USGS
science for a changing world

SIMULATED EFFECTS OF WATER EXCHANGES ON STREAMFLOW AND SPECIFIC CONDUCTANCE IN THE ARKANSAS RIVER UPSTREAM FROM AVONDALE, COLORADO

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 98–4140

Prepared in cooperation with the
COLORADO SPRINGS UTILITIES; PUEBLO BOARD OF WATER WORKS; SOUTHEASTERN COLORADO WATER CONSERVANCY DISTRICT; PUEBLO COUNTY, DEPARTMENT OF PLANNING AND DEVELOPMENT; CITY OF AURORA, DEPARTMENT OF UTILITIES; ST. CHARLES MESA WATER DISTRICT; UPPER ARKANSAS AREA COUNCIL OF GOVERNMENTS; UPPER ARKANSAS WATER CONSERVANCY DISTRICT; CITY OF PUEBLO, DEPARTMENT OF UTILITIES; PUEBLO WEST METROPOLITAN DISTRICT; FREMONT SANITATION DISTRICT; CITY OF ROCKY FORD; CITY OF LAS ANIMAS; AND CITY OF LAMAR

Simulated Effects of Water Exchanges on Streamflow and Specific Conductance in the Arkansas River Upstream from Avondale, Colorado

By Michael E. Lewis

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 98–4140

Prepared in cooperation with the
COLORADO SPRINGS UTILITIES; PUEBLO BOARD OF WATER WORKS; SOUTHEASTERN COLORADO WATER CONSERVANCY DISTRICT; PUEBLO COUNTY, DEPARTMENT OF PLANNING AND DEVELOPMENT; CITY OF AURORA, DEPARTMENT OF UTILITIES; ST. CHARLES MESA WATER DISTRICT; UPPER ARKANSAS AREA COUNCIL OF GOVERNMENTS; UPPER ARKANSAS WATER CONSERVANCY DISTRICT; CITY OF PUEBLO, DEPARTMENT OF UTILITIES; PUEBLO WEST METROPOLITAN DISTRICT; FREMONT SANITATION DISTRICT; CITY OF ROCKY FORD; CITY OF LAS ANIMAS; AND CITY OF LAMAR

Denver, Colorado
1999

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information write to:

District Chief
U.S. Geological Survey
Box 25046, Mail Stop 415
Denver Federal Center
Denver, CO 80225-0046

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Box 25286
Federal Center
Denver, CO 80225

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND ACRONYMS

Multiply	By	To obtain
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per day (acre-ft/d)	1,233	cubic meter per day
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer

The following terms and abbreviations are used in this report:

microsiemens per centimeter at 25 degrees Celsius (µS/cm)
milligrams per liter (mg/L)

Simulated Effects Of Water Exchanges on Streamflow and Specific Conductance in the Arkansas River Upstream from Avondale, Colorado

By Michael E. Lewis

Abstract

The potential effects of future water-exchange scenarios on streamflow and specific conductance in the Arkansas River were simulated with two accounting models. The major processes in the models simulated the historical exchange potential in the Arkansas River and the operation of a native and a nonnative Arkansas River water exchange. The potential effects of future exchange conditions were simulated using streamflow and specific-conductance data from the 1986–93 water-year study period. Hydrologic conditions during the study period were considered about average, compared to the long-term (1966–96) conditions. Therefore, the simulation results were indicative of the potential effects of future exchange conditions on streamflow and specific conductance during periods of average hydrologic conditions.

The city of Colorado Springs, Colorado, currently (1998) has an Arkansas River transmountain return-flow exchange demand of about 60 acre-feet per day. In the future, that exchange demand could increase to about 360 acre-feet per day. The city of Aurora has an exchange demand, which varies seasonally from 21.8 to 63.5 acre-feet per day, for Arkansas River Basin agricultural water that the city purchased for municipal use. Potential future exchange scenarios involving increases in the historical (1986–93) transmountain return-flow exchange demand for Colorado Springs combined with the maximum potential exchange demand for Aurora were simulated. In addition, the size of the storage space in Pueblo Reservoir, which is used for the temporary storage of exchanged transmountain return flows, was varied in the simulations.

Simulated streamflow in the Arkansas River decreased at all streamflow-gaging stations located between Twin Lakes Reservoir and the mouth of Fountain Creek for all exchange scenarios. The decrease in streamflow was proportional to the magnitude of the simulated exchanges. The simulated decrease in streamflow ranged from about 4 percent for a simulation of Aurora's maximum exchange demand and a 50-percent increase in Colorado Springs' historical exchange demand to about 23 percent for a simulation of the maximum exchange demand for both exchanges. Simulated streamflow at Avondale, a site located 14 miles downstream from the confluence with Fountain Creek, was relatively unaffected by most scenarios; however, simulated streamflow increased about 8 to 12 percent at Avondale in response to the simulations of the maximum increase in exchange demand.

Simulated specific conductance increased at all stations in response to the simulated exchanges. The median increase in the daily mean specific conductance at all stations ranged from a minimum of about 1 percent for a simulation of Aurora's maximum exchange demand and a 50-percent increase in Colorado Springs' historical exchange demand to about 7 percent for a

simulation of the maximum exchange demand for both exchanges. The simulated increase in specific conductance resulted in an increased frequency of exceedance of the secondary drinking-water standard for dissolved solids of 500 milligrams per liter during low-flow months at a site located 9 miles downstream from Pueblo Reservoir. The simulated increase in salinity did not result in any changes in the historical irrigation salinity hazard for water in the Arkansas River.

INTRODUCTION

The Arkansas River in southeastern Colorado (fig. 1) is an important municipal water supply and is the primary supply for agricultural irrigation for about 400,000 acres of land in the Arkansas River Basin. Much of the Arkansas River is affected by high salinity, a problem that Batie and Healy (1983, p. 50) described as the "most pervasive problem associated with irrigated agriculture" in the United States. Specific conductance, which is a surrogate measurement for salinity, increases from a mean of about 230 μS/cm in the headwaters near Leadville to about 3,770 μS/cm at the Colorado-Kansas State line 370 mi downstream (Cain, 1987). The downstream increase in specific conductance is largely due to the consumptive use of surface water and ground water by agricultural irrigation (Miles, 1977; Cain, 1987). Elevated salinity can impair the suitability of water for domestic, agricultural, and industrial use.

The use of water exchanges as a management tool for municipal water supplies in the Arkansas River Basin has raised concerns about their potential effect on salinity. A water exchange is made by diverting water at one location in the river system and replacing it with a like quantity of water at another location. Exchanges are generally made from a downstream location to an upstream location, where storing or diverting the water may be more economically beneficial. During an exchange, streamflow in the reach between the two exchange locations is decreased by the amount of the exchange. The water that is replaced at the downstream location of the exchange maintains streamflow downstream from that location at a pre-exchange level, thus avoiding injury to any senior water-right holders. For example, an exchange of 100 acre-ft of water from storage in Pueblo Reservoir to storage in Twin Lakes Reservoir (fig. 1) would result in the outflow from Twin Lakes Reservoir being decreased by 100 acre-ft and the outflow from Pueblo Reservoir being increased by 100 acre-ft. Additionally, the water that is replaced to the river at the downstream end of the exchange reach is required to be of a quality that meets the requirements of use to which senior water-right appropriations have normally been put. The decreased streamflow in the stream reach between the two exchange locations has less dilutive capacity and might be susceptible to increased salinity. The problem of susceptibility to increased salinity could be compounded if the exchange water that is replaced at the downstream end of the exchange reach has a higher salinity than the water that was diverted or stored at the upstream end of the exchange reach.

The city of Colorado Springs currently (1998) exchanges sewered and nonsewered return flows, which originate from its importation and use of nonnative water, for water in the Arkansas River. Likewise, the city of Aurora currently (1998) exchanges water associated with its purchase of Arkansas River agricultural water rights in Rocky Ford Ditch for water used to augment Aurora's municipal water supply. Water exchanges by Colorado Springs and Aurora are anticipated to increase in the future and potentially could affect salinity in the Arkansas River.

Beginning in 1988, the U.S. Geological Survey initiated a basinwide study of water quality in the Arkansas River and of the effects of certain water-supply operations on water quality, including the potential effects of water exchanges on streamflow and specific conductance in the lower Arkansas River. The study was conducted in cooperation with the Colorado Springs Utilities; Pueblo Board of Water Works; Southeastern Colorado Water Conservancy District; Pueblo County, Department of Planning and Development; City of Aurora, Department of Utilities; St. Charles Mesa Water District; Upper Arkansas Area Council of Governments; Upper Arkansas Water Conservancy District; City of Pueblo, Department of Utilities; Pueblo West Metropolitan District; Fremont Sanitation District; and the Cities of Rocky Ford, Las Animas, and Lamar.

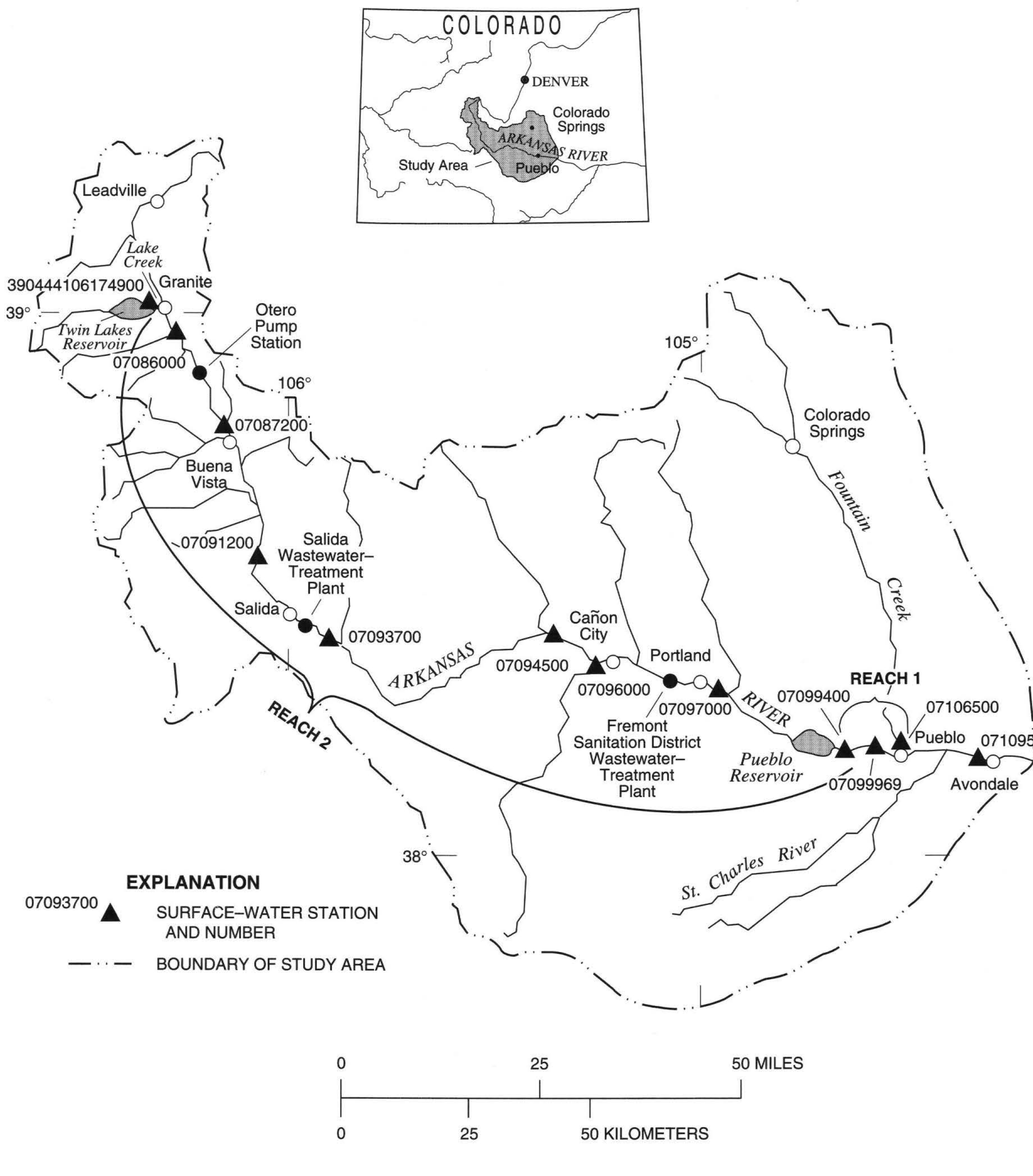


Figure 1. Location of the study area and selected surface-water stations.

Purpose and Scope

This report presents the results of a study of the simulated effects of water exchanges on streamflow and specific conductance in the Arkansas River. The cumulative effects of two different exchanges were simulated: (1) Colorado Springs' transmountain return-flow exchange, and (2) Aurora's Rocky Ford Ditch exchange. The two accounting models selected for the exchange simulation were modified from models used by Enartech Consulting Engineers and Hydrologists (1992) to simulate exchange operations between Pueblo Reservoir and alternate points of storage and diversion in the upper basin of the Arkansas River. For the current (1998) study, nine different scenarios of exchange were simulated for water years 1986–93. The nine scenarios span a range of potential future exchange rates and storage conditions. The 8-year study period was selected for use in the simulations because of the availability of daily streamflow and specific-conductance data at several key locations on the Arkansas River and on Fountain Creek. The models use basic accounting procedures and relations between streamflow and specific conductance to superimpose potential future exchange scenarios on hydrologic conditions for water years 1986–93.

Description of Study Area

The study area is located in the Arkansas River Basin of southeastern Colorado and includes the main stem of the Arkansas River from Twin Lakes Reservoir 167 mi downstream to streamflow-gaging station 07109500 near Avondale (fig. 1). Precipitation and transmountain (nonnative) diversions are the principal sources of water in the basin. The average annual precipitation varies areally from more than 40 to less than 10 in., generally decreasing with decreasing elevation. Snowmelt supplies a large percentage of the total annual streamflow. Transmountain diversions of water from west of the Continental Divide are supplied from several sources. Much of this water is routed to Twin Lakes Reservoir (fig. 1). Transmountain water is routinely released to the Arkansas River from storage in Twin Lakes Reservoir to meet downstream irrigation and municipal-supply demands. Alternatively, native or transmountain water belonging to Colorado Springs or Aurora can be directly diverted from Twin Lakes Reservoir into a pipeline for delivery to the municipal water-supply systems of the two cities. A detailed description of the transmountain-water diversion and delivery systems is provided by Abbott (1985).

Pueblo Reservoir, located on the main stem of the Arkansas River, is used for the storage and regulation of native and transmountain water as part of the Fryingpan-Arkansas Project. The Fryingpan-Arkansas Project is a multipurpose water project constructed by the Bureau of Reclamation. Most of the storage space in Pueblo Reservoir is reserved for Fryingpan-Arkansas Project water, although storage of some non-project water is granted when space is available under a limited number of storage contracts. Colorado Springs currently (1998) has a 6,000-acre-ft storage contract and Aurora has a 10,000-acre-ft storage contract. This storage space may be used for the storage of exchangeable water.

Streamflow in the study area is affected by the timing and magnitude of snowmelt and rainfall runoff; tributary inflow; streamflow diversions for agricultural, municipal, and industrial use; and reservoir operations. Daily streamflow in the Arkansas River averaged about 748 ft^3/s at station 07097000 Arkansas River at Portland, 700 ft^3/s at station 07099400 Arkansas River above Pueblo, and 908 ft^3/s at station 07109500 Arkansas River near Avondale during water years 1986–93. At the Avondale station, which is the farthest downstream station in the study area, the median annual streamflow during the study period was 800 ft^3/s, which was not significantly different (two-sided p-value equals 0.98 using the Wilcoxon rank sum test) from the median annual streamflow (829 ft^3/s) for water years 1966–96. Because streamflow conditions for water years 1986–93 were about average compared to long-term conditions (water years 1966–96), it is believed that the results of this study are indicative of the potential response of streamflow and specific conductance to different scenarios of exchange for periods of average hydrologic conditions.

