South Platte Decision Support System Alluvial Groundwater Model Report

April 2013

Prepared for
the Colorado Water Conservation Board
and Colorado Division of Water Resources

CDM Smith

Table of Contents

Appendices

List of Figures

List of Tables

Acronyms

AF	acre-feet
AFY	acre-feet per year
AWAS	Alluvial Water Accounting System
CDOW	Colorado Division of Wildlife
CDSS	Colorado's Decision Support Systems
CFWE	Colorado Foundation for Water Education
CGWC	Colorado Groundwater Commission
CSU	Colorado State University
CWCB	Colorado Water Conservation Board
DMI	data management interface
DNR	Department of Natural Resources
DSS	Decision Support System
DWR	Division of Water Resources
ET	Evapotranspiration
ETS	MODFLOW ET Segments
Feasibility Study	SPDSS Feasibility Study
GIS	geographic information system
GMS	Groundwater Modeling Software
gpm	gallons per minute
HydroBase	The state's central water resources database
K	hydraulic conductivity
M&I	municipal and industrial
MODFLOW	USGS 3D Finite-Difference Groundwater Flow Model
NED	National Elevation Dataset
RGDSS	Rio Grande Decision Support System
S	storage coefficient
SB	Senate Bill
SFR	Streamflow Routing
SFR2	MODFLOW Streamflow-Routing package
SPDSS	South Platte Decision Support System
State	State of Colorado
StateDGI	State Data Graphic Interface
Sy	specific yield
T	Transmissivity
TM	Technical Memorandum
UDFCD	Urban Drainage and Flood Control District
USGS	U.S. Geological Survey
WDID	Water District ID

This page intentionally left blank.

Executive Summary

Introduction and the South Platte Alluvial Groundwater Model Development Process

This report documents the development and calibration of a numerical model developed for a major portion of the alluvial groundwater system within the South Platte River Basin. The numerical groundwater model was developed in MODFLOW, the widely used U.S. Geological Survey (USGS) finite-difference groundwater flow model. This alluvial groundwater model is part of the ongoing development of the South Platte Decision Support System (SPDSS). The SPDSS will also include a surface water model, which at the time of this report is currently under development, for the South Platte River and its major tributaries.

The SPDSS is one of four Decision Support System (DSS) initiatives that are part of Colorado's Decision Support Systems (CDSS), a joint effort of the Colorado Water Conservation Board (CWCB) and the Division of Water Resources (DWR). These DSSs include:

- ArkDSS (Arkansas Basin) – (Under development since 2011)
- CRDSS (includes the Colorado mainstem, Gunnison, White, Yampa, and San Juan/Dolores Basins)
- RGDSS (Rio Grande Basin)
- SPDSS (South Platte and North Platte Basins – excludes Republican River Basin)

CDSS includes a comprehensive set of data and analytical tools to aid in water resources planning and management. This report will focus on the groundwater component of the SPDSS. The South Platte Alluvial Groundwater Model was developed under a series of technical tasks over a multi-year period. The early work focused on data collection; data analysis and presentation; and the later work focused on developing the conceptual model, calibration, and documentation. A significant data collection and analysis effort was completed to support the model development and has been documented in a series of technical memoranda (TM).

During the early work tasks, approximately 50 TMs were completed to support the model development. The majority of these are referenced or incorporated in the appendices of this report. All TMs are available via the CDSS website (http://cdss.state.co.us/); a listing of the TMs is summarized in **Table 1-1** located at the end of the body of this report. Please refer to the TMs and the respective appendices for additional information on the SPDSS Alluvial Groundwater Model development and documentation.

The South Platte Basin is one of the most complex water use and water administration basins in Colorado and in the western United States. Extending from its headwaters in Park County, the South Platte River flows northeasterly through the Denver Metropolitan area and northern Front Range to the Nebraska state line near Julesburg, Colorado. The South Platte Basin is approximately 22,000 square miles and in 2008 contained about 69 percent of the State of Colorado's (State's) residents. With a 2008 population of 3.5 million people and 830,000 irrigated acres of farmland, the South Platte River, its tributaries, and groundwater resources are heavily relied upon to meet the social and economic needs of the basin. The entire South Platte River Basin alluvial groundwater system covers about 4,000 square miles (Colorado Geological Survey 2003); the SPDSS Alluvial Groundwater Model covers approximately 2,507 square miles or about 63 percent of the entire alluvial groundwater system within the South Platte Basin.

Given these complexities, during the scoping of the SPDSS Alluvial Groundwater Model several important decisions were made to ensure that a modeling effort would provide usable and reliable information within the available schedule and budget for the project. These decisions included:

- The alluvial groundwater model boundaries would focus on the areas of higher use.
- The availability of data would dictate that a selected number of tributaries would be included in this initial development of the SPDSS Alluvial Groundwater Model.
- Given the large geographic extent of the alluvial aquifer it was determined that a regional model would be the logical first step. In addition, since the model includes such a large area, it was determined that a uniform 1,000-foot model grid would be most appropriate.
- The model would be developed for larger regional scale planning, not for regulatory or water rights administration decisions. The model would provide overall trends and resource use information that could be used to frame and design smaller scale or site-specific water resource investigations.

