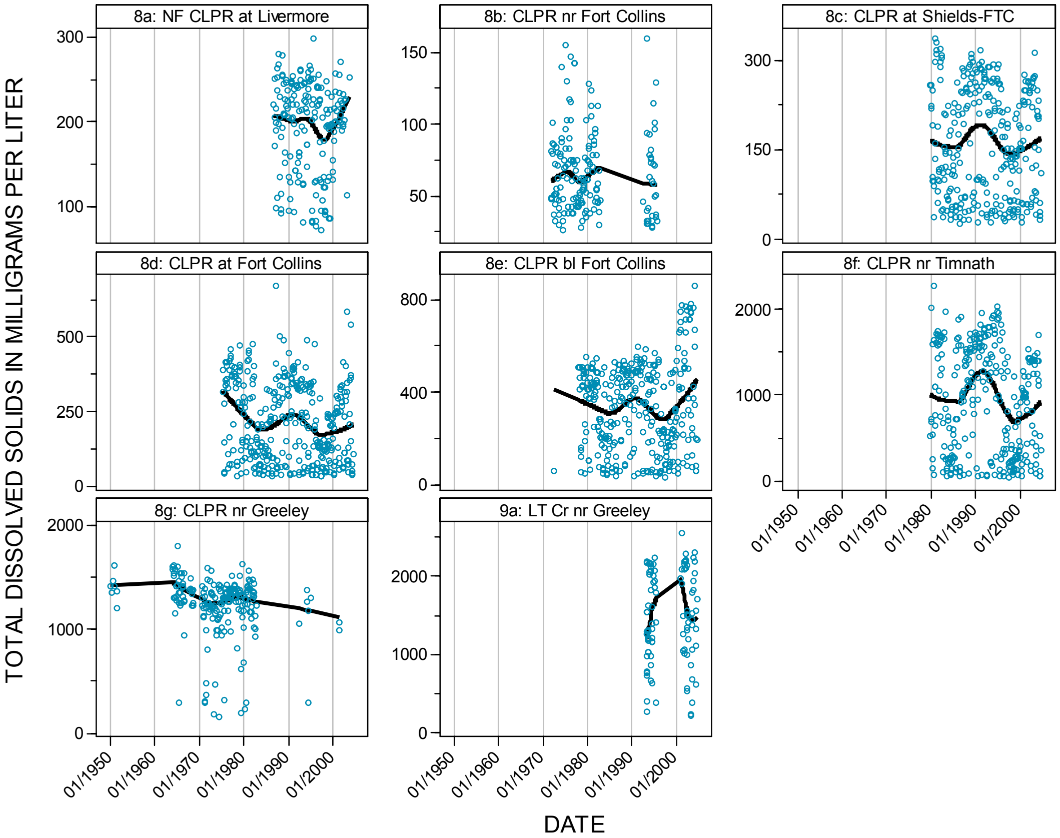

Figure C-6. Time series plots of TDS concentration with LOWESS smoothing lines at selected monitoring sites along the Cache la Poudre River and Lone Tree Creek, January 1950–October 2004.

APPENDIX D. TIME-SERIES PLOTS OF REGRESSION-CALCULATED DAILY DISSOLVED SOLIDS LOADS AND LOADS DETERMINED FROM PERIODIC SAMPLING