Fountain Creek is an important tributary in the study area because it is used to convey transmountain return flows from Colorado Springs 42 mi downstream to the Arkansas River (fig. 1). Expected future growth by the city of Colorado Springs would result in greater water use and large volumes of discharge from the wastewater-treatment plant. In addition, the proportion of transmountain return flows probably would increase because additional native water supplies currently (1998) are not available to the city of Colorado Springs, which means increased dependence on transmountain water for new water supplies.

Specific conductance in the study area varies spatially and temporally (fig. 2). Specific conductance increases downstream because of several factors, including: (1) A transition from chemically resistant igneous and metamorphic geology upstream from Cañon City to less chemically resistant sedimentary geology downstream from Cañon City, (2) inflows of agricultural irrigation return flows, and (3) inflows of sewered and nonsewered return flows from municipal areas. Specific conductance generally is inversely proportional to streamflow, is lowest during the high flow of late spring and summer, and increases with decreasing streamflow in the fall and winter.

Acknowledgments

The author wishes to thank Julie Krause and Jerry Knapp, City of Aurora, Department of Utilities; Philip Saletta and Brett Gracely, Colorado Springs Utilities; and Bud O'Hara, Pueblo Board of Water Works, for discussions relating to water exchanges. Additionally, the assistance provided by Kerry D. Sundeen, Enartech Consulting Engineers and Hydrologists, in discussions related to the simulation of exchange potential and exchange operations in the Arkansas River is acknowledged. Finally, streamflow and streamflow-diversion data provided by Steve Witte, Colorado Division of Water Resources, are greatly appreciated.

DESCRIPTION OF WATER EXCHANGES

Colorado Springs, like most large cities along the Front Range of Colorado, augments its water supplies with water imported from the western slope of the Continental Divide (transmountain water). Such water is nonnative to the basin in which it is used, and Colorado water laws that govern use of nonnative water are different from laws that govern use of water that originates in the basin (native water). For nonnative water, Colorado water law provides: (1) The right for reuse of nonnative water (subsequent use for same purpose as original use); (2) the right for successive use of nonnative water (subsequent use for a different use); and (3) the right of disposition, or right to sell, lease, exchange, or otherwise dispose of nonnative water (Radosevich and others, 1976). Transmountain water, then, can be used and reused until totally consumed, whereas native water can be used only once by any given water-right holder. Historically, Colorado Springs has directly reused or exchanged part of the return flows that originated from the use of its transmountain water (Kuhn, 1988). The remaining transmountain return flows have been discharged to Fountain Creek through the Colorado Springs wastewater-treatment plant. Lesser volumes of transmountain return flow enter Fountain Creek from nonsewered return-flow sources, such as lawn watering. In the future, and in accordance with its transmountain return-flow exchange decrees (case 84–CW–203 and 89–CW–36, District Court, Water Division No. 2, State of Colorado) and its Arkansas River exchange plan (Gronning Engineering Company, 1986), Colorado Springs plans to completely use its transmountain return flows by water exchanges and other arrangements.

The transmountain return-flow exchange decrees allow Colorado Springs to use, reuse, and successively use its transmountain return flows to extinction. The exchange plan allows for the conveyance of return flows down Fountain Creek from Colorado Springs to the Arkansas River, the exchange from the Fountain Creek confluence into Pueblo Reservoir, and the exchange into other upstream storage and diversion facilities. The essence of the Colorado Springs Arkansas River exchange plan is that transmountain return flows reaching the Arkansas River at the mouth of Fountain Creek would be used to satisfy downstream senior priority water rights on the Arkansas River. Satisfaction of this need would enable storage of a similar volume of water in Pueblo Reservoir (fig. 1). After diversion to storage at Pueblo Reservoir, Colorado Springs' transmountain return flows then may be exchanged for water in the upper basin (upstream from Pueblo Reservoir). Temporary storage of transmountain return flows in Pueblo Reservoir enables Colorado Springs to maintain legal dominion over its exchangeable water at times when streamflow conditions prevent an exchange into upper basin reservoirs or diversion facilities. The most

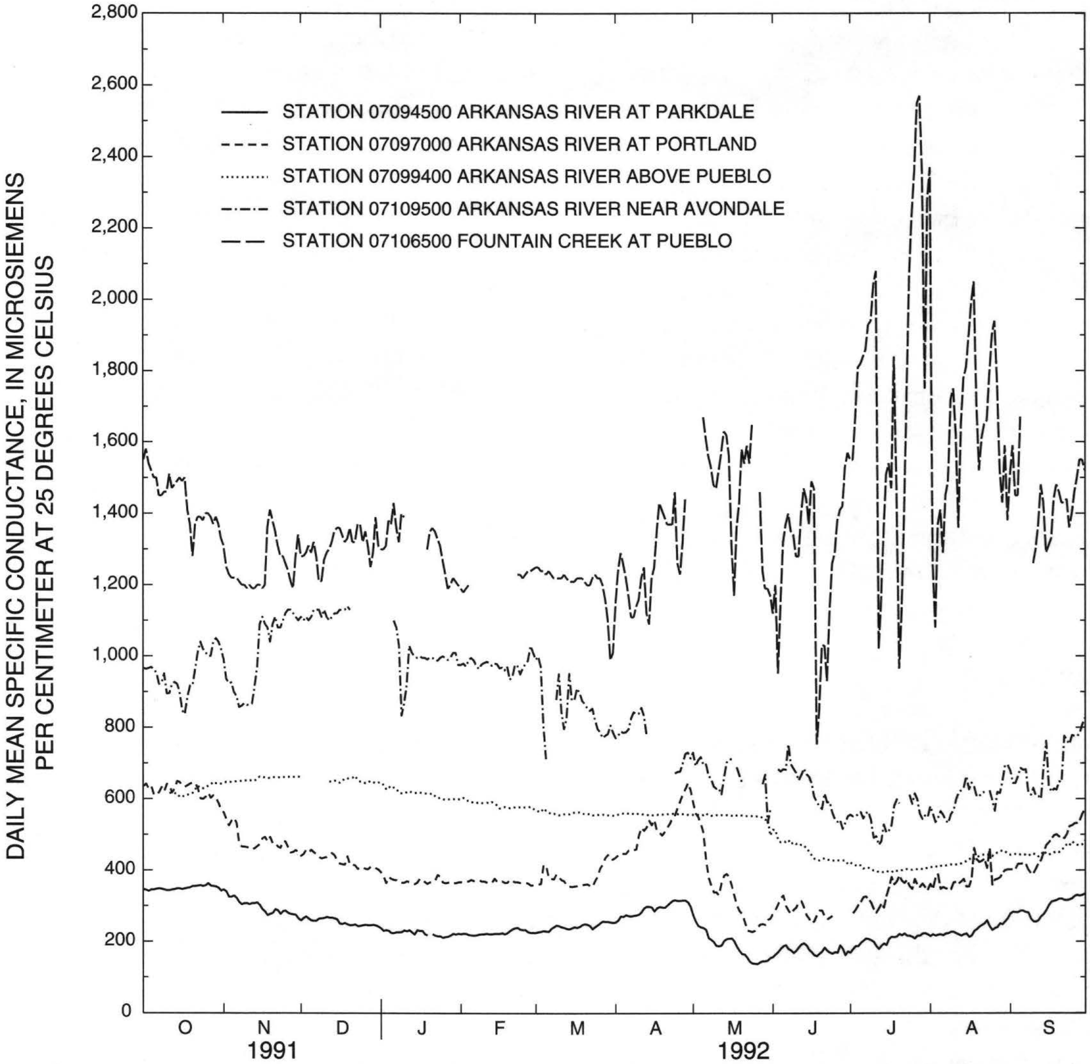


Figure 2. Daily mean specific conductance in the Arkansas River and Fountain Creek, water year 1992.

commonly used upstream storage facility is Twin Lakes Reservoir. Once exchanged to Twin Lakes Reservoir, the water can be stored for later use or may be pumped directly into the water-collection system for Colorado Springs through the Otero pump station (fig. 1) and pipeline, a structure co-owned by Aurora.

Colorado Springs first executed the transmountain return-flow exchange in 1981 and currently (1998) has an exchange demand of about 60 acre-ft/d and a potential maximum exchange demand of about 360 acre-ft/d (Gronning Engineering Company, 1986; Brett Gracely, City of Colorado Springs, written commun., 1997). The water-collection system and the Arkansas River exchange plan for Colorado Springs are described in detail by the Gronning Engineering Company (1986).

Aurora is located east of Denver outside the Arkansas River Basin. In 1983, Aurora augmented its municipal water supply with the purchase of a 60-percent share of the Rocky Ford Ditch and a prorated share of the associated native Arkansas River water rights; the Rocky Ford Ditch is an irrigation canal located in the Arkansas River Basin about 32 mi downstream from Pueblo. In case number 83–CW–18 of the Colorado District Court, Water Division 2, Aurora was granted a change in water right for its share of the Rocky Ford Ditch Company's water. This change in water right authorizes the use of the water for municipal and domestic purposes and the successive use of the water to the extent that it was historically consumed. The historical consumptive use of Aurora's share of the canal company's water was about 8,250 acre-ft/yr. As specified in the decree, Aurora may annually divert and, subsequently, use and reuse as much as 8,250 acre-ft/yr of Rocky Ford Ditch water at Pueblo Reservoir. The water that Aurora diverts at Pueblo Reservoir is of little direct use to Aurora because Aurora has no direct means of delivering the water from the reservoir to the city. However, as outlined in its exchange plan (Enartech Consulting Engineers and Hydrologists, 1991), Aurora may exchange its water from storage in Pueblo Reservoir for water in the upper basin (upstream from Pueblo Reservoir) after diverting water to storage at Pueblo Reservoir. The most commonly used upstream storage facility is Twin Lakes Reservoir.

Under the terms of its Rocky Ford Ditch exchange decree, Aurora may divert streamflow into storage at Pueblo Reservoir during the irrigation season (March 15–October 31) at a monthly variable rate (table 1). The diversion rate varies from a minimum of 21.8 acre-ft/d in March to a maximum of 63.5 acre-ft/d in June and July. Once exchanged to Twin Lakes Reservoir, the water can be stored for later use or pumped directly into the water-collection system for Aurora through the Otero pump station and pipeline. Once water is exchanged from Pueblo Reservoir to the upper basin, Aurora must release a like amount of water from Pueblo Reservoir to satisfy downstream priority water rights on the Arkansas River. Since 1994, Aurora has exchanged an average volume of water of about 1,000 acre-ft/yr (Jerry Knapp, City of Aurora, oral commun., 1997). The exchange from Pueblo Reservoir to upstream points of storage or diversion is limited by a maximum exchange rate of 992 acre-ft/d (Enartech Consulting Engineers and Hydrologists, 1991). The decreed change in water right for Aurora's Rocky Ford Ditch water and Aurora's Arkansas River exchange plan are described in detail by Enartech Consulting Engineers and Hydrologists (1991).

Table 1. Diversion rates for Aurora's Rocky Ford Ditch water at Pueblo Reservoir

[acre-ft/d, acre-feet per day; acre-ft, acre-feet]

Period	Daily diversion rate (acre-ft/d)	Total monthy diversion (acre-ft)
March 15–31	21.8	370
April	37.7	1,129
May	45.6	1,412
June	63.5	1,901
July	63.5	1,964
August	59.5	1,841
September 1–15	39.7	594
September 16–30	49.6	743
October	25.7	798

Because the transmountain return-flow exchange for Colorado Springs has a senior administration date, compared to Aurora's Rocky Ford Ditch exchange, Aurora can implement its exchange only if exchange potential remains after the Colorado Springs transmountain return-flow exchange has been operated. Exchange potential is equal to the amount of water that can be exchanged between two locations without depriving senior water-rights holders in the Arkansas River Basin of their legal share of water;

actual exchanges are constrained by physical availability, limitations imposed by State water laws, and legal stipulations to an exchange decree. If insufficient exchange potential precludes Aurora from exchanging its water from Pueblo Reservoir to the upper basin, Aurora may retain the water in its Pueblo Reservoir storage account.

As discussed in the preceding paragraph, an exchange cannot cause material harm to other water appropriators in the Arkansas River Basin. Additionally, the transmountain return-flow exchange for Colorado Springs and the Rocky Ford Ditch exchange for Aurora are restricted by several other legal or voluntary stipulations. For example, the exchanges must be operated to maintain streamflow in the Arkansas River so as not to interfere with the operation of the Salida wastewater-treatment plant and the Fremont Sanitation District wastewater-treatment plant (fig. 1). Specifically, the exchanges may not decrease streamflow at the Salida wastewater-treatment plant to less than 240 ft^3/s in September through June or to less than 260 ft^3/s in July and August. Exchanges may not decrease streamflow at the outfall of the Fremont Sanitation District wastewater-treatment plant to less than 190 ft^3/s throughout the year. Additionally, exchanges into Twin Lakes Reservoir may not diminish streamflow in Lake Creek downstream from Twin Lakes Reservoir to the confluence with the Arkansas River to less than a minimum in-stream flow of 15 ft^3/s, as mandated by the Colorado Water Conservation Board.

The Colorado Department of Natural Resources has recommended that exchanges not diminish streamflow in the Arkansas River below levels necessary to maintain a quality boating environment and a viable fishery. These minimum streamflow levels are intended to "provide an annual flow regime that helps maintain the brown trout fishery, meets the public's demand for boating recreation (i.e. rafting and kayaking) and supports the ability of the Arkansas Headwaters Recreation Area to meet its obligation to manage both recreation and natural resources within its boundaries" (Colorado Department of Natural Resources, written commun., 1996). Recommendations by the Department of Natural Resources include (1) the maintenance of a minimum year-round streamflow (as measured at streamflow-gaging station 07093700 Arkansas River near Wellsville) of at least 250 ft^3/s to protect the fishery; (2) the maintenance of streamflow during mid-November through April (the winter incubation period for brown trout eggs) at an optimal flow range of 250 to 400 ft^3/s, depending on conditions that existed during the spawning period (October 15–November 15); and (3) the maintenance of streamflow during July through August 15 at a minimum of 700 ft^3/s to provide adequate streamflow for boating recreation. These recommendations are not legally stipulated.

SIMULATIONS

The simulations of the effects of exchanges on streamflow and specific conductance consisted of seven basic steps: (1) Simulation of the historical exchange potential in the Arkansas River from the mouth of Fountain Creek upstream to Twin Lakes Reservoir; (2) simulation of the exchange of Colorado Springs' transmountain return flows from the mouth of Fountain Creek upstream to storage in Pueblo Reservoir; (3) simulation of the exchange of water from Colorado Springs' Pueblo Reservoir account upstream to Twin Lakes Reservoir; (4) simulation of the diversion of Aurora's share of Rocky Ford Ditch water at Pueblo Reservoir; (5) simulation of the exchange of water from Aurora's Pueblo Reservoir account to Twin Lakes Reservoir; (6) simulation of the cumulative effect of all exchanges on main-stem streamflow; and (7) simulation of the cumulative effect of all exchanges on main-stem specific conductance. Step 1 was accomplished with an accounting model that used historical (water years 1986–93) daily streamflow and daily diversion data to estimate the historical daily exchange potential. Steps 2 through 7 were accomplished with an accounting model that used the simulated historical daily exchange-potential (step 1) and user-defined exchange conditions to simulate the daily exchange operations of Colorado Springs' transmountain return-flow exchange and Aurora's Rocky Ford Ditch exchange. Both models used a daily step. The accounting models are described in greater detail later in the report.

