# USE OF A STREAM-AQUIFER MODEL TO DEVELOP METHODS TO ESTIMATE TRANSIT LOSSES FOR REUSABLE RETURN FLOWS IN FOUNTAIN AND MONUMENT CREEKS, EL PASO AND PUEBLO COUNTIES, COLORADO

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## Abstract

A stream-aquifer model was applied to Fountain Creek in a previously (1988) completed study and to Monument Creek in an ongoing (2006) study to develop methods to estimate transit losses for return flows of imported (includes transmountain) water along the two streams. Bank-storage, channel-storage, and evaporative losses were considered in estimating the transit losses. For each study, 15 stream subreaches (delimited by 16 model nodes) were established. Physical data needed for model input were channel (stream) length, aquifer length, and aquifer width for each subreach and stage-discharge relation data for each node. Wave celerity and wave-dispersion coefficient data were used to define the channel hydraulics for purposes of streamflow routing, and values for transmissivity and storage coefficient were used to define the aquifer hydraulics. For calibration and verification, recorded streamflow, at 1- or 2-hour intervals, was input at the upstream node (at a streamflow-gaging station) and routed downstream to the next gaging- station node. Simulated streamflow at the downstream node then was compared to recorded streamflow. Following calibration and verification of the stream-aquifer model, the model was used to estimate transit losses for about 15–20 imported water return-flow rates ranging from 1 to 100 cubic feet per second and for about 15–20 native discharges ranging from 1 to 1,000 cubic feet per second for each subreach. Through linear and logarithmic interpolation, the model results were expanded to provide a series of transit-loss “look-up” tables, one for each subreach, for the full ranges of imported water return-flow rates and native streamflows in 1 cubic foot per second increments. Results from the model simulations for the Fountain Creek study, including the look-up tables and the estimated percentages of channel storage, were incorporated into a transit-loss and streamflow accounting program; the accounting program for the Monument Creek study currently (2006) is being developed.

## INTRODUCTION

In 1988, the U.S. Geological Survey (USGS), in cooperation with Colorado Springs Utilities (CSU), completed a study to develop a method to estimate transit losses along Fountain Creek for return flows of transmountain water discharged into Fountain Creek at the CSU Las Vegas Street wastewater-treatment facility (WWTF) (fig. 1). The study, described in detail in Kuhn (1988), used a stream-aquifer model to estimate the volume of transmountain return flow in Fountain Creek at a number of locations along the stream reach for a large range of transmountain and native discharges. Results from applying the stream-aquifer model were incorporated into a FORTRAN-based transit-loss and streamflow accounting program (Kuhn et al., 1998). Under Colorado water law, imported water, which includes transmountain water, can be used and reused to the point of extinction if the imported water can be quantified at the point of intended reuse (Radosevich et al., 1976). The transit-loss accounting program that was developed enabled quantification and, hence, reuse of the transmountain return flows at selected locations along Fountain Creek. The accounting program has been in continual use since April 1989 and has provided a tool to effectively administer and manage transmountain and native streamflow rights along Fountain Creek on a daily basis (Kuhn et al., 1998).

Partly because of recent and estimated future population increases and partly because of increased potential to use reclaimed water (Colorado Springs Utilities, 2004), CSU is constructing the Northern water-reclamation facility (scheduled to become operational in 2006) adjacent to Monument Creek in the northern part of Colorado Springs (fig. 1). When completed, the facility will receive some of the wastewater currently discharged at the Las Vegas Street WWTF. Also, a number of other municipal entities in the Monument Creek basin, such as Monument, Palmer Lake, and Woodmoor, also either currently (2006) derive a portion of their water from imported sources or in the future plan to derive a portion of their water from imported sources. Implementation of any reuse programs by Colorado Springs or other municipal entities for the return flows of imported water likely would include transportation of the imported water return flows along Monument Creek downstream to some undetermined location; this transportation would require estimation of transit losses. Because no methods were available to