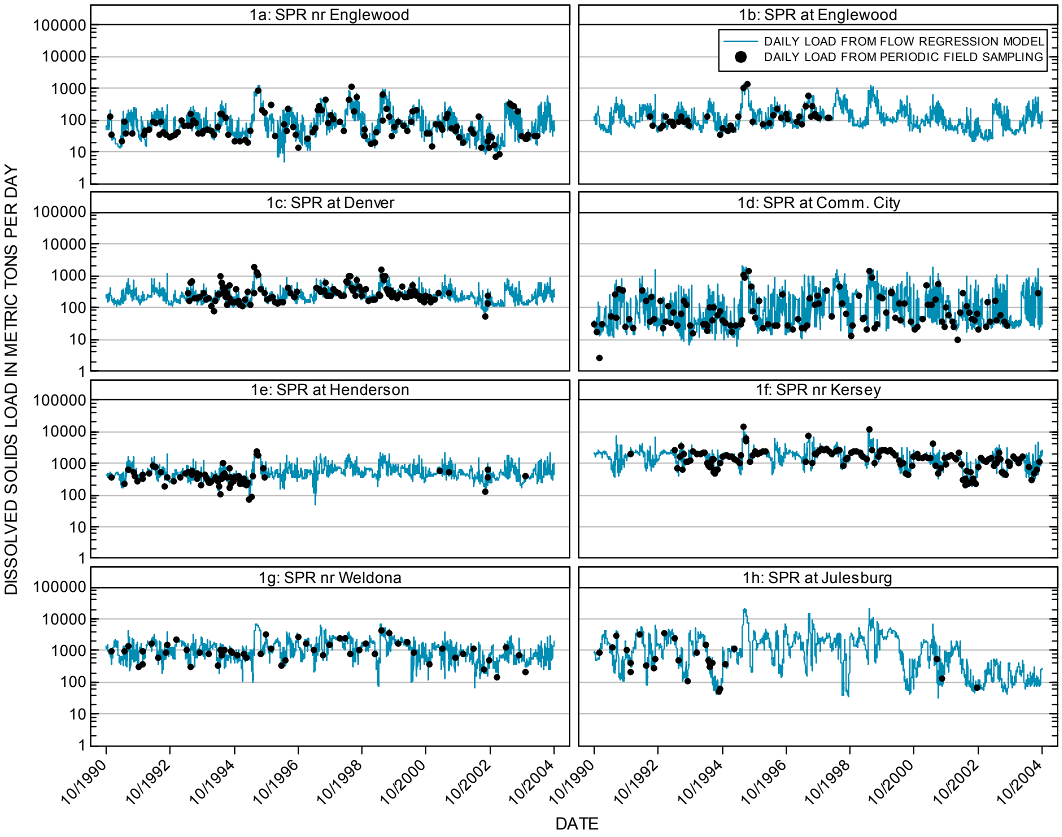

Figure D-1. **Comparison of loads calculated from periodic TDS measurements and daily loads estimated from daily flow for water years 1991 – 2004, mainstem South Platte River.**