The potential effects of exchanges on streamflow and specific conductance were simulated at three surface-water stations on the main stem of the Arkansas River: streamflow-gaging station 07097000 Arkansas River at Portland, streamflow-gaging station 07099400 Arkansas River above Pueblo, and streamflow-gaging station 07109500 Arkansas River near Avondale (fig. 1). Additionally, the potential effects of exchanges on specific conductance were simulated at water-quality monitoring station 07099969 Arkansas River at St. Charles Mesa Diversion at Pueblo. These stations were selected for simulation because of the availability of long-term water-quantity and water-quality data. Additionally, the locations of these stations are appropriate for demonstrating the operation of the exchanges and their potential effects on streamflow and specific conductance.

Data used in the simulations were obtained from several sources. Daily streamflow data were collected by the U.S. Geological Survey at streamflow-gaging stations 07087200, 07091200, 07094500, 07106500, and 07109500 (fig. 1). Additionally, daily streamflow data were collected by the Colorado Division of Water Resources at streamflow-gaging stations 390444106174900, 07086000, 07093700, 07096000, 07097000, and 07099400 (fig. 1). Daily diversion data for all municipal, irrigation, and industrial water diversions from the Arkansas River between the confluence with Lake Creek and the confluence with Fountain Creek were provided by the Colorado Division of Water Resources. Daily specific-conductance data were collected by the U.S. Geological Survey using multi-parameter monitors at stations 07097000, 07099400, 07099969, and 07109500 (fig. 1).

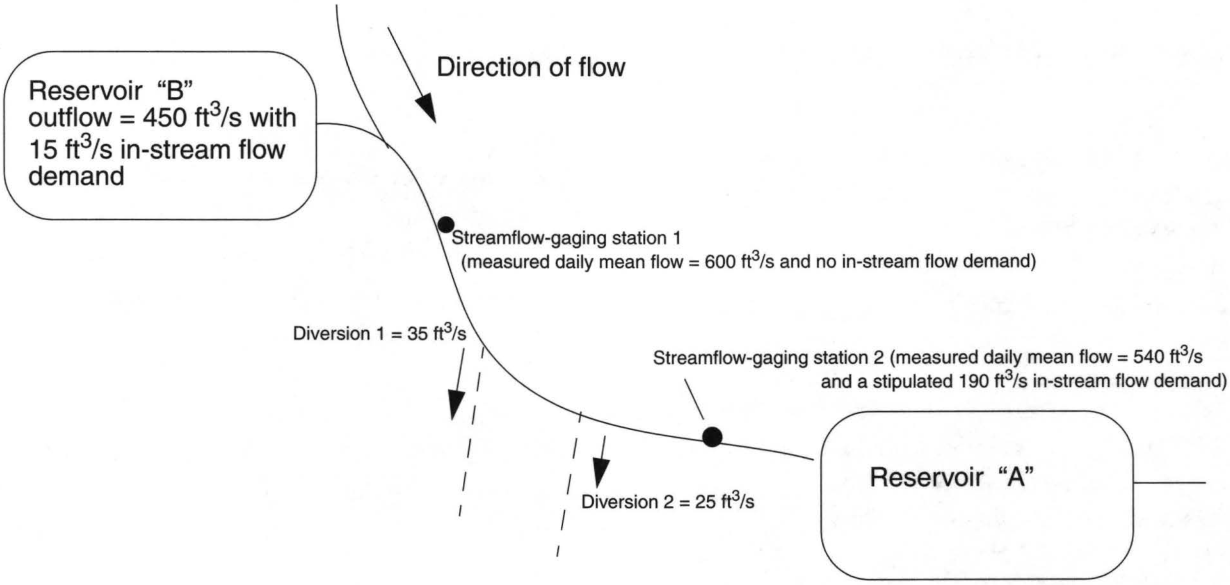
Exchange Potential

As briefly discussed in the "Description of Water Exchanges" section, exchange potential is equal to the amount of water that can be exchanged between two locations without depriving senior water-right holders of their legal share of water in the Arkansas River Basin. The accounting model that was used in this study to simulate historical (water years 1986–93) exchange potential was initially developed and applied by Enartech Consulting Engineers and Hydrologists (1992) to support Aurora's then pending water-right application and to demonstrate Aurora's ability to exchange all of its Rocky Ford Ditch water (8,250 acre-ft/yr) from Pueblo Reservoir to Twin Lakes Reservoir or to the Otero pipeline. That original model was modified for use in this study to evaluate exchange potential in the Arkansas River between the confluence with Fountain Creek and Pueblo Reservoir (hereinafter referred to as reach 1) and between Pueblo Reservoir and Twin Lakes Reservoir (hereinafter referred to as reach 2). Historical exchange potential was simulated by calculating the volume of water that could be removed from reach 1 and reach 2 without depriving senior water-right holders of their historical daily streamflow diversions or violating any stipulated minimum in-stream flows.

The method used to simulate historical exchange potential on one day in a hypothetical stream reach located between Reservoir "A" and Reservoir "B" is shown in figure 3. In this hypothetical reach, there is a 15-ft^3/s in-stream flow demand at the outflow of Reservoir "B" and a 190-ft^3/s minimum in-stream flow demand at streamflow-gaging station 2. Additionally, there are two historical streamflow diversions in the reach that have a total daily diversion of 60 ft^3/s. Exchange potential was analyzed at the outflow of Reservoir "B," at each diversion structure, and at each streamflow-gaging station. The total daily exchange potential that was estimated for the reach would be the minimum exchange potential at the five sites [694 acre-ft/d (fig. 3)]. An exchange in excess of 694 acre-ft/d would deprive water appropriators of their legal share of water or would violate the stipulated in-stream flow demands.

Fountain Creek to Pueblo Reservoir—Reach 1

Historical daily exchange potential in reach 1 was simulated by subtracting the sum of all daily streamflow diversions from the daily mean outflow of Pueblo Reservoir, as measured at station 07099400 Arkansas River above Pueblo, located 0.4 mi downstream from Pueblo Dam (fig. 1). The basic assumption inherent to this approach is that any water in reach 1 that exceeded the amount required by the historical daily diversions was available for exchange. The simulated daily exchange potential for reach 1 was proportional to streamflow—streamflow generally was smallest in fall and winter and largest in spring and summer. The median simulated exchange potential in reach 1 ranged from a minimum of 177 acre-ft/d in December to a maximum of 3,170 acre-ft/d in June (fig. 4).



Exchange-Potential Simulation Method

Step 1 -- Exchange potential at Reservoir "B" = outflow minus in-stream flow demand = 450 ft^3/s – 15 ft^3/s = 435 ft^3/s

Step 2 -- Exchange potential at station 1 = streamflow minus in-stream flow demand = 600 ft^3/s – 0 ft^3/s = 600 ft^3/s

Step 3 -- Exchange potential at diversion 1 = streamflow at station 1 minus diversion 1 = 600 ft^3/s – 35 ft^3/s = 565 ft^3/s

Step 4 -- Exchange potential at diversion 2 = streamflow at station 1 minus diversions 1 and 2 = 600 ft^3/s – 35 ft^3/s – 25 ft^3/s = 540 ft^3/s

Step 5 -- Exchange potential at station 2 = streamflow at station 2 minus in-stream flow demand = 540 ft^3/s – 190 ft^3/s = 350 ft^3/s

Step 6 -- Total daily exchange potential in stream reach located between Reservoir "A" and Reservoir "B" is the minimum of steps 1 through 5 = 350 ft^3/s

Step 7 -- Conversion of total daily exchange potential to units of acre-feet per day = 350 $ft^3/s \times$ 1.9834 acre-ft/d per cubic foot per second = 694 acre-ft/d

Figure 3. Example of method used to simulate the total daily exchange potential as applied to a hypothetical steam reach.

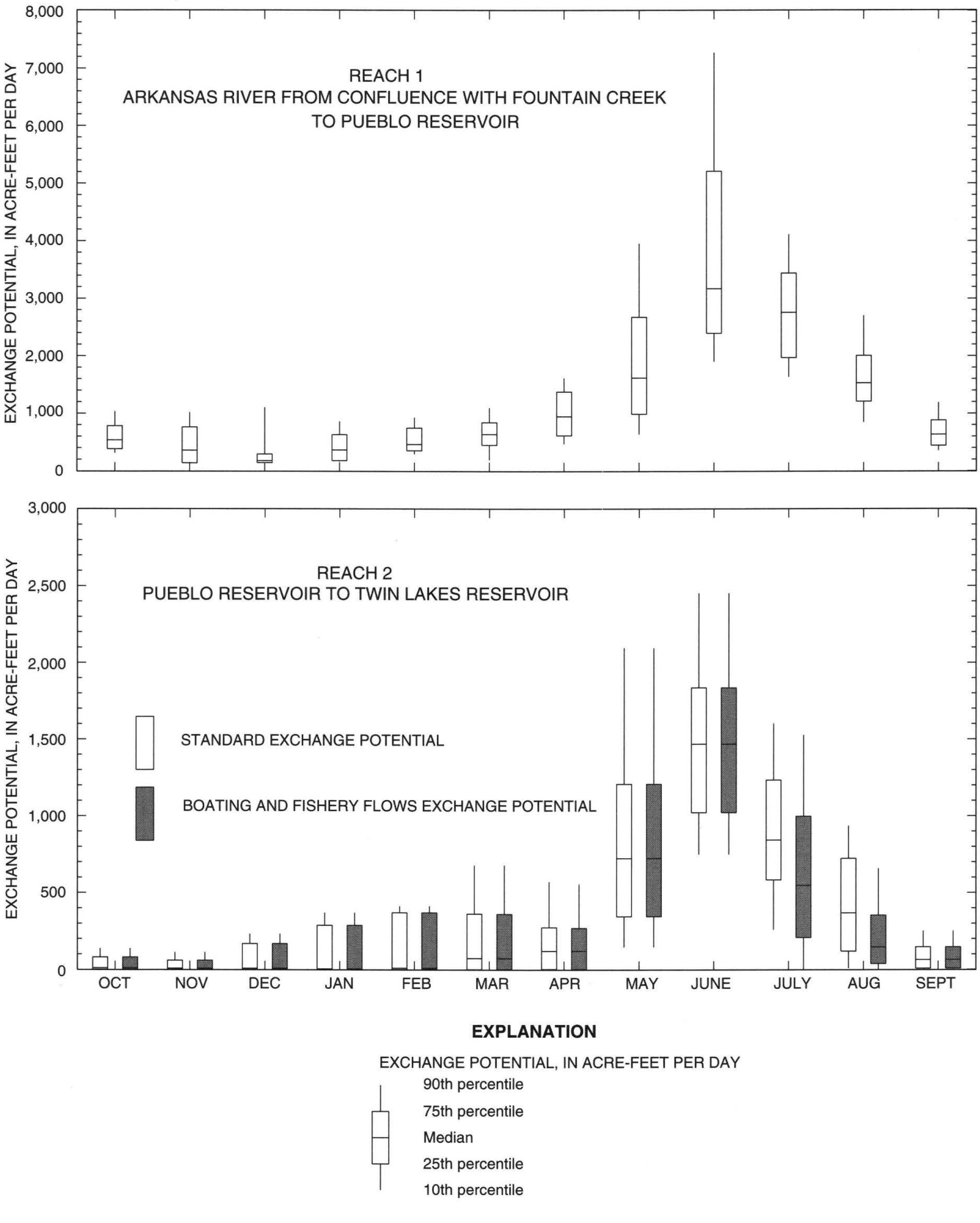


Figure 4. Boxplots of simulated daily exchange potential in the Arkansas River between the Fountain Creek confluence and Pueblo Reservoir and between Pueblo Reservoir and Twin Lakes Reservoir, water years 1986–93.

Pueblo Reservoir to Twin Lakes Reservoir—Reach 2

Historical daily exchange potential in reach 2 was computed to be the minimum of the simulated daily exchange potential in nine subreaches located between Twin Lakes Reservoir and Pueblo Reservoir. The nine subreaches are: (1) Lake Creek from the outflow of Twin Lakes Reservoir to the confluence with the Arkansas River; (2) the Arkansas River from the confluence with Lake Creek to station 07086000 Arkansas River at Granite; (3) station 07086000 Arkansas River at Granite to station 07087200 Arkansas River at Buena Vista; (4) station 07087200 Arkansas River at Buena Vista to station 07091200 Arkansas River near Nathrop; (5) station 07091200 Arkansas River near Nathrop to station 07093700 Arkansas River near Wellsville; (6) station 07093700 Arkansas River near Wellsville to station 07094500 Arkansas River at Parkdale; (7) station 07094500 Arkansas River at Parkdale to station 07096000 Arkansas River at Cañon City; (8) station 07096000 Arkansas River at Cañon City to station 07097000 Arkansas River at Portland; and (9) station 07097000 Arkansas River at Portland to Pueblo Reservoir (fig. 1). Daily exchange potential in each of the nine subreaches was simulated by subtracting the sum of historical diversions and minimum in-stream flow demands in each subreach from the daily mean streamflow for the subreach, as measured at the upstream end of the subreach. The basic assumption inherent to this approach is that any water in reach 2 that exceeded the amount required by the historical daily diversions and the minimum in-stream flow requirements was available for exchange.

Historical daily exchange potential in reach 2 was simulated for two scenarios of exchange-potential conditions. The first condition, hereinafter referred to as the standard exchange potential, was constrained by historical daily streamflow diversions and by legally stipulated minimum in-stream flow requirements in the following three subreaches: (1) Subreach 1 (Colorado Water Conservation Board minimum in-stream flow requirement of 15 ft^3/s in Lake Creek downstream from Twin Lakes Reservoir); (2) subreach 5 (minimum in-stream flow at Salida wastewater-treatment plant of 240 ft^3/s in September through June and 260 ft^3/s in July and August); and (3) subreach 8 (minimum in-stream flow of 190 ft^3/s throughout the year at the Fremont Sanitation District wastewater-treatment plant). The second exchange-potential condition, hereinafter referred to as the boating and fishery flows exchange potential, was constrained by the same limitations as the standard exchange potential and by the minimum flow conditions recommended for maintaining a quality boating and fishery environment, as previously described in the "Description of Water Exchanges" section. The minimum flows set for the boating and fishery environments, measured at station 07093700 Arkansas River near Wellsville, affect the simulated exchange potential in subreach 6. Exchange potential was simulated for both exchange-potential conditions to determine if they substantially differed in limiting simulated exchange potential.

For both exchange-potential conditions, the simulated exchange potential in reach 2 generally was equivalent in most months, except for July and August (fig. 4). The median simulated exchange potential was equal to about 0 acre-ft/d during October through February, a period of seasonally low streamflow. However, on about 50 percent of the days during this period, the simulated exchange potential was greater than 0 acre-ft/d, ranging to about 400 acre-ft/d in February (fig. 4). Streamflow diversions generally were negligible during these months; therefore, they did not substantially limit simulated exchange potential. Seasonally low streamflow and the generally small discharge from Twin Lakes Reservoir to Lake Creek (subreach 1) were the conditions that most limited the simulated exchange potential in reach 2. The median simulated exchange potential for both exchange-potential conditions reached a maximum of 1,468 acre-ft/d in June (fig. 4). The maintenance of streamflow during July through August 15 at a minimum of 700 ft^3/s, as measured at station 07093700 Arkansas River near Wellsville, to provide adequate streamflow for boating recreation did have a substantial effect on the simulated exchange potential in July and August. In July, the median simulated exchange potential was 843 acre-ft/d based on the standard exchange potential and was 548 acre-ft/d based on the boating and fishery flows exchange potential, which is a difference of about 35 percent. Likewise, in August, the estimated median exchange potential was 368 acre-ft/d based on the standard exchange potential and was 147 acre-ft/d based on the boating and fishery flows exchange potential, which is a difference of about 60 percent.