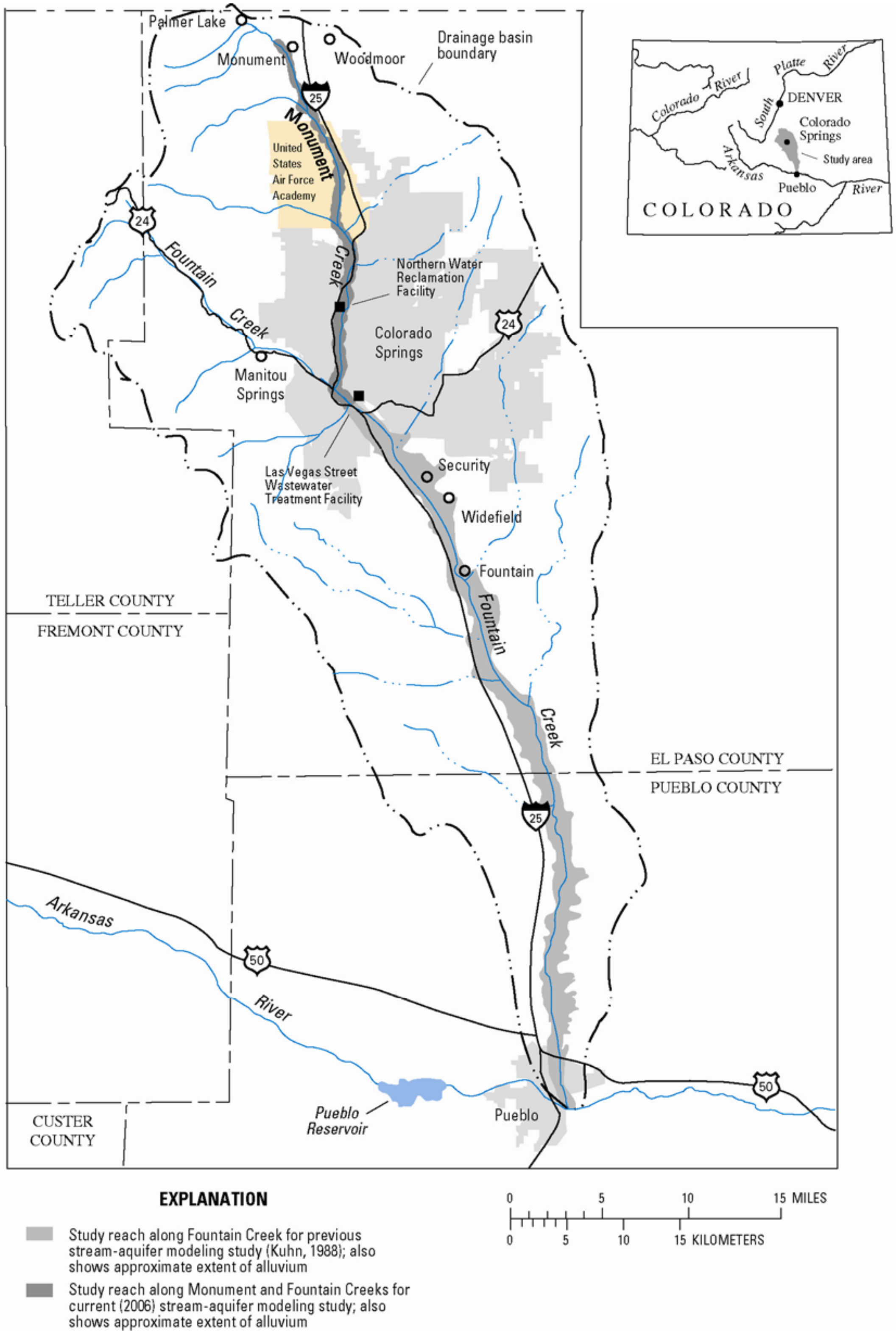


Figure 1. Study reaches along Fountain and Monument Creeks used in application of stream-aquifer model for development of transit-loss accounting programs.

estimate transit losses along Monument Creek, the USGS began a study in 2004, in cooperation with CSU, the El Paso County Water Authority, and the Colorado Water Conservation Board, to develop a transit-loss accounting program for Monument Creek similar to the program previously developed for Fountain Creek.