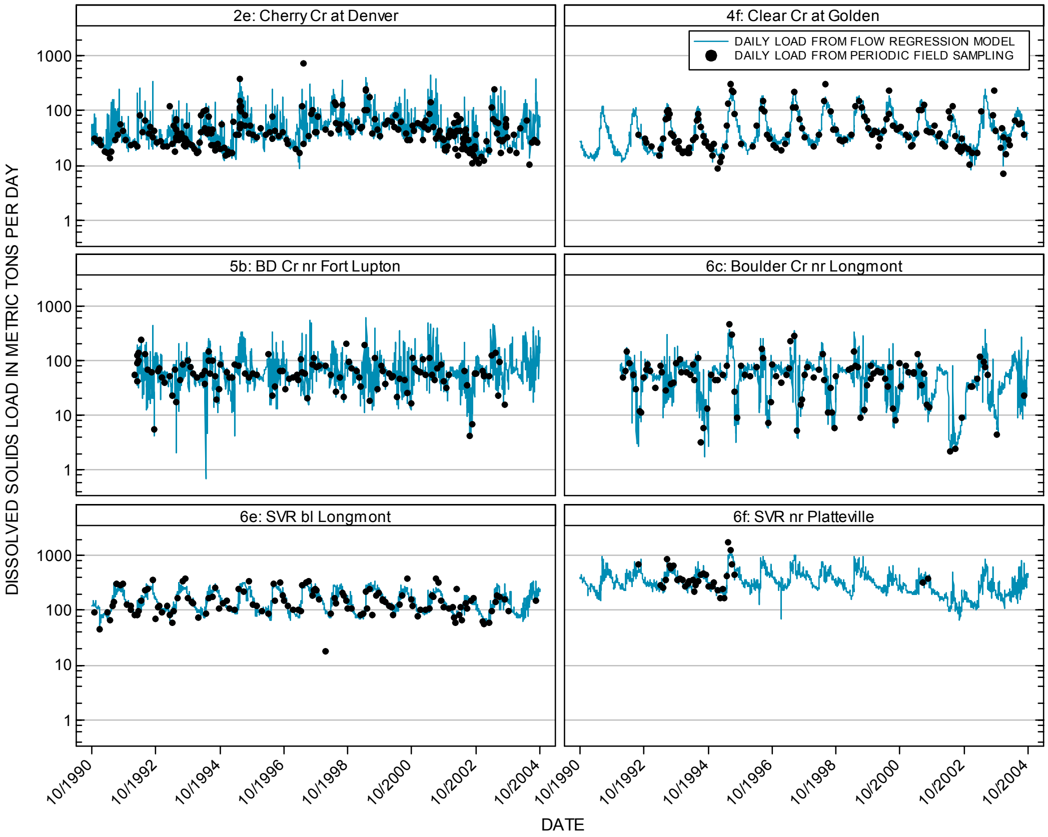

Figure D-2. **Comparison of loads calculated from periodic TDS measurements and daily loads estimated from daily flow for water years 1991 – 2004, Cherry, Clear, Big Dry, and Boulder Creeks and the Saint Vrain River.**

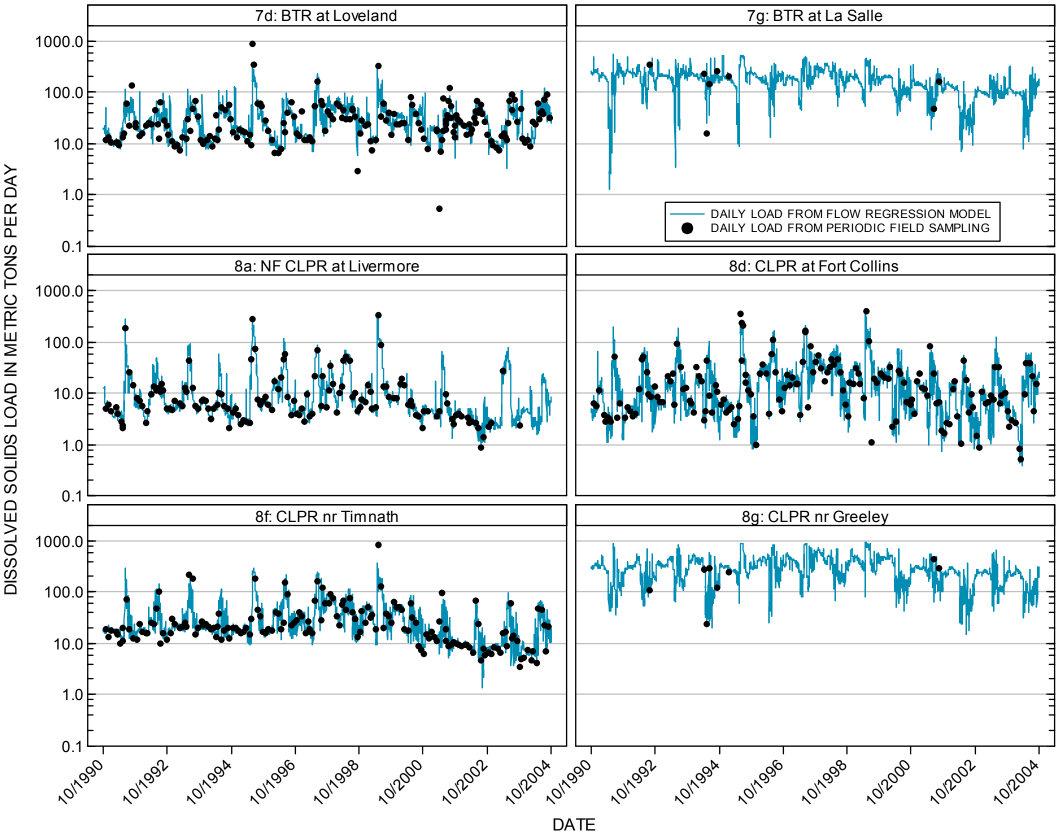

Figure D-3. **Comparison of loads calculated from periodic TDS measurements and daily loads estimated from daily flow for water years 1991 – 2004, Big Thompson and Cache la Poudre Rivers.**