Water Exchanges

The exchange simulation model, modified from the accounting model by Enartech Consulting Engineers and Hydrologists (1992), was used to simulate the daily operation of exchanges in reaches 1 and 2 for the 8-year study period using simulated daily exchange potential, historical daily mean streamflow, and specific conductance as input data. The results of the exchange simulation include simulated daily mean streamflow at station 07097000 Arkansas River at Portland, station 07099400 Arkansas River above Pueblo, and station 07109500 Arkansas River near Avondale (fig. 1). In addition, daily mean specific conductance was simulated at these three stations and at station 07099969 Arkansas River at St. Charles Mesa Diversion (fig. 1). A flowchart depicting the processes simulated in the exchange simulation model is presented in figure 5, and the definitions of model variables are presented in table 2.

Exchange scenarios

Nine scenarios of exchange conditions (table 3) were simulated for each exchange-potential condition (standard exchange potential and boating and fishery flows exchange potential) to reflect a wide range in the transmountain return-flow exchange demand (TRX) and the maximum available storage space in Pueblo Reservoir for transmountain return flows (STORMAX_CS). Each scenario was simulated individually with the exchange-operation model. In each simulated exchange scenario, the selected values of TRX and STORMAX_CS were held constant for the entire simulation period. It was assumed in each simulation scenario that Aurora's Rocky Ford Ditch exchange would operate at its maximum court-decreed monthly variable rate. Likewise, Aurora's maximum storage in Pueblo Reservoir was held constant at 10,000 acre-ft in all simulations. The nine scenarios that were simulated represented a stepwise increase in TRX and a wide range in values of STORMAX_CS. Colorado Springs currently (1998) has a daily exchange demand of about 60 acre-ft for its transmountain return flows and a 6,000-acre-ft storage space in Pueblo Reservoir.

Simulation scenarios 1, 2, and 3 (table 3) represent an increase in the current (1998) value of TRX of about 50 percent and an increase in the current (1998) value of STORMAX_CS of 0 percent for scenario 1, 100 percent for scenario 2, and 300 percent for scenario 3. Scenarios 4, 5, and 6 (table 3) represent an increase in TRX of about 100 percent and an increase in STORMAX_CS of 0 percent for scenario 4, 100 percent for scenario 5, and 300 percent for scenario 6. Scenarios 7, 8, and 9 (table 3) represent an increase in TRX of about 500 percent and an increase in STORMAX_CS of 0 percent for scenario 7, 100 percent for scenario 8, and 300 percent for scenario 9.

Transmountain return flows

Fountain Creek to Pueblo Reservoir

The first step in the exchange simulation process was the simulation of the exchange of Colorado Springs' transmountain return flows from the mouth of Fountain Creek to storage in Pueblo Reservoir. On the initial day of each simulation (DAY_START), the volume of transmountain return flows in the Pueblo Reservoir storage account for Colorado Springs (STOR_CS) was set to zero and the available storage space in Colorado Springs' Pueblo Reservoir storage account (STOR_AVAIL_CS) was computed by:

$$\text{STOR\_AVAIL\_CS} = \text{STORMAX\_CS} - \text{STOR\_CS} \qquad (1)$$

The simulated exchange of return flows from Fountain Creek to Pueblo Reservoir was limited by the available return flows in Fountain Creek, the available storage space in Pueblo Reservoir, and the simulated exchange potential in reach 1. For each day of simulation, the volume of return flows exchanged from Fountain Creek to Pueblo Reservoir (TRX_PUEB) was computed as the minimum of three values: TRX, STOR_AVAIL_CS, and EXPOT1 (table 2). EXPOT1 is the daily exchange potential in reach 1 as simulated by the exchange-potential model.

After computing the daily exchange of return flows into Pueblo Reservoir, the volume of return flows stored in Colorado Springs' Pueblo Reservoir account was recomputed:

$$\text{STOR\_CS} = \text{STOR\_CS} + \text{TRX\_PUEB} \qquad (2)$$

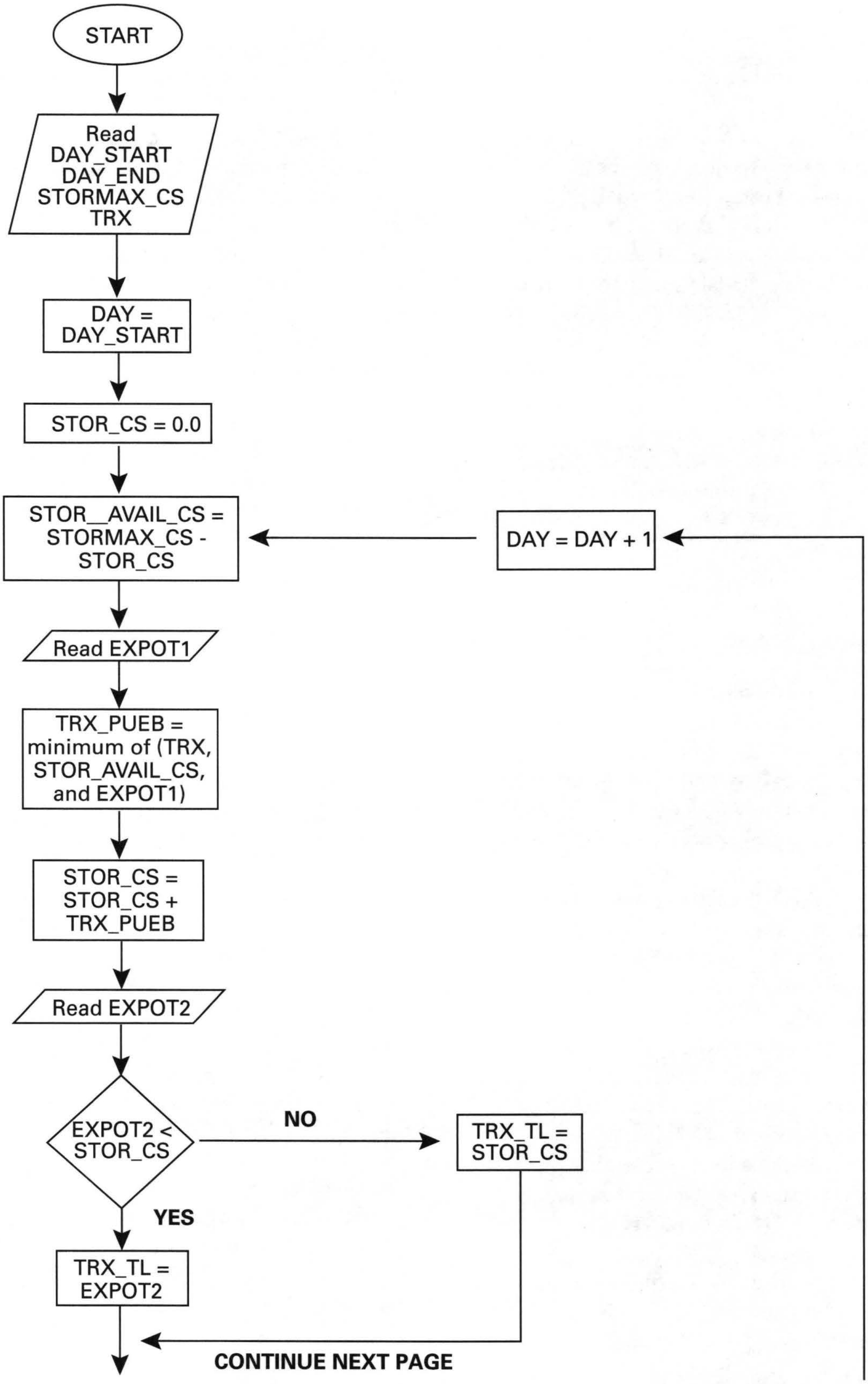


Figure 5. Flowchart showing the exchange simulation model.

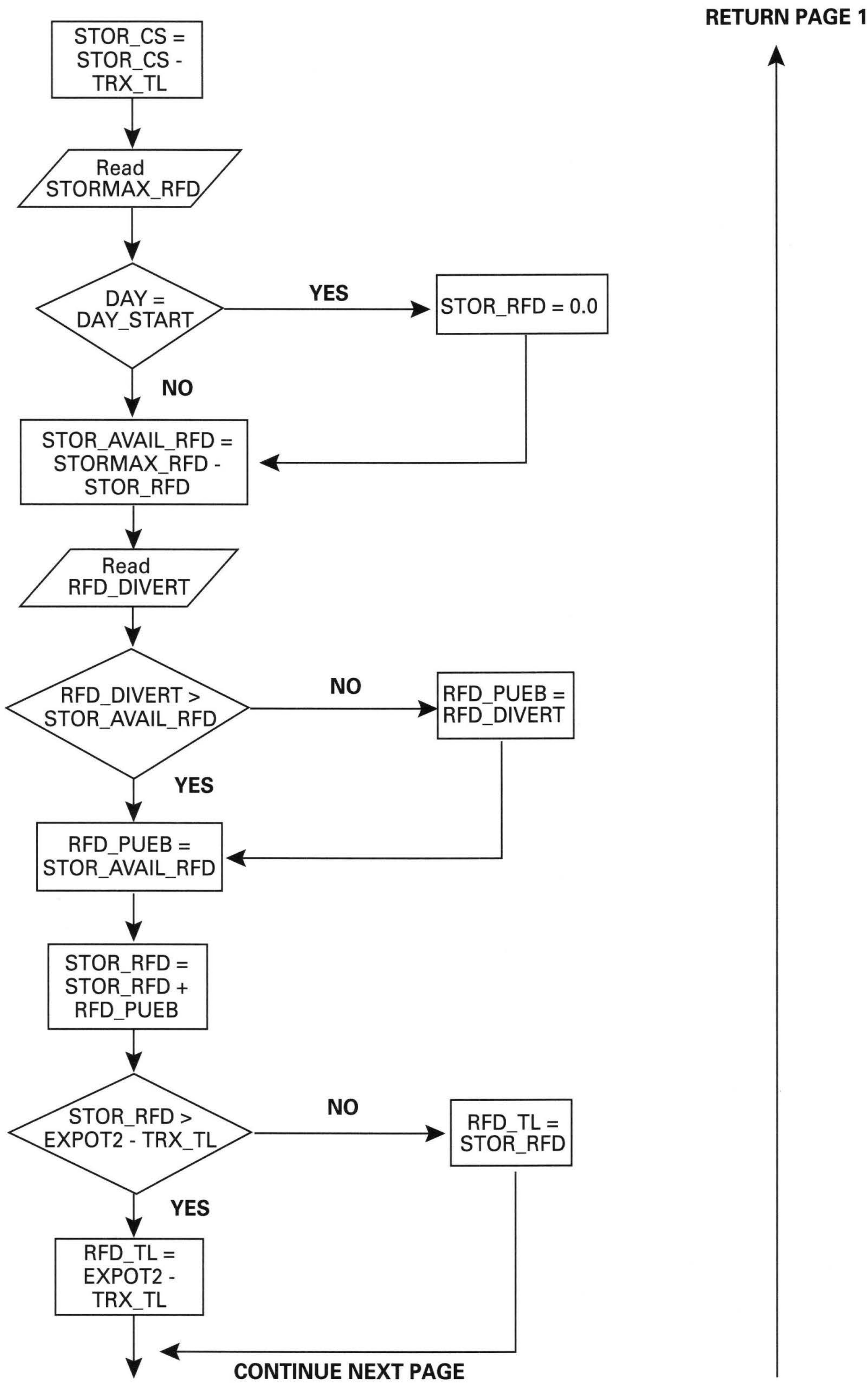


Figure 5. Flowchart showing the exchange simulation model—Continued.

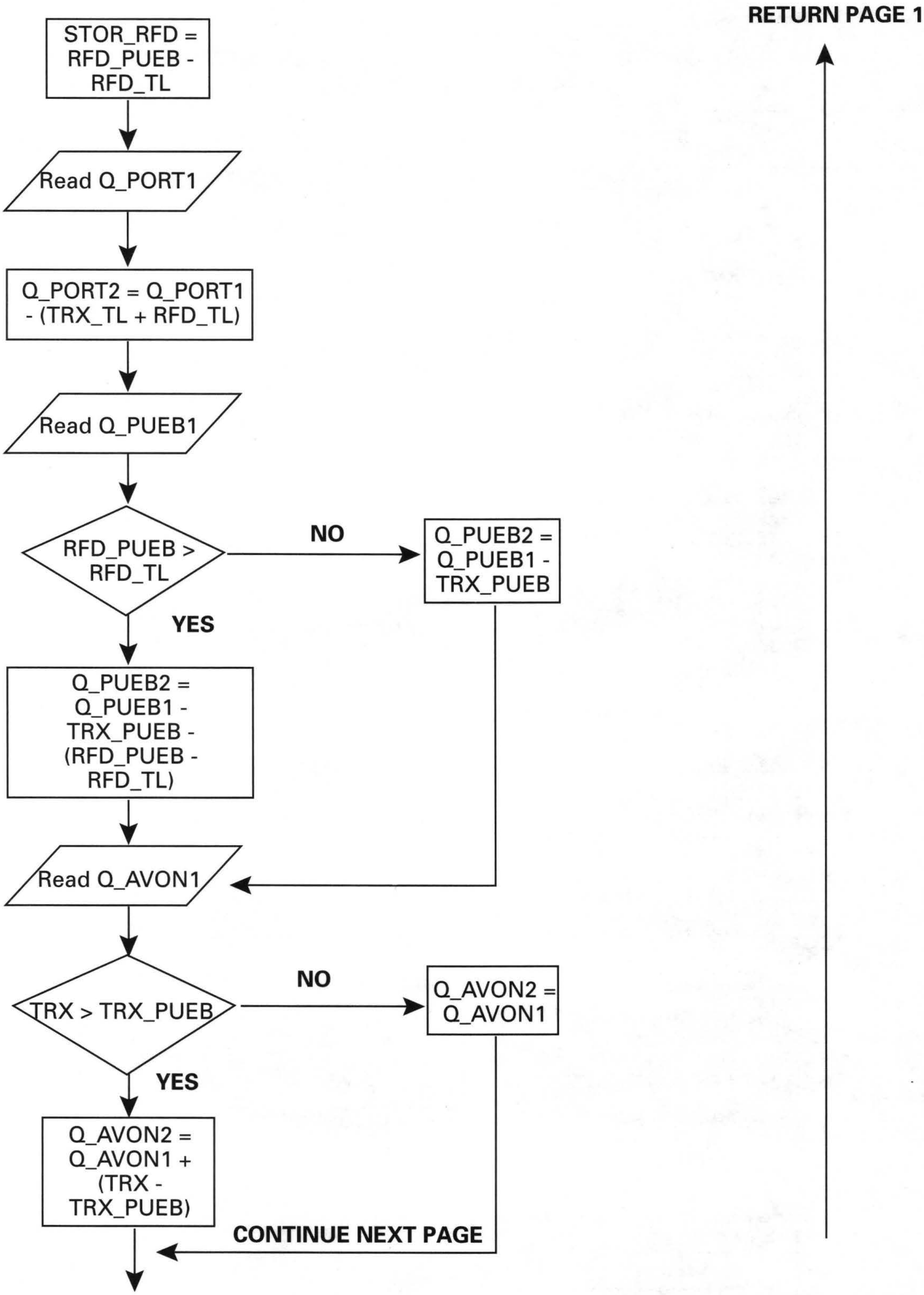


Figure 5. Flowchart showing the exchange simulation model—Continued.