The purpose of this paper is to briefly describe the methods and results of applying a stream-aquifer model to Fountain Creek for the previously completed study (Kuhn, 1988) (hereinafter the Fountain Creek study) and to Monument Creek for the current (2006) study (hereinafter the Monument Creek study). The Fountain Creek study area consists of the alluvial valley along Fountain Creek from the Las Vegas Street WWTF in Colorado Springs downstream to the Arkansas River at Pueblo (fig. 1); the area is about 42 miles long and varies in width from about 0.5 to 2 miles. The Monument Creek study area consists of the alluvial valley along Monument Creek (and a small part along Fountain Creek) from north of Monument downstream to the Las Vegas Street WWTF in Colorado Springs (fig. 1); the area is about 22 miles long and varies in width from about 0.15 to 0.25 mile.

## POTENTIAL TRANSIT-LOSSES

Most streamflow in Fountain and Monument Creeks is derived from the following sources: (1) Snowmelt runoff from the mountainous headwaters of the main streams and perennial tributaries, primarily during April, May, and June; (2) rainfall runoff from thunderstorms in the basin, usually during May through September; (3) return flows from municipal, agricultural, and industrial water use; and (4) ground-water discharge from the alluvium. Because the study areas consist of a stream system that is hydraulically connected to the adjoining alluvium (Livingston et al., 1976), the potential transit losses used in development of the transit-loss accounting programs were bank storage, channel storage, and evaporation losses (Kuhn, 1988).

In a typical stream-aquifer system, the introduction of a water wave in the stream increases the head (water level) in the stream to a level greater than the head in the alluvium, resulting in the flow of water from the stream to the alluvium, termed “bank storage.” For this study, the water wave results from introduction of imported water into Fountain or Monument Creeks; the flow antecedent to the water wave is native streamflow. As head in the stream decreases, bank-storage water returns to the stream whenever head in the aquifer is greater than head in the stream. However, the rate at which bank-storage water returns to the stream is less than the rate at which the water flowed into the alluvium. After passage of a water wave, the rate of return initially may be large but decreases steadily with time. Therefore, a long period of time may be needed for bank-storage water resulting from a given water wave to return to the stream. In theory, if the time period is sufficiently long, virtually all bank-storage water could return to the stream; thus, bank-storage loss only would be a temporary loss. In practice, it is impractical to use long recovery periods because the volumes of water in consideration after long time periods are too small to measure accurately. Thus, some volume of the return flows from imported water generally is lost permanently to bank storage.

Channel storage is the volume of water in a reach of a stream at any given time. The introduction of a water wave results in an increase in channel storage in the reach. The volume of water lost to channel storage, however, is only a temporary loss because after passage of the water wave, channel storage rapidly decreases and becomes a part of the downstream flow. Changes in channel storage can have a substantial effect on the volume of return flows of imported water in Fountain or Monument Creeks at various locations; however, channel storage is not considered to be a permanent transit loss.

Return flows of imported water are evaporated either by (1) direct evaporation from the stream surface or (2) indirect evaporation through soil surfaces of water in bank storage. Transit loss resulting from direct evaporation was considered to be a permanent transit loss and was included in the two studies. Only the increase in evaporation resulting from the increase in stream width because of introduction of return flows of imported water was considered. Transit losses resulting from indirect evaporation are not considered to be substantial; moreover, these losses would, to some extent, be derived from the permanent losses to bank storage.