With these points in mind, a modeling domain (geographic area) and model grid (spatial scale of analysis) was developed.

CDSS Helping Colorado Make Informed Water Resource Decisions

Each DSS within Colorado's Decision Support Systems is uniquely developed to address and conform to the water resource conditions and needs of their respective basins; however, they share some overarching characteristics. At their core, the DSSs are designed to help water users, engineers/scientists, policy makers, and other interests make informed decisions regarding water resource management in Colorado. The goals of the CDSS are to:

- Develop accurate, user-friendly databases that are helpful in water resources planning and management in the State of Colorado.
- Provide data, tools, and models to evaluate alternative water administration strategies in various hydrologic conditions.
- Be a functional system that can be used by decision-makers and others and be maintained and upgraded by the state.
- Promote information sharing among government agencies and water users.

You can learn more about CDSS by visiting: http://cdss.state.co.us/Pages/CDSSHome.aspx

SPDSS Model Configuration – Model Domain and Grid

The alluvial groundwater model includes the unconsolidated deposits of the South Platte River mainstem, extending downstream from Chatfield Reservoir to the Nebraska state line near Julesburg, and the unconsolidated deposits of selected tributaries to the South Platte River. Key tributaries and their alluvial aquifers included in the model are, in upstream to downstream order:

- Plum Creek
- Cherry Creek
- Sand Creek
- Clear Creek
- Big Dry Creek
- St. Vrain Creek
- Big Thompson River
- Beebe Draw
- Cache la Poudre River
- Lonetree Creek
- Crow Creek
- Box Elder Creek
- Lost Creek
- Kiowa Creek
- Bijou Creek
- Badger Creek
- Beaver Creek

The alluvial deposits of the South Platte River Basin in the study area consist primarily of sand and gravel with finer grain floodplain deposits present in valley floor areas. The alluvium in the major tributaries and the mainstem comprises a continuously connected aquifer system. The alluvial aquifer is in hydraulic communication with the surface water system throughout most of the study area. The extensive development of irrigation with surface water diversions and groundwater pumping results in gaining conditions for the majority of streams, since percolation of applied irrigation water raises water levels. The maximum thickness of alluvial deposits increases in a downstream direction on the mainstem, with saturated aquifer thickness of 20 to 40 feet at the upstream extent near Denver, to more than 200 feet near Julesburg. Saturated aquifer thickness is typically lower in tributary streams. The hydraulic characteristics of the alluvial aquifer allow development of high yield groundwater wells, with yields as high as 1,500 to 2,000 gallons per minute in some areas with thick alluvial deposits. Hydraulic conductivity values range from 100 to 2,000 feet per day, depending on the degree of sorting and the amount of fine grain material present.

The alluvial groundwater model consists of a single layer but includes flow into and out of the underlying bedrock aquifers of the Denver Basin based on results from the groundwater model developed by the USGS (2011). The model area is divided into a series of rows and columns referred to as the model grid for the purpose of numerical simulation. The model grid is uniform with model cells that are 1,000 feet on each side, resulting in 655 rows and 848 columns and 555,440 individual cells, of which 69,895 are in the active model domain. This cell size was dictated by data availability (spatial distribution), overall model size and complexity, estimated simulation times,

A Quick Overview of Modeling

Models are typically developed to simulate complex systems or resources. They can help us simulate "what if" scenarios that allow us to better understand how resource management decisions may affect the resource. There are a number of different types of models ranging from conceptual to numerical models. For the SPDSS, it was decided to develop a finite-difference numerical groundwater flow model using MODFLOW. In simple terms, *finite difference* is a numerical method utilized to solve the mathematical equations that are developed to characterize the condition of the resource (groundwater in this case) over time and space. Overall, the SPDSS MODFLOW model uses mathematical relationships to simulate groundwater flow and estimate water table levels.

schedule, and budget. In order to represent complex surface water and groundwater flows, the active model domain includes a series of inputs and outputs including, but not limited to, recharge from applied irrigation water and precipitation, well pumping for agricultural and municipal uses, stream gains and losses, seepage from irrigation canals and reservoirs, lateral boundary inflows, and phreatophyte evapotranspiration. The SPDSS Alluvial Groundwater Model simulates this complex water resource system, and is well suited for regional resource planning applications. **Figure ES-1** (located at the end of the Executive Summary) identifies the alluvial groundwater modeling extent and includes information on some of the major features of the basin and model development effort.

Data Centered Groundwater Modeling Approach

CDSS utilizes a "data centered" approach in its various analytical tools, including groundwater modeling. As shown in **Figure ES-2**, HydroBase, the State's central water resources database containing observed and measured data, is at the center of the various DSS tools. Various data management interfaces (DMIs) and other data centered tools facilitate a linkage between data sources, such as HydroBase and State geographic information system (GIS) coverages, and the numerical groundwater model. This approach facilitates updating of the groundwater model when changes or updates occur to underlying data sets, when model simulation periods change, or if additional processes are incorporated.