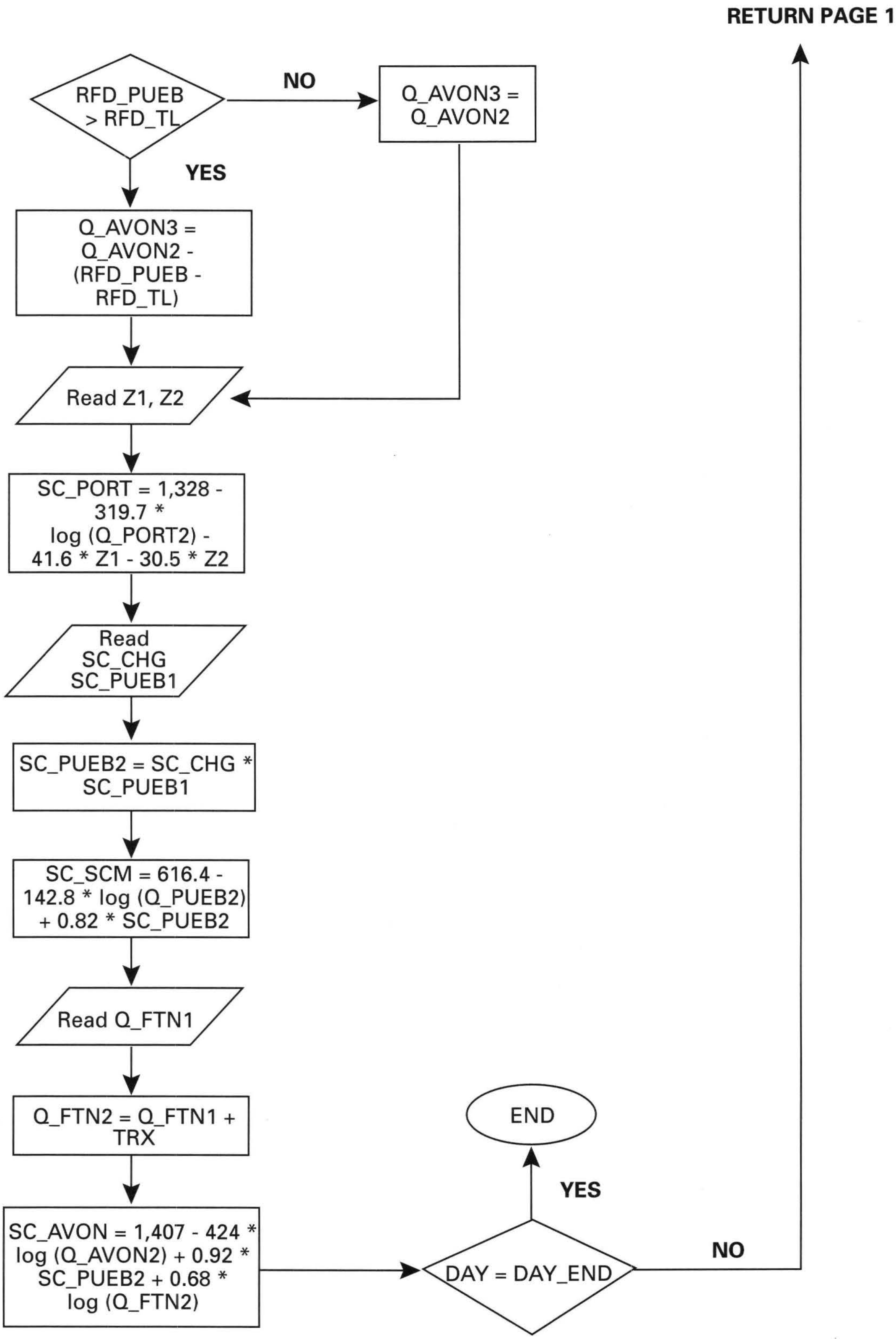


Figure 5. Flowchart showing the exchange simulation model—Continued.

Table 2. Definitions of variables for exchange simulation model

Variable name	Variable definition
DAY	Current simulation day
DAY_START	Initial day of simulation period
DAY_END	Final day of simulation period
EXPOT1	Simulated daily exchange potential in the Arkansas River between the confluence with Fountain Creek and Pueblo Reservoir
EXPOT2	Simulated daily exchange potential in the Arkansas River between Pueblo Reservoir and Twin Lakes Reservoir
Q_AVON1	Historical daily mean streamflow at station 07109500
Q_AVON2	Post-exchange daily mean streamflow at station 07109500 after the daily return-flow exchange
Q_AVON3	Post-exchange daily mean streamflow at station 07109500 after the daily return-flow exchange and the diversion and exchange of Aurora's Rocky Ford Ditch water
Q_FTN1	Historical daily mean streamflow at station 07106500
Q_FTN2	Post-exchange daily mean streamflow at station 07106500
Q_PORT1	Historical daily mean streamflow at station 07097000
Q_PORT2	Post-exchange daily mean streamflow at station 07097000
Q_PUEB1	Historical daily mean streamflow at station 07099400
Q_PUEB2	Post-exchange daily mean streamflow at station 07099400
RFD_DIVERT	Maximum daily diversion of Aurora's Rocky Ford Ditch water at Pueblo Reservoir
RFD_PUEB	Daily volume of Aurora's Rocky Ford Ditch water diverted at Pueblo Reservoir
RFD_TL	Daily volume of Aurora's Rocky Ford Ditch water exchanged from Pueblo Reservoir to Twin Lakes Reservoir
SC_AVON	Post-exchange daily mean specific conductance at station 07109500
SC_CHG	Median increase in the post-exchange daily mean specific conductance at station 07097000 for a given simulation scenario
SC_PORT	Post-exchange daily mean specific conductance at station 07097000
SC_PUEB1	Historical daily mean specific conductance at station 07099400
SC_PUEB2	Post-exchange daily mean specific conductance at station 07099400
SC_SCM	Post-exchange daily mean specific conductance at station 07099969
STOR_CS	Volume of transmountain return flows stored in Pueblo Reservoir
STOR_RFD	Volume of Aurora's Rocky Ford Ditch water stored in Pueblo Reservoir
STOR_AVAIL_CS	Available storage space for transmountain return flows in Pueblo Reservoir
STOR_AVAIL_RFD	Maximum available storage space in Pueblo Reservoir for Aurora's Rocky Ford Ditch water
STORMAX_CS	Maximum available storage space in Pueblo Reservoir for transmountain return flows
STORMAX_RFD	Maximum available storage space in Pueblo Reservoir for Aurora's Rocky Ford Ditch water
TRX	Daily return-flow exchange demand
TRX_PUEB	Daily volume of return flows exchanged from Fountain Creek to Pueblo Reservoir
TRX_TL	Daily volume of return flows exchanged from Pueblo Reservoir to Twin Lakes Reservoir
Z1	Seasonal dummy variable equal to 0 in September through December and in April through August; equal to 1 in January through March
Z2	Seasonal dummy variable equal to 0 in September through March; equal to 1 in April through August

Table 3. Exchange simulation scenarios

[acre-feet per day. acre-ft/d; acre-feet, acre-ft]

Simulation scenario	Simulated increase in transmountain return-flow exchange rate (acre-ft/d)[1]	Simulated increase in maximum available storage in Pueblo Reservoir for transmountain return-flow exchange (acre-ft)[2]
Scenario 1	30	0
Scenario 2	30	6,000
Scenario 3	30	18,000
Scenario 4	60	0
Scenario 5	60	6,000
Scenario 6	60	18,000
Scenario 7	298	0
Scenario 8	298	6,000
Scenario 9	298	18,000

[1]The simulated increase is relative to the current (1998) transmountain return-flow exchange rate of about 60 acre-feet per day.

[2]The simulated increase is relative to the current (1998) 6,000 acre-feet of maximum available storage in Pueblo Reservoir for transmountain return-flow exchanges.

Pueblo Reservoir to Twin Lakes Reservoir

On a daily basis, the exchange model minimizes the storage of transmountain return flows in Pueblo Reservoir by exchanging water from Pueblo Reservoir to Twin Lakes Reservoir. Storage space in Twin Lakes Reservoir was assumed not to limit the exchange of water from Pueblo Reservoir to Twin Lakes Reservoir. The volume of return flows exchanged from storage in Colorado Springs' Pueblo Reservoir account to Twin Lakes Reservoir (TRX_TL) was computed by:

$$\text{TRX\_TL} = \text{STOR\_CS} \quad \text{if} \quad \text{EXPOT2} \geq \text{STOR\_CS}$$

$$\text{TRX\_TL} = \text{EXPOT2} \quad \text{if} \quad \text{EXPOT2} < \text{STOR\_CS} \qquad (3)$$

If the simulated exchange potential in reach 2 (EXPOT2) precludes the exchange of all stored return flows from Pueblo Reservoir to Twin Lakes Reservoir, the unexchanged water remains in Pueblo Reservoir. After computing the exchange of return flows into Twin Lakes Reservoir, STOR_CS was recomputed:

$$\text{STOR\_CS} = \text{STOR\_CS} - \text{TRX\_TL} \qquad (4)$$

Aurora's Rocky Ford Ditch Water

Diversion at Pueblo Reservoir

Following the exchange of the transmountain return flows into Twin Lakes Reservoir by Colorado Springs, the diversion of Aurora's Rocky Ford Ditch water at Pueblo Reservoir was simulated. For each simulation scenario, the maximum storage in Aurora's Pueblo Reservoir account (STORMAX_RFD) was held constant at 10,000 acre-ft to simulate Aurora's storage contract. Prior to initiating a simulation for the full study period, the volume of water in Aurora's Pueblo Reservoir storage account (STOR_RFD) was set to zero. The available storage space in Aurora's Pueblo Reservoir account (STOR_AVAIL_RFD) was computed by:

$$\text{STOR\_AVAIL\_RFD} = \text{STORMAX\_RFD} - \text{STOR\_RFD} \qquad (5)$$

For each day of simulation, the volume of Aurora's water diverted into the Pueblo Reservoir account (RFD_PUEB) for the city was computed by:

$$\text{RFD\_PUEB} = \text{RFD\_DIVERT} \quad \text{if} \quad \text{RFD\_DIVERT} \leq \text{STOR\_AVAIL\_RFD}$$

$$\text{RFD\_PUEB} = \text{STOR\_AVAIL\_RFD} \quad \text{if} \quad \text{RFD\_DIVERT} > \text{STOR\_AVAIL\_RFD} \qquad (6)$$

where RFD_DIVERT is the court-decreed, seasonally variable maximum daily diversion (table 1).

After diversion into Pueblo Reservoir, the water stored in Aurora's Pueblo Reservoir account (STOR_RFD) was recomputed:

$$\text{STOR\_RFD} = \text{STOR\_RFD} + \text{RFD\_PUEB} \qquad (7)$$

Pueblo Reservoir to Twin Lakes Reservoir

The exchange model minimizes the daily storage of Aurora's water in Pueblo Reservoir by attempting to exchange the water into Twin Lakes Reservoir. Owing to the priority system of exchanges, which gives Colorado Springs first priority to exchange water from Pueblo Reservoir to the upper basin and a finite exchange potential in reach 2 (EXPOT2), the maximum daily exchange rate for Aurora in reach 2 (RFD_TL) was computed by:

$$\text{RFD\_TL} = \text{STOR\_RFD} \quad \text{if} \quad \text{STOR\_RFD} \leq \text{EXPOT2} - \text{TRX\_TL}$$

$$\text{RFD\_TL} = \text{EXPOT2} - \text{TRX\_TL} \quad \text{if} \quad \text{STOR\_RFD} > \text{EXPOT2} - \text{TRX\_TL} \qquad (8)$$

If the daily transmountain return-flow exchange by Colorado Springs in reach 2 (TRX_TL) is equal to the simulated daily exchange potential in reach 2 (EXPOT2), then Aurora cannot operate an exchange on that day and must retain all of its water in Pueblo Reservoir. In addition, a court-decreed maximum exchange rate of 500 ft^3/s further limits RFD_TL.

After exchanging Aurora's water from Pueblo Reservoir to Twin Lakes Reservoir, STOR_RFD was recomputed:

$$\text{STOR\_RFD} = \text{STOR\_RFD} - \text{RFD\_TL} \qquad (9)$$

Streamflow

Daily mean streamflow was simulated for the Arkansas River at the Portland, Pueblo, and Avondale stations following simulation of the daily exchanges in reach 1 and reach 2. The Portland station, located about 14 mi upstream from Pueblo Reservoir, is the farthest downstream station in reach 2 and represents inflow to Pueblo Reservoir. Exchanges of Colorado Springs' transmountain water and Aurora's Rocky Ford Ditch water in reach 2 decrease streamflow at this station. Daily mean streamflow at the Portland station (Q_PORT2) was simulated by:

$$\text{Q\_PORT2} = \text{QPORT1} - (\text{TRX\_TL} + \text{RFD\_TL}) \qquad (10)$$

where Q_PORT1 is the historical daily mean streamflow at station 07097000 Arkansas River at Portland.

The Pueblo station is located 0.4 mi downstream from Pueblo Reservoir and represents reservoir outflow to the Arkansas River. Streamflow at the Pueblo station is affected by the exchange of transmountain return flows in reach 1 and by the diversion of Aurora's Rocky Ford Ditch water at Pueblo Reservoir. All exchanges of transmountain return flows in reach 1 decrease streamflow in reach 1 by the amount of the exchange because the exchange replacement water (transmountain return flows) enters the Arkansas River 9.6 mi downstream from the Pueblo station at the mouth of Fountain Creek. The diversion and exchange of Aurora's Rocky Ford Ditch water decrease streamflow in reach 1 only when the daily diversion rate at Pueblo Reservoir is greater than the daily exchange rate for reach 2. Under these circumstances, the amount of Aurora's daily diversion at Pueblo Reservoir that cannot be immediately exchanged from Pueblo Reservoir to Twin Lakes Reservoir (RFD_PUEB minus RFD_TL) is retained in Pueblo Reservoir, and streamflow at the Pueblo station is decreased by an equal amount. For example, if Aurora diverted 50 acre-ft at Pueblo Reservoir and could only exchange 25 acre-ft to Twin Lakes Reservoir, Aurora would store the 25 acre-ft that could not be exchanged in Pueblo Reservoir. Daily streamflow at the Pueblo station would be decreased by 25 acre-ft.

If Aurora's daily diversion at Pueblo Reservoir were equal to or less than its reach 2 exchange, streamflow at the Pueblo station would not be affected because a like amount of water would be released from storage in Pueblo Reservoir. For example, if Aurora diverted 50 acre-ft at Pueblo Reservoir and exchanged that 50 acre-ft and an additional 25 acre-ft from storage in Pueblo Reservoir to Twin Lakes Reservoir, Aurora would release 75 acre-ft to the Arkansas River from its storage account in Pueblo Reservoir.

Daily mean streamflow at the Pueblo station (Q_PUEB2) was simulated by:

$$\text{Q\_PUEB2} = \text{Q\_PUEB1} - \text{TRX\_PUEB} \quad \text{if} \quad \text{RFD\_PUEB} \leq \text{RFD\_TL}$$

$$\text{Q\_PUEB2} = \text{Q\_PUEB1} - \text{TRX\_PUEB} - (\text{RFD\_PUEB} - \text{RFD\_TL}) \quad \text{if} \quad \text{RFD\_PUEB} > \text{RFD\_TL} \qquad (11)$$

where Q_PUEB1 is the historical daily mean streamflow at station 07099400 Arkansas River above Pueblo.