## STREAM-AQUIFER MODEL

Transit loss in a complex stream-aquifer system, such as the Fountain and Monument Creek alluvial valleys, only can be determined readily by use of computer models. These models provide the capability to simulate streamflow in a given stream and to simulate the interaction of the streamflow with an alluvial aquifer with reasonable accuracy.

The stream-aquifer model that was used in the Fountain Creek study and is being used in the Monument Creek study is described in detail in Land (1977). The model has two basic components: a bank-storage-discharge component and a streamflow-routing component; the streamflow-routing component is used to estimate channel storage. A detailed description of the model is beyond the scope of this paper; the model documentation (Land, 1977) and the references cited therein provide ample discussion of theory of operation. The model (Land, 1977) has been applied to estimate transit losses on several streams in southeastern Kansas (Carswell and Hart, 1985; Jordan and Hart, 1985). Also, a similar model was used to estimate transit losses along the Arkansas River in Colorado (Livingston, 1973, 1978).

The stream-aquifer model, however, has no capability to compute losses due to evaporation. Therefore, evaporation was computed using the evaporation-loss component from another model that has been used to determine transit losses for reservoir releases on the lower Arkansas River (Livingston, 1978). The evaporation-loss component was modified and adapted to the Fountain and Monument Creeks studies.

## System of Subreaches and Nodes

For use of the model, a stream reach to be studied is divided into one or more subreaches; the end points of the subreaches are referred to as "nodes." The location of nodes is based on location of streamflow-gaging stations, agricultural diversions, major tributaries, and return flows of imported water (WWTFs). Nodes at gaging stations are denoted by letters without a number (A–F), and nodes between gaging stations are denoted by a letter and number (figs. 2–3). For the Fountain Creek study, 15 stream subreaches (delimited by16 nodes) were established (fig. 2); one additional node (node A) was established to include an upstream gaging station. Transit losses, however, were not determined for the subreach between nodes A and A1; the subreach was used only for purposes of streamflow routing. For the Monument Creek study, 15 stream subreaches (delimited by16 nodes) also were established (fig. 3). The two most downstream nodes (E and E1) for the Monument Creek study are identical to the two most upstream nodes (A and A1) for the Fountain Creek study.

## Physical and Hydraulic Characteristics of Subreaches and Nodes

To apply the stream-aquifer model, the physical and hydraulic characteristics of the subreaches and nodes need to be defined. Physical characteristics data that are needed for model input are channel (stream) length, aquifer length, and aquifer width for each subreach and a stage-discharge relation needs to be defined for each node. Data for the subreaches were estimated from available topographic and geologic maps. Stage-discharge relations were available for the nodes located at gaging stations. For other nodes, stage-discharge relations were estimated by application of Manning's equation and step-backwater analysis (J.M. Kuzmiak, U.S. Geological Survey, written commun., 1986 and 2004). Stage-discharge relations also were estimated by the same methods for nodes at gaging stations to facilitate comparison of the estimated relations to the actual relations.

Values for wave celerity and wave-dispersion coefficient are needed for input to the model to define the channel hydraulics for purposes of streamflow routing. Wave celerity provides a measure of the rate of movement of a water wave through a stream reach, whereas wave-dispersion coefficient provides a measure of the amount of attenuation of a water wave within a stream reach. Equations are presented by Land (1977) to make preliminary estimates of wave celerity and wave-dispersion coefficient; initial estimates of the variables may be adjusted during the model calibration process. Values for transmissivity (hydraulic conductivity x saturated thickness) and storage coefficient (specific yield) are needed for input to the model to define the aquifer hydraulics. Transmissivity is a measure of the rate of water movement through an aquifer under standardized conditions, and storage coefficient is a measure of the volume of water that an aquifer could take into or release from storage (Heath, 1983; Lohman, 1972). Average transmissivities for subreaches in the Fountain Creek study were estimated from available hydrogeologic maps and aquifer-test data and ranged from 8,000 to 20,000 feet squared per day (Kuhn, 1988). Average transmissivities for subreaches in the Monument Creek study also were estimated from available hydrogeologic maps and aquifer-test data and ranged from 2,000 to 9,000 feet squared per day (L.R. Arnold, U.S. Geological Survey, written commun., 2005). A uniform value of 0.25 was used for storage coefficient in the Fountain Creek study (Kuhn, 1988), and a uniform value of 0.20 was used in the Monument Creek study (L.R. Arnold, U.S. Geological Survey, written commun., 2005).