The Avondale station is located about 24 mi downstream from Pueblo Reservoir and 14 mi downstream from the confluence with Fountain Creek, making it the farthest downstream station in the study area. Simulated streamflow at the Avondale station is affected by the inflow of transmountain return flows from Fountain Creek and by the diversion of Rocky Ford Ditch water at Pueblo Reservoir. The transmountain return flows exchanged from the confluence of Fountain Creek to Pueblo Reservoir always are equal to or less than the return flows that are tributary to the Arkansas River. For a scenario where the return-flow exchange in reach 1 is equivalent to the return flows entering the river, simulated streamflow at the Avondale station would equal historical streamflow. When the volume of water stored in Colorado Springs' Pueblo Reservoir account limits the return-flow exchange into Pueblo Reservoir, the excess return flows would increase streamflow at the Avondale station above historical levels. The increase would be equal to the difference between the simulated daily return-flow exchange demand and the return-flow exchange in reach 1. For example, if the simulated increase in transmountain return flows is 298 acre-ft/d and only 198 acre-ft/d can be exchanged into Pueblo Reservoir, then daily streamflow at the Avondale station would increase by a volume equal to the volume of water that could not be exchanged (TRX minus TRX_PUEB). The daily mean streamflow at the Avondale station, after the daily return-flow exchange, was computed by:

$$Q\_AVON2 = Q\_AVON1 \quad \text{if} \quad TRX = TRX\_PUEB$$

$$Q\_AVON2 = Q\_AVON1 + (TRX - TRX\_PUEB) \quad \text{if} \quad TRX > TRX\_PUEB \qquad (12)$$

where,

Q_AVON2 is the simulated daily mean streamflow at station 07109500 Arkansas River near Avondale after the transmountain return-flow exchange; and

Q_AVON1 is the historical daily mean streamflow at station 07109500 Arkansas River near Avondale.

Aurora's diversion and exchange of Rocky Ford Ditch water only affects streamflow at the Avondale station when Aurora's diversion rate at Pueblo Reservoir exceeds its exchange rate in reach 2, as was described for the simulation of streamflow at the Pueblo station. The daily mean streamflow at the Avondale station (Q_AVON3) was simulated by:

$$Q\_AVON3 = Q\_AVON2 - (RFD\_PUEB - RFD\_TL) \quad \text{if} \quad RFD\_PUEB > RFD\_TL$$

$$(QAVON3 = Q\_AVON2 \quad \text{if} \quad RFD\_PUEB \leq RFD\_TL \qquad (13)$$

Specific Conductance

At the Portland, Pueblo, and Avondale stations, the net effect of the simulated exchanges in reach 1 and reach 2 typically would be decreased historical daily mean streamflow and, consequently, potentially altered historical specific conductance—decreased streamflow results in decreased dilution potential and potentially increased specific conductance. At the Avondale station, specific conductance may be affected either by increased specific conductance in the main stem of the river upstream from the Avondale station or by increased inflow of transmountain diversions from Fountain Creek. Daily mean specific conductance was simulated at the Portland, Pueblo, St. Charles Mesa, and Avondale stations to characterize these potential changes in specific conductance. Daily mean specific conductance was simulated with relations between historical streamflow and specific-conductance data. These relations were developed with daily mean streamflow and specific-conductance data that were representative of a broad range of streamflow conditions in the Arkansas River. In this study, it was assumed that the historical relations of streamflow and specific conductance were valid for the hydrologic conditions of the simulated exchange scenarios.

The simulated reach 2 exchanges would always result in decreased streamflow at the Portland station. The daily mean specific conductance at Portland was simulated by:

$$SC\_PORT = 1{,}328 - 319.7 * \log(Q\_PORT2) - 41.6 * Z1 - 30.5 * Z2 \qquad (14)$$

where,

SC_PORT is the simulated daily mean specific conductance at station 07097000 Arkansas River at Portland;

Z1 is a seasonal dummy variable equal to 0 in September through December and in April through August and equal to 1 in January through March; and

Z2 is a seasonal dummy variable equal to 0 in September through March and equal to 1 in April through August.

Equation 14 was developed based on daily mean streamflow and specific conductance measured during the study period. The term "dummy variable" indicates that the values of Z1 and Z2 were not measured but were used simply to categorize the relation by season (Draper and Smith, 1981). Seasonality was detected in an analysis of the residuals of monthly regression relations between streamflow and specific conductance at the Portland station. Equation 14 has a coefficient of determination (r^2) of 0.76 and a standard error of 13.6 percent. The median increases (percent) in the simulated daily mean specific conductance, compared to historical values, that were predicted at the Portland station for the simulated exchange scenarios are listed in table 4.

Table 4. Percent increase in the simulated daily mean specific conductance at station 07097000 Arkansas River at Portland

Simulation scenario	Average increase in the simulated exchange scenario daily mean specific conductance, relative to historical conditions (percent)	
	Standard exchange potential	Boating and fishery flows exchange potential
1	1	1
2	1	1
3	1	1
4	2	2
5	2	2
6	2	2
7	5	5
8	6	6
9	6	6

Specific conductance at the Pueblo station is affected by the specific conductance of water flowing into Pueblo Reservoir and by flow routing and mixing in Pueblo Reservoir (Lewis and Brendle, 1998). Although specific conductance at the Pueblo station varies with streamflow (fig. 2), developing a satisfactory regression equation relating specific conductance at the Pueblo station to streamflow at the Pueblo station or to streamflow or specific conductance at the Portland station was not possible, probably owing to the temporally irregular nature of flow routing and mixing of water in Pueblo Reservoir (Lewis and Edelmann, 1994). Therefore, simulated specific conductance at the Pueblo station was assumed to increase proportionately to the median increase in the simulated daily mean specific conductance at the Portland station, as predicted by equation 14 (table 4). Daily mean specific conductance at the Pueblo station (SC_PUEB2) was simulated by:

$$SC\_PUEB2 = SC\_CHG * SC\_PUEB1 \qquad (15)$$

where,

SC_CHG is the median increase, in percent, in the daily mean specific conductance at station 07097000 Arkansas River at Portland (table 4) for a given exchange simulation scenario; and

SC_PUEB1 is the historical daily mean specific conductance at station 07099400 Arkansas River above Pueblo.

The St. Charles Mesa station is located about 9 mi downstream from Pueblo Dam. Although specific conductance at St. Charles Mesa is correlated with specific conductance at Pueblo, specific conductance at St. Charles Mesa also is strongly correlated with streamflow. Therefore, daily mean specific conductance at station 07099969 Arkansas River at St. Charles Mesa diversion (SC_SCM) was simulated by:

$$SC\_SCM = 616.4 - 142.8 * \log(Q\_PUEB2) + 0.82 * (SC\_PUEB2) \qquad (16)$$

Equation 16 was developed based on daily mean streamflow and specific conductance measured during the study period. The equation has an r^2 of 0.88 and a standard error of 7.4 percent. There was no significant seasonality in the regression relation, probably owing to the effects of routing and mixing of water in Pueblo Reservoir; therefore, no seasonality terms were included in the equation.

At the Avondale station, specific conductance is greatly affected by the quality of water in the Arkansas River that is discharged from Pueblo Reservoir and by the percentage of streamflow at Avondale that is contributed to the river by Fountain Creek. Daily mean specific conductance at station 07109500 Arkansas River near Avondale (SC_AVON) was simulated by:

$$SC\_AVON = 1{,}407 - 424 * \log(Q\_AVON2) + 0.92 * (SC\_PUEB2) + 0.68 * \log(Q\_FTN2) \qquad (17)$$

where Q_FTN2 is the simulated daily mean streamflow at station 07106500 Fountain Creek at Pueblo.

Q_FTN2 was simulated by adding the simulated increased transmountain return flow in Fountain Creek (TRX) to the historical daily mean streamflow at station 07106500 Fountain Creek at Pueblo (Q_FTN1). The historical relation between streamflow and specific conductance at the Fountain Creek station was assumed to remain constant as TRX increased. An analysis of the relations between daily mean streamflow and daily mean specific conductance at Fountain Creek at Pueblo for 3 years that had relatively low streamflow (1988–89 and 1993) and 3 years that had relatively high streamflow (1994–96) (fig. 6) indicates that the relation may not change substantially with changes in streamflow caused by increases in transmountain return flows; this analysis substantiates the aforementioned assumption.

SIMULATED EFFECTS OF WATER EXCHANGES ON STREAMFLOW AND SPECIFIC CONDUCTANCE

Nine exchange scenarios were simulated for the study period (water years 1986–93) for each of the two simulated exchange-potential conditions (standard exchange potential and boating and fishery flows exchange potential). The simulated exchanges had a marked effect on historical streamflow and specific conductance. However, the differences between the effects for a given scenario simulated using the standard exchange-potential condition and a scenario simulated using the boating and fishery exchange potential condition were negligible. Therefore, the discussion of simulation results focuses only on the scenarios with the standard exchange-potential condition. The results are presented graphically for simulation scenarios 3, 6, and 9 in the following discussion. There was little visually discernible difference in the simulated effects of the exchanges on streamflow and specific conductance for scenarios with the same transmountain return-flow exchange demand (TRX) and different maximum available storage volumes for return flows in Pueblo Reservoir (STORMAX_CS). For example, the effects of scenarios 1, 2, and 3 were virtually indistinguishable from each other. Therefore, a graphic display of scenario 3 results is representative of the results for scenarios 1, 2, and 3. Statistical summaries of the results for streamflow with the standard exchange-potential condition for all nine scenarios are shown in table 5.

Simulated streamflow at the Portland and Pueblo stations (table 5) decreased proportionately with the increase in the annual exchanges in reach 2 (fig. 7). The median simulated decrease in streamflow ranged from about 4 percent for a simulation of Aurora's maximum exchange demand and a 50-percent increase in Colorado Springs' historical exchange demand (scenario 1) to about 16 percent for a simulation of the maximum exchange demand for both exchanges (scenario 9) (table 5). The effects on streamflow did not vary substantially as a result of increasing the available storage space in Pueblo Reservoir for a return-flow exchange demand of either 30 acre-ft/d (scenarios 1, 2, and 3) or 60 acre-ft/d (scenarios 4, 5, and 6) (table 5). Simulated streamflow at the Portland and Pueblo stations did decrease substantially for a return-flow exchange demand of 298 acre-ft/d (scenarios 7, 8, and 9) when available storage space in Pueblo Reservoir was increased (table 5). This response is the result of limited storage space in Pueblo Reservoir restricting the exchange in reach 2 at the maximum return-flow exchange demand. With a return-flow exchange demand of 298 acre-ft/d (scenarios 7, 8, and 9), simulated exchange potential in reach 2 often limited the reach 2 exchange, which resulted in the storage of the unexchanged return flows in Pueblo Reservoir. As the available storage in Pueblo Reservoir filled, the reach 1 exchange could not be operated and excess return flows in Fountain Creek were unavailable for exchange after they flowed into the Arkansas River. Increasing the available storage in Pueblo Reservoir allowed the unexchanged return flows to be retained in Pueblo Reservoir and exchanged at a later time. Aurora's annual reach 2 exchange (fig. 7) and the corresponding effect on streamflow at the Portland and Pueblo stations were almost constant throughout the study period.

Generally, the decrease in simulated streamflow at the Portland and Pueblo stations, compared to historical conditions, was largest during snowmelt runoff in May and June (fig. 8); otherwise, there was little seasonality in the decrease in streamflow at these two stations. The lack of seasonality may be partly attributable to the basic modeling assumption that unlimited storage space existed in Twin Lakes Reservoir for the storage of exchanged water. As a result of

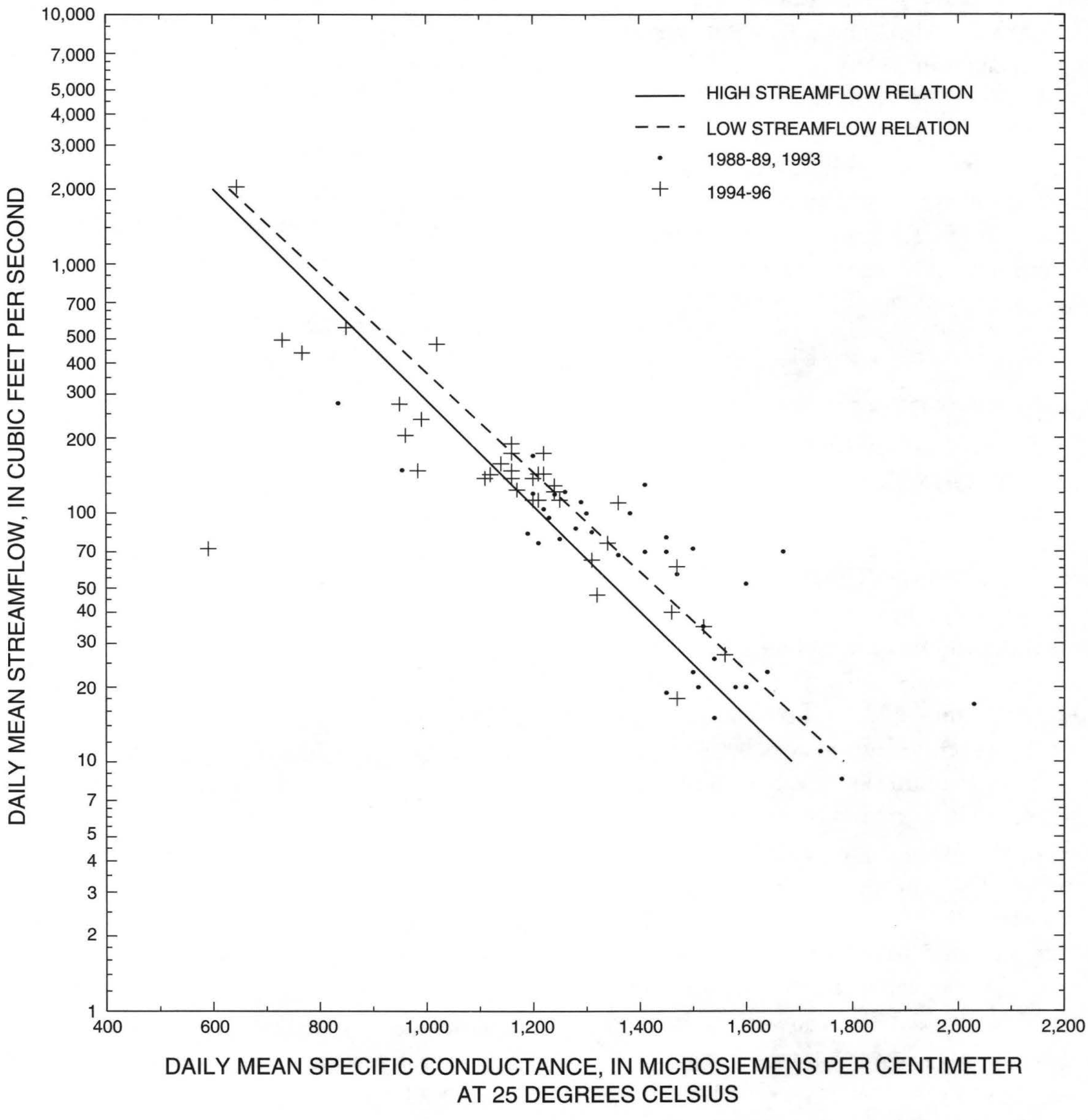


Figure 6. Relations of daily mean streamflow and daily mean specific conductance at station 07106500 Fountain Creek at Pueblo for years that have low streamflow (1988–89, 1993) and for years that have high streamflow (1994–96).