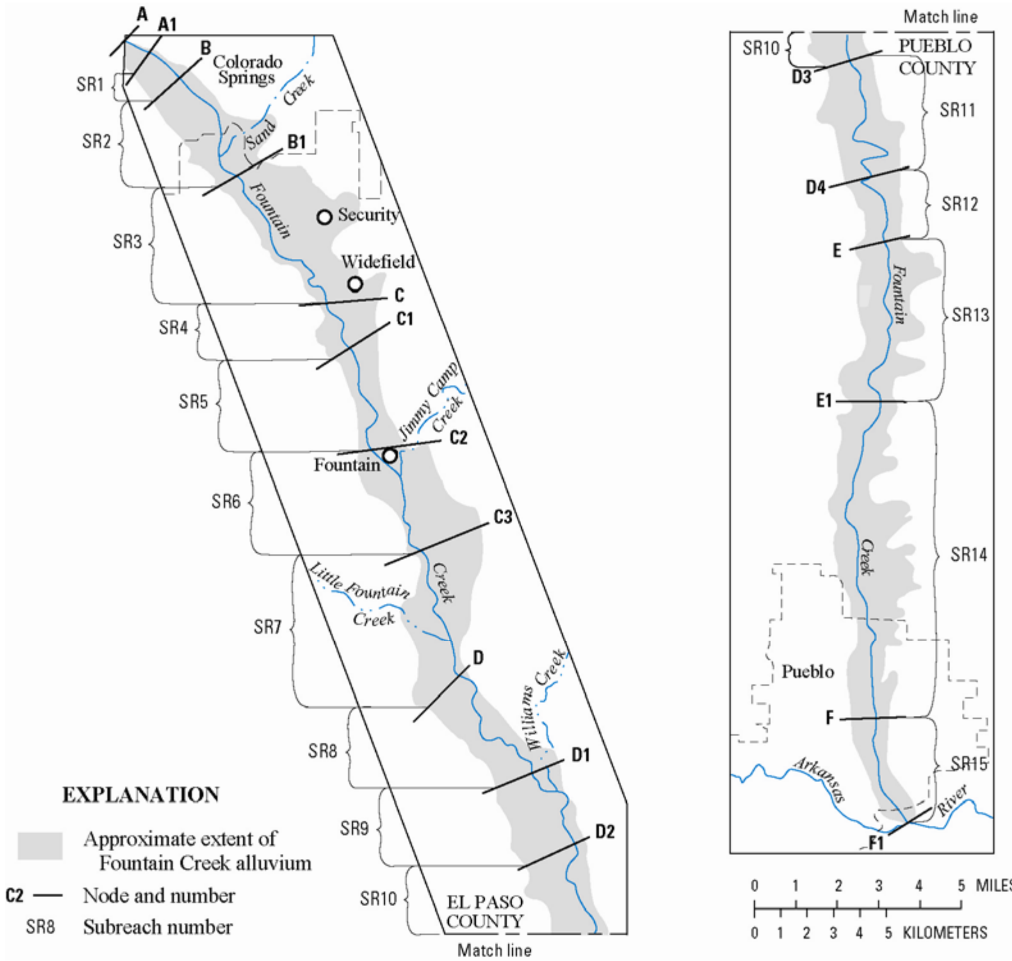


Figure 2. Subreaches and nodes along Fountain Creek used in application of stream-aquifer model in the Fountain Creek study.

## Model Calibration and Verification

Calibration and verification of the model consisted of (1) selection of streamflow hydrographs; (2) simulations of streamflow for purposes of adjusting model parameters (calibration); and (3) additional simulations of streamflow to ensure adjusted model parameters are appropriate (verification). Generally, a streamflow hydrograph suitable for calibration or verification should exhibit an initial period of steady streamflow, followed by a noticeable increase in flow, and followed by a return to steady flow similar in magnitude to the flow prior to the increase. Tributary inflow needs to be small during the period, or if substantial, needs to be available from streamflow records. Streamflow diversions, if operating during the period, need to be steady, especially during the time prior to the streamflow increase.

For calibration and verification, recorded streamflow, at 1- or 2-hour intervals, was input at the upstream node (at a gaging station) and routed downstream to the next gaging-station node. Simulated streamflow at the downstream node then was compared to recorded streamflow. For the Fountain Creek study, initial values for wave celerity and wave-dispersion coefficient were adjusted during model calibration; for the Monument Creek study, no model variables were adjusted during model calibration. Differences between simulated and recorded streamflow ranged from - 8.8 to 7.5 percent for the Monument Creek study (table 1) and ranged from -8.9 to 6.9 percent for the Fountain Creek study (Kuhn, 1988). Results for both studies indicate that streamflow was simulated to a reasonable accuracy. [Note: Data for some discontinued gaging stations on Monument Creek (not shown on figure 3) were used for model calibration and verification.]