Table 5. Statistical summary of the simulated daily mean streamflow in the Arkansas River, water years 1986–93, with the standard exchange-potential condition

[ft^3/s, cubic feet per second; --, not applicable]

Model scenario	Mean (ft^3/s)	Percent change in the simulated daily mean streamflow relative to historical conditions[1]	Twenty-fifth percentile (ft^3/s)	Median (ft^3/s)	Seventy-fifth percentile (ft^3/s)
		Station 07097000 Arkansas River at Portland			
Historical conditions	749	--	361	495	767
Scenario 1	721	-3.7	344	474	718
Scenario 2	721	-3.7	344	474	718
Scenario 3	721	-3.7	344	474	718
Scenario 4	708	-5.5	338	461	699
Scenario 5	706	-5.7	338	460	695
Scenario 6	706	-5.7	338	460	695
Scenario 7	654	-12.7	313	424	636
Scenario 8	645	-13.9	310	412	629
Scenario 9	630	-15.9	309	403	611
		Station 07099400 Arkansas River above Pueblo			
Historical conditions	700	--	254	446	866
Scenario 1	682	-2.6	236	427	849
Scenario 2	682	-2.6	236	427	849
Scenario 3	682	-2.6	236	427	849
Scenario 4	669	-4.4	223	412	831
Scenario 5	666	-4.8	221	410	831
Scenario 6	666	-4.8	221	410	831
Scenario 7	612	-12.6	192	376	729
Scenario 8	603	-13.8	158	364	722
Scenario 9	587	-16.1	133	343	710
		Station 07109500 Arkansas River near Avondale			
Historical conditions	908	--	404	630	1,030
Scenario 1	906	-.2	401	629	1,030
Scenario 2	906	-.2	401	629	1,030
Scenario 3	906	-.2	401	629	1,030
Scenario 4	907	-.1	404	630	1,030
Scenario 5	905	-.3	401	626	1,027
Scenario 6	905	-.3	401	626	1,027
Scenario 7	970	+6.8	496	706	1,050
Scenario 8	962	+5.9	486	700	1,050
Scenario 9	946	+4.2	456	681	1,040

[1]Represents the median value of all differences between the simulated daily mean streamflow and historical conditions for the simulation period.

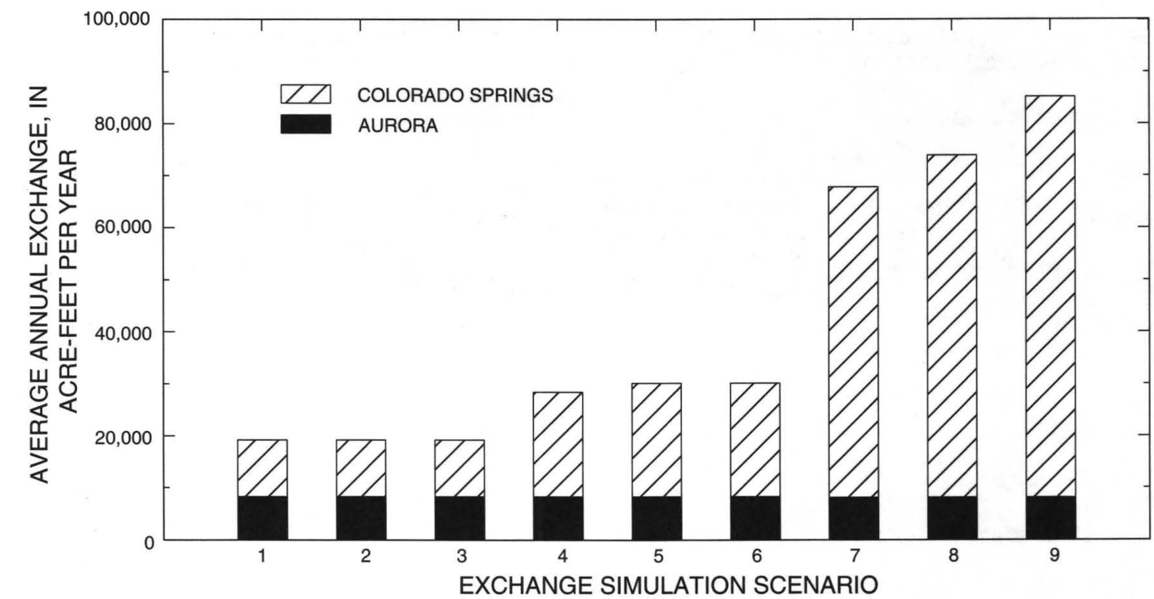


Figure 7. Average simulated annual exchange of Colorado Springs' transmountain return flows and Aurora's Rocky Ford Ditch water from Pueblo Reservoir to Twin Lakes Reservoir, water years 1986–93.

this assumption, the simulated reach 2 exchanges were only limited by exchange potential and not by available storage in Twin Lakes Reservoir. The simulation of reservoir operations and storage in Twin Lakes Reservoir was beyond the scope of this study. This assumption may not be completely valid because limited storage space in Twin Lakes Reservoir can limit exchanges, especially during the snowmelt-runoff period when reservoir storage generally is filled. If storage in Twin Lakes Reservoir were included in the exchange model, exchanges probably would be somewhat limited during snowmelt runoff (May-June) and exchanges in the latter part of the summer and fall would be increased to offset this effect.

Simulated streamflow at Avondale was relatively unaffected by most scenarios of increased return-flow exchange demand, except for the maximum exchange-demand scenarios (scenarios 7–9, table 5). Any decrease in streamflow at Avondale due to reach 1 exchanges generally was offset by the inflow of return flows from Fountain Creek. Simulated streamflow actually increased about 8 to 12 percent at Avondale in response to the simulations of the maximum increase in exchange demand (scenarios 7–9). Increased streamflow at Avondale resulted at times when reach 1 exchanges were limited by available storage space in Pueblo Reservoir and more water flowed into the river from Fountain Creek than was exchanged in reach 1.

Seasonality was apparent in the simulated streamflow at the Avondale station for a 298-acre-ft/d increase (scenario 9) in return flows (fig. 8). For scenario 9, streamflow was relatively unaffected in May through October, but streamflow increased in November through April. This seasonal pattern was caused by limited exchange potential in reach 2 during November through April, which resulted in decreased return-flow exchanges in reach 2. The lack of available storage in Pueblo Reservoir limited return-flow exchanges in reach 1, which resulted in unexchanged return flows flowing into the river from Fountain Creek. The unexchanged return flows increased streamflow in the Arkansas River at Avondale.

Simulated specific conductance in the Arkansas River increased in all scenarios at the Portland, Pueblo, and St. Charles Mesa stations (table 6 and fig. 9). The increase in specific conductance was

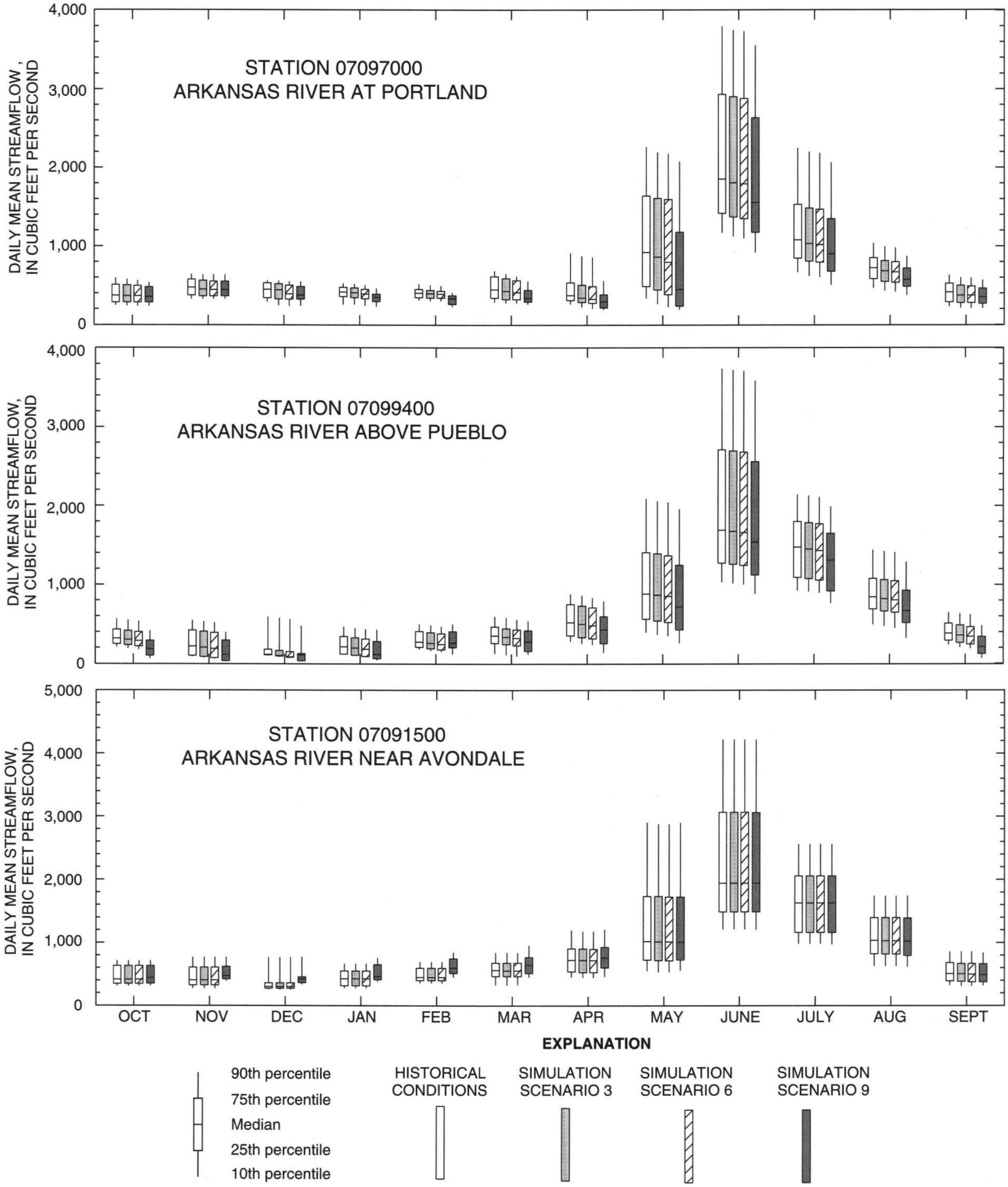


Figure 8. Boxplots of daily mean streamflow in the Arkansas River, by month, for historical and simulated exchange scenarios, water years 1986–93.

caused by the decrease in streamflow and the subsequent decrease in dilutive capacity in the Arkansas River. The median simulated increase in the daily mean specific conductance ranged from about 1 percent (scenarios 1–3) at all three sites to about 7 percent for scenario 9 at the St. Charles Mesa station (table 6). Increasing storage space for a given total exchange rate had little effect on simulated specific conductance (table 6) due to a corresponding lack of effect on simulated streamflow (table 5).

At the Avondale station, the response of specific conductance to the simulated exchange scenarios was different from the other stations (table 6 and fig. 9), due to the effect of increased return flows entering the Arkansas River from Fountain Creek. For scenarios 1 through 6, the maximum increase in specific conductance in the study area occurred at Avondale (table 6), although simulated streamflow at Avondale was relatively unaffected in these scenarios (table 5). The increased specific conductance largely was a result of decreased dilution p12.8otential in the main stem of the Arkansas River upstream from the Fountain Creek confluence, as indicated by the 4- to 8-percent decrease in streamflow at the Pueblo station (table 5). For scenarios 7 through 9, the increase in specific conductance was somewhat mitigated by the increased inflow of return flows from Fountain Creek, which contributed to the 8- to 12-percent increase in streamflow at the Avondale station (table 5). As the volume of return flows in Fountain Creek increased in the simulation scenarios, specific conductance in Fountain Creek actually decreased due to increased dilution capacity.

The Pueblo station is located about 4 mi upstream from the municipal water-supply intake for the Pueblo Board of Water Works, and the St. Charles Mesa station is located at the municipal water-supply intake for the St. Charles Mesa Water District. Therefore, water quality at these stations is particularly important from a drinking-water-quality perspective. The secondary maximum contaminant level (SMCL) for dissolved solids in drinking water is 500 mg/L (U.S. Environmental Protection Agency, 1986), which is about equal to a specific conductance of 718 μS/cm at these two stations (Lewis and Brendle, 1998). At the Pueblo station, none of the exchange scenarios caused the specific conductance of the Arkansas River to exceed 718 μS/cm (fig. 9). At the St. Charles Mesa station, the historical specific conductance routinely exceeded 718 μS/cm in November through February of 1986–93 (fig. 9). All exchange simulation scenarios resulted in increased exceedance of the SMCL during these months (fig. 9). In scenario 9, the simulated specific conductance regularly exceeded 718 μS/cm in October and April (fig. 9). At the Avondale station, where the SMCL for dissolved solids is about equal to a specific conductance of 752 μS/cm (Cain, 1987), most historical and simulated values of specific conductance usually exceeded 752 μS/cm during September through May (fig. 9). Simulated specific conductance generally remained less than 752 μS/cm in June through August. The salinity hazard for irrigated agriculture remained at its historical moderate (250–750 μS/cm) to high (750–2,250 μS/cm) levels in all scenarios. Additional information on the percentage of days during the study period that the simulated daily mean specific conductance was equaled or exceeded for historical conditions and for scenarios 3, 6, and 9 is presented in table 7.

Table 6. Statistical summary of the simulated daily mean specific conductance in the Arkansas River, water years 1986–93, with the standard exchange-potential condition

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; --, not applicable]

Model scenario	Mean (µS/cm)	Percent increase in simulated daily mean specific conductance, relative to historical conditions[1]	Twenty-fifth percentile (µS/cm)	Median (µS/cm)	Seventy-fifth percentile (µS/cm)
Station 07097000 Arkansas River at Portland					
Historical conditions	423	--	375	445	486
Scenario 1	429	1	384	451	495
Scenario 2	429	1	384	451	495
Scenario 3	429	1	384	451	495
Scenario 4	432	2	388	454	499
Scenario 5	433	2	389	454	499
Scenario 6	433	2	389	454	499
Scenario 7	445	5	405	467	513
Scenario 8	446	5	410	470	513
Scenario 9	449	6	416	471	514
Station 07099400 Arkansas River above Pueblo					
Historical conditions	502	--	441	524	566
Scenario 1	509	1	447	531	574
Scenario 2	509	1	447	531	574
Scenario 3	509	1	447	531	574
Scenario 4	514	2	452	537	580
Scenario 5	514	2	452	537	580
Scenario 6	514	2	452	537	580
Scenario 7	528	5	464	551	595
Scenario 8	529	6	466	554	598
Scenario 9	533	6	468	556	601
Station 07099969 Arkansas River at St. Charles Mesa Water District Diversion					
Historical conditions	646	--	564	658	742
Scenario 1	656	1	571	666	754
Scenario 2	656	1	571	666	754
Scenario 3	656	1	571	666	754
Scenario 4	663	2	576	673	763
Scenario 5	663	2	576	673	763
Scenario 6	663	2	576	673	763
Scenario 7	683	5	598	690	780
Scenario 8	687	6	601	696	784
Scenario 9	694	7	604	702	790
Station 07109500 Arkansas River near Avondale					
Historical conditions	785	--	653	817	940
Scenario 1	800	2	670	832	955
Scenario 2	800	2	670	832	955
Scenario 3	800	2	670	832	955
Scenario 4	808	3	680	841	962
Scenario 5	810	3	682	842	964
Scenario 6	810	3	681	842	964

Table 6. Statistical summary of the simulated daily mean specific conductance in the Arkansas River, water years 1986–93, with the standard exchange-potential condition—Continued

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; --, not applicable]

Model scenario	Mean (μS/cm)	Percent increase in simulated daily mean specific conductance, relative to historical conditions[1]	Twenty-fifth percentile (μS/cm)	Median (μS/cm)	Seventy-fifth percentile (μS/cm)
Scenario 7	823	4	712	852	961
Scenario 8	827	5	716	858	965
Scenario 9	836	6	721	868	974

[1]Represents the median value of all differences between the simulated daily mean specific conductance and historical conditions for the simulation period.

Table 7. Percentage of days historical and simulated daily mean specific conductance in the Arkansas River was equaled or exceeded, water years 1986–1993

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; --, not applicable

Model scenario	Percentage of days indicated specific conductance was equaled or exceeded					
	Specific conductance					
	500 μS/cm	600 μS/cm	700 μS/cm	800 μS/cm	900 μS/cm	1,000 μS/cm
Station 07097000 Arkansas River at Portland						
Historical conditions	19	2	--	--	--	--
Scenario 3	23	2	--	--	--	--
Scenario 6	24	1	--	--	--	--
Scenario 9	32	2	--	--	--	--
Station 07099400 Arkansas River above Pueblo						
Historical conditions	60	13	--	--	--	--
Scenario 3	61	15	--	--	--	--
Scenario 6	62	17	--	--	--	--
Scenario 9	66	26	1	--	--	--
Station 07099969 Arkansas River at St. Charles Mesa Diversion						
Historical conditions	87	67	36	9	--	--
Scenario 3	88	68	39	12	--	--
Scenario 6	88	69	40	16	--	--
Scenario 9	90	76	50	22	5	--
Station 07109500 Arkansas River near Avondale						
Historical conditions	91	82	71	55	33	13
Scenario 3	93	83	72	58	36	15
Scenario 6	94	84	74	60	38	17
Scenario 9	95	88	79	69	47	27

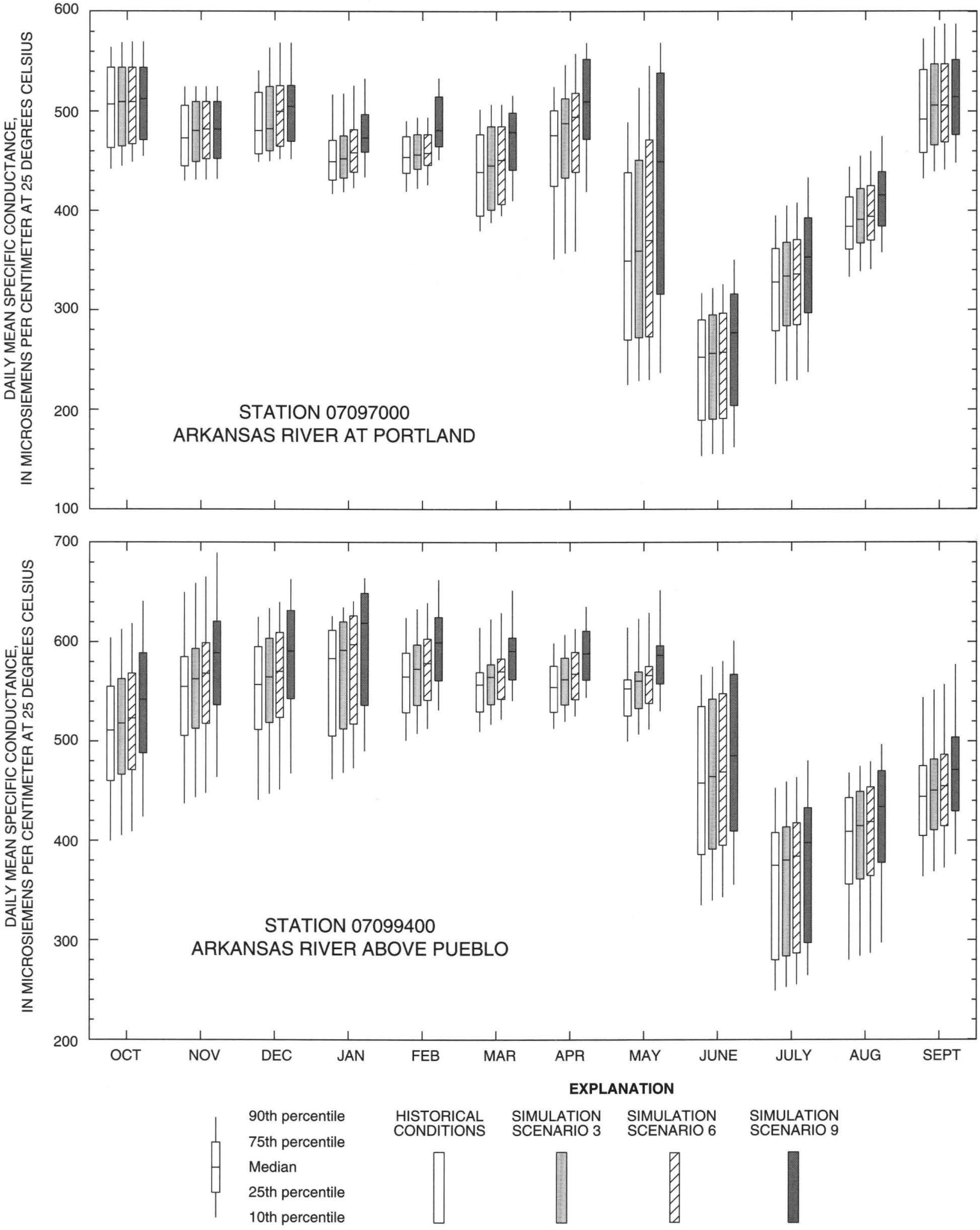


Figure 9. Boxplots of daily mean specific conductance in the Arkansas River, by month, for historical and simulated exchange scenarios, water years 1986–93.

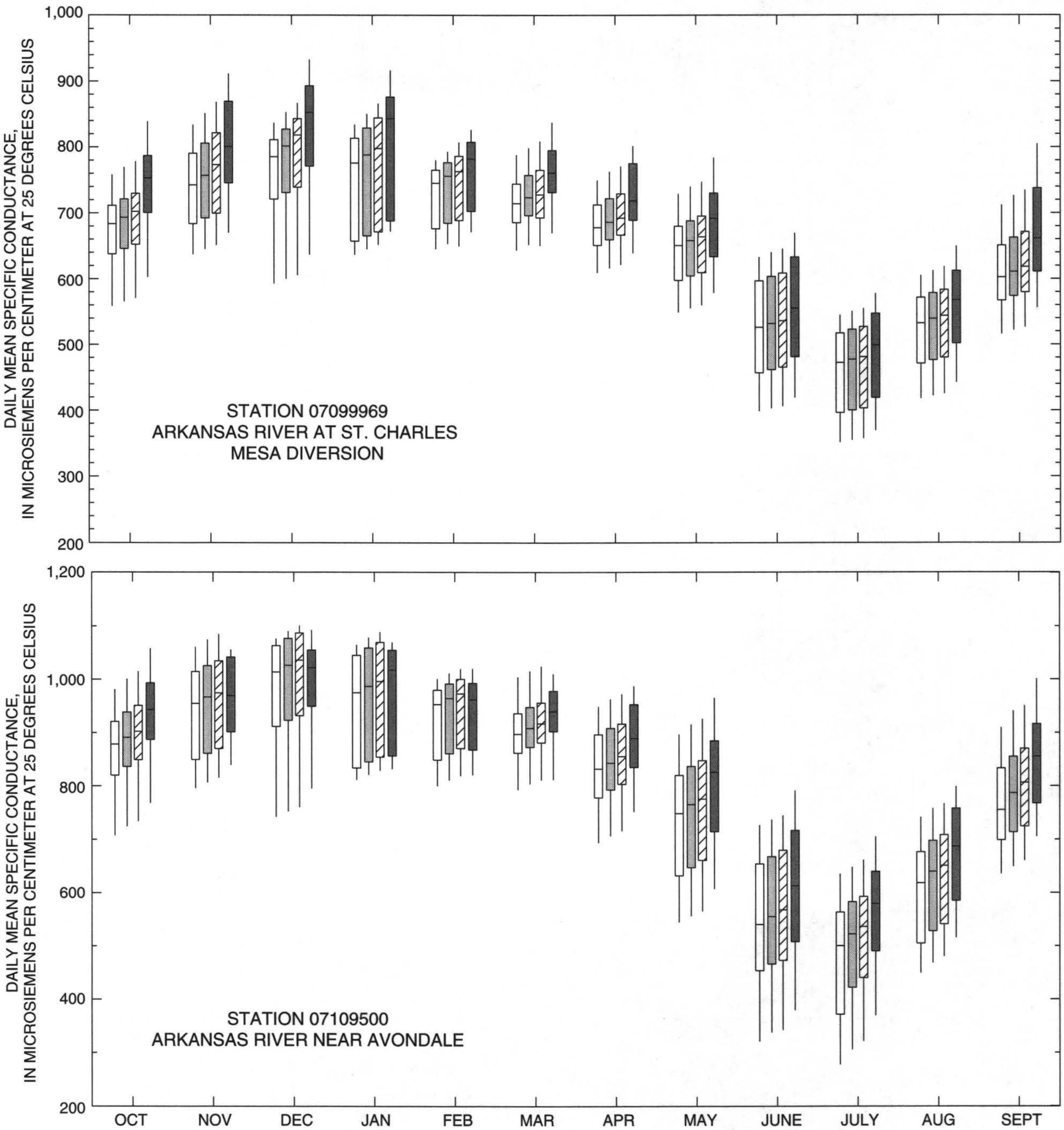


Figure 9. Boxplots of daily mean specific conductance in the Arkansas River, by month, for historical and simulated exchange scenarios, water years 1986–93—Continued.

SUMMARY

The cities of Colorado Springs and Aurora use water exchanges to make full use of their municipal water supplies in the Arkansas River Basin. Decreased streamflow in the exchange reach or the replacement of the exchanged water with water having higher specific conductance could result in increased specific conductance in the Arkansas River.

Potential future exchange scenarios involving increases in the historical (1986–93) transmountain return-flow exchange demand for Colorado Springs combined with the maximum potential exchange demand for Aurora's Rocky Ford Ditch exchange were simulated with two accounting models. The models use basic accounting procedures and relations between streamflow and specific conductance to superimpose future exchange scenarios on hydrologic conditions for water years 1986–93. Water years 1986–93 are representative of long-term hydrologic conditions in the Arkansas River. The two accounting models were used to simulate (1) the historical exchange potential in the Arkansas River from the mouth of Fountain Creek upstream to Twin Lakes Reservoir; (2) the exchange of Colorado Springs' transmountain return flows from the mouth of Fountain Creek upstream to storage in Pueblo Reservoir; (3) the exchange of water from Colorado Springs' Pueblo Reservoir account upstream to Twin Lakes Reservoir; (4) the diversion of Aurora's share of Rocky Ford Ditch water at Pueblo Reservoir; (5) the exchange of water from Aurora's Pueblo Reservoir account to Twin Lakes Reservoir; (6) the cumulative effect of all exchanges on main-stem streamflow; and (7) the cumulative effect of all exchanges on main-stem specific conductance.

Simulated streamflow in the Arkansas River between the mouth of Fountain Creek and Twin Lakes Reservoir decreased proportionately to increased exchange rate. The median simulated decrease in streamflow ranged from about 4 percent for a simulation of Aurora's maximum exchange demand and a 50-percent increase in Colorado Springs' historical exchange demand to about 23 percent for a simulation of the maximum exchange demand for both exchanges. Downstream from the confluence with Fountain Creek, simulated streamflow at station 07109500 Arkansas River near Avondale was relatively unaffected by most exchange scenarios. This result was due to the inflow of transmountain return flows from Fountain Creek, which generally offset any upstream streamflow depletion. For exchange scenarios involving a 298-acre-ft/d increase in the transmountain return-flow exchange, simulated streamflow at the Avondale station increased about 8 to 12 percent. For these maximum exchange scenarios, available storage space in Pueblo Reservoir limited the exchange of return flows, and the unexchanged return flows from Fountain Creek entered the river and increased streamflow downstream at Avondale.

Simulated specific conductance in the Arkansas River increased at all sites in all simulation scenarios. The increase in specific conductance was proportionate to the magnitude of the total exchange. The median simulated increase in the daily mean specific conductance ranged from about 1 percent to about 7 percent. For scenarios involving the maximum transmountain return-flow exchange rate, the increase in the simulated specific conductance at the Avondale station was somewhat mitigated by the increased inflow of return flows from Fountain Creek. As the volume of return flows in Fountain Creek increased in the simulation scenarios, specific conductance in Fountain Creek actually decreased due to increased dilution capacity.

The simulated increase in specific conductance in the Arkansas River resulted in an increased frequency of exceedance of the secondary drinking-water standard for dissolved solids of 500 mg/L during low-flow months at the St. Charles Mesa station. This station is located at the diversion point for a public water supply. The simulated increase in salinity did not result in any changes in the historical irrigation salinity hazard for water in the Arkansas River.

REFERENCES CITED

Abbott, P.O., 1985, Description of water-systems operations in the Arkansas River Basin, Colorado: U.S. Geological Survey Water-Resources Investigations Report 85–4092, 67 p.

Batie, S.S., and Healy, R.G., 1983, The future of American agriculture: Scientific American, v. 248, no. 2, p. 45–53.

Cain, Doug, 1987, Relations of specific conductance to streamflow and selected water-quality characteristics of the Arkansas River Basin, Colorado: U.S. Geological Survey Water-Resources Investigations Report 87–4041, 93 p.

Draper, N.R., and Smith, Harry, 1981, Applied regression analysis (2d ed.): New York, Wiley, 709 p.

Enartech Consulting Engineers and Hydrologists, 1991, Arkansas River exchange plan—City of Aurora: Glenwood Springs, Colo., 1 v.

Enartech Consulting Engineers and Hydrologists, 1992, Simulation of Rocky Ford Ditch exchange—Pueblo Reservoir to upstream sites: Glenwood Springs, Colo., 1 v.

Gronning Engineering Company, 1986, City of Colorado Springs Arkansas River exchange plan: Denver, Colo., 1 v.

Kuhn, Gerhard, 1988, Methods to determine transit losses for return flows of transmountain water in Fountain Creek between Colorado Springs and the Arkansas River, Colorado: U.S. Geological Survey Water-Resources Investigations Report 87–4119, 183 p.

Lewis, M.E., and Brendle, D.L., 1998, Relations of streamflow and specific conductance to reservoir operations in the lower Arkansas River, Colorado: U.S. Geological Survey Water-Resources Investigations Report 97–4239, 48 p.

Lewis, M.E., and Edelmann, Patrick, 1994, Physical, chemical, and biological characteristics of Pueblo Reservoir, Colorado, 1985-89: U.S. Geological Survey Water-Resources Investigations Report 94–4097, 71 p.

Miles, D.L., 1977, Salinity in the Arkansas Valley of Colorado: U.S Environmental Protection Agency and Colorado State University, Interagency Agreement EPA-IAG–D4–0544, 80 p.

Radosevich, G.E., Nobe, K.C., Allardice, D., and Kirkwood, C., 1976, Evolution and administration of Colorado water law—1876–1976: Fort Collins, Colo., Water Resources Publications, 280 p.

U.S. Environmental Protection Agency, 1986, National secondary drinking-water regulations; part 143, section 143.3: Code of Federal Regulations, Title 40, Parts 100 to 149, p. 587-590.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1999 — 773-084 / 20056 Region No. 8