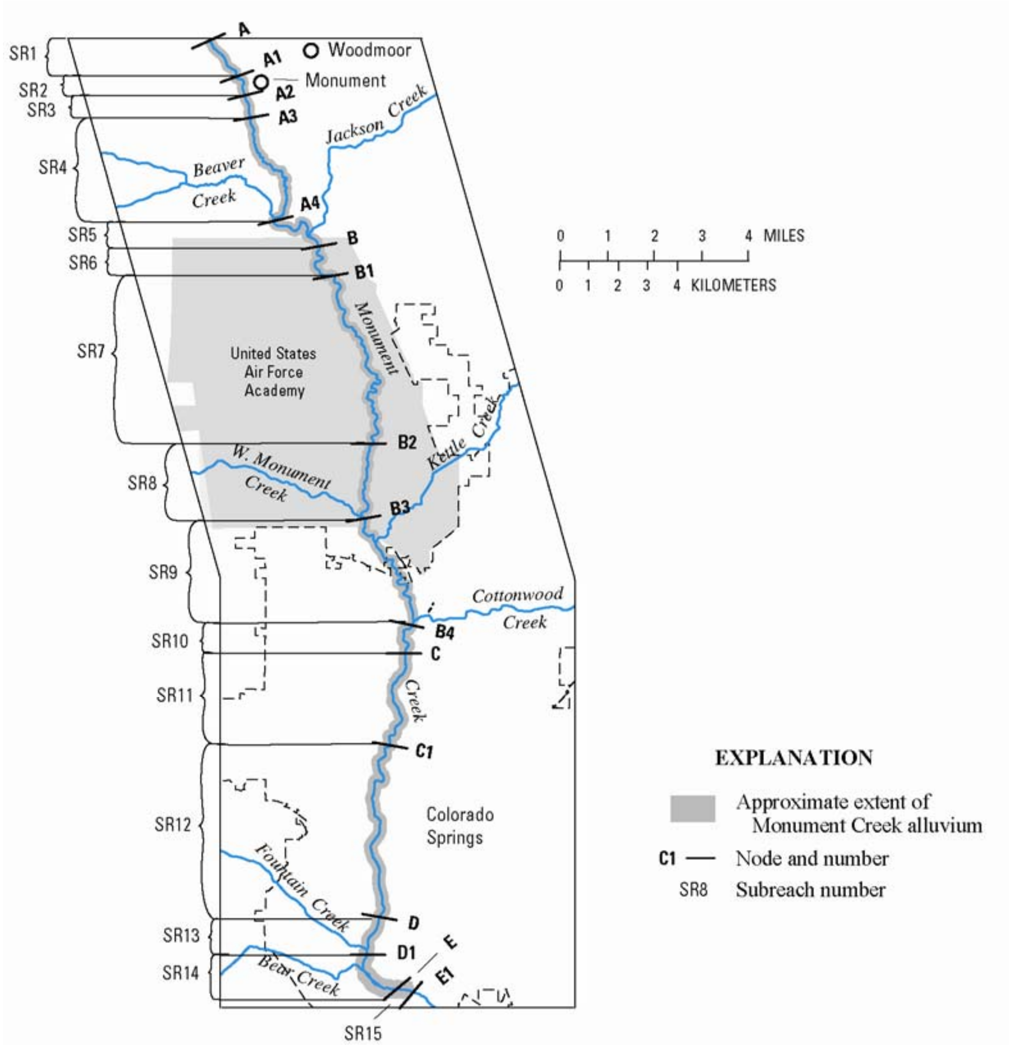


Figure 3. Subreaches and nodes along Monument and Fountain Creeks used in application of stream-aquifer model in the Monument Creek study.

## TRANSIT-LOSS ACCOUNTING PROGRAMS

Following calibration and verification of the stream-aquifer model, it was used to estimate bank-storage and channel- storage losses for about 15–20 imported water return-flow rates ranging from 1 to 100 cubic feet per second and for about 15–20 native discharges ranging from 1 to 1,000 cubic feet per second for each subreach (figs. 2–3). A daily time step was used for these model simulations because the accounting of return flows of imported water and the associated transit losses were made on a daily basis. Graphical analysis and linear regression were used to develop relations between bank-storage loss and the volumes of imported water and native streamflow. Through linear and logarithmic interpolation, the relations were expanded to provide a series of transit-loss “look-up” tables, one for each subreach, for the full ranges of imported water return-flow rates and native streamflows in 1 cubic foot per second increments. Modeling results indicated that channel-storage loss generally was a fixed percentage (about 10–20 percent) of the imported water return-flow rate. Results from the model simulations for the Fountain Creek study, including the look-up tables and the estimated percentages of channel storage, were incorporated into the transit-loss and streamflow accounting program (Kuhn et al., 1998). The accounting program for the Monument Creek study currently (2006) is being developed.

Table 1. Recorded and simulated streamflow and differences between the streamflows for selected time periods for subreaches along Monument Creek.

| Simulation period | Subreach number (fig. 3) | Recorded downstream streamflow (acre-feet) | Simulated downstream streamflow (acre-feet) | [1]Difference (acre-feet) | [2]Difference (percent) |
|---|---|---|---|---|---|
| April 2–30, 2001 | 7 | 1,062.6 | 1,045.4 | –17.2 | –1.6 |
| April 3–26, 2003 | 7 | 847.1 | 882.1 | 34.9 | 4.1 |
| October 3–12, 2001 | 8 | 237.7 | 225.8 | –12.0 | –5.1 |
| June 4–30, 2003 | 8 | 650.9 | 631.8 | –19.1 | –2.9 |
| October 3–13, 2001 | 9 | 350.1 | 351.8 | 1.7 | 0.5 |
| April 13–22, 2003 | 9 | 455.3 | 459.2 | 3.8 | 0.8 |
| May 7–10, 2000 | 10 | 664.1 | 637.6 | –26.5 | –4.0 |
| April 28–30, 2003 | 10 | 269.6 | 265.9 | –3.7 | –1.4 |
| July 19–20, 2003 | 11–12 | 72.3 | 72.0 | –0.3 | –0.3 |
| July 26–29, 2003 | 11–12 | 182.2 | 166.8 | –15.4 | –8.5 |
| August 9–10, 2003 | 11–12 | 84.6 | 80.9 | –3.7 | –4.4 |
| September 6–7, 2003 | 11–12 | 104.3 | 110.0 | 5.8 | 5.5 |
| May 13–14, 2004 | 11–12 | 107.8 | 104.9 | –3.0 | –2.7 |
| July 9–10, 2004 | 11–12 | 472.5 | 495.0 | 22.4 | 4.7 |
| April 3–4, 2003 | 13–14 | 174.6 | 187.7 | 13.1 | 7.5 |
| May 15–16, 2003 | 13–14 | 164.9 | 150.5 | –14.4 | –8.8 |
| May 23–24, 2003 | 13–14 | 120.2 | 121.2 | 1.0 | 0.8 |
| September 4–5, 2004 | 13–14 | 255.0 | 242.5 | 12.5 | 4.9 |

[1]Simulated – recorded.

[2][(Simulated – recorded) / recorded] x 100.

The transit-loss and streamflow accounting program for Fountain Creek requires daily inputs of streamflow at 6 gaging stations, return flows of imported water at 4 WWTFs, and diversion of both imported water and native streamflow at 24 ditches. Streamflow at the first gaging station (node A, fig. 2) is assumed to be all native discharge, and the first known volumes of imported water are input a short distance downstream (node A1, fig, 2). At the next downstream gaging station, total streamflow in Fountain Creek is known, but the proportion that is attributable to return flows of imported water is unknown. Therefore, the accounting program uses an iterative process to calculate the volume of imported water. Initially, it is assumed that the volume of imported water at the downstream gaging station is the same as at the upstream station. The known individual flow volumes at the upstream station are "routed" through all the subreaches to the next gaging station, while adjusting the imported return-flow volumes for the applicable estimated transit losses; the adjustments result in a calculated return-flow volume at the downstream station that differs from the assumed volume. The transit-loss calculations then are repeated for the same set of subreaches, but the calculated downstream imported return-flow volume from the previous iteration is used for the assumed volume of imported water at the downstream gaging station; the process is repeated until the assumed and calculated volumes of imported water at the downstream gaging station differ by less than 1 percent. The downstream station then becomes the upstream station and the calculations are repeated for the next set of subreaches until calculations have been completed for all 15 subreaches. In each iteration, native streamflow is estimated as the difference between total streamflow and the imported return flows.

## FUTURE STUDY ACTIVITY

Changes in the reuse programs for CSU transmountain return flows and implementation of reuse programs for transmountain return flows by other municipal entities along Fountain Creek downstream from Colorado Springs, such as Fountain, Security, and Widefield, have necessitated a number of comprehensive revisions to the accounting program (Kuhn et al., 1998; K.J. Lucey, U.S. Geological Survey, written commun., 2001). Additional changes to the program likely will be needed because of future changes proposed in the management and reuse of wastewater return flows by CSU (Colorado Springs Utilities, 2005; S.E. Howell, Colorado Springs Utilities, oral commun.,

2004) and the potential that some of the imported water accounted for in the transit-loss accounting program for Monument Creek also might need to be accounted for in the existing program for Fountain Creek. The existing accounting program is used on a daily basis by the Colorado Division of Water Resources to manage and administer both native and imported water rights along Fountain Creek and a need is foreseen for additional capabilities within the current accounting program, such as the capability to determine transit losses for well-augmentation water that may be transported between selected points along Fountain Creek. In order to facilitate the implementation of new capabilities currently needed and any potential future capabilities, a greater degree of flexibility is needed in the transit-loss accounting program for Fountain Creek.

Revisions to the Fountain Creek transit-loss accounting program to provide additional capability and increased flexibility will be made during 2006. A transit-loss accounting program with similar capabilities and flexibility also will be developed for Monument Creek during 2006. Finally, the two accounting programs will be integrated into a single accounting program, providing an effective tool for management of imported and native water rights along Fountain and Monument Creeks. A Web-based interface to the integrated transit-loss accounting program also will be developed that incorporates automated data input to the fullest extent possible.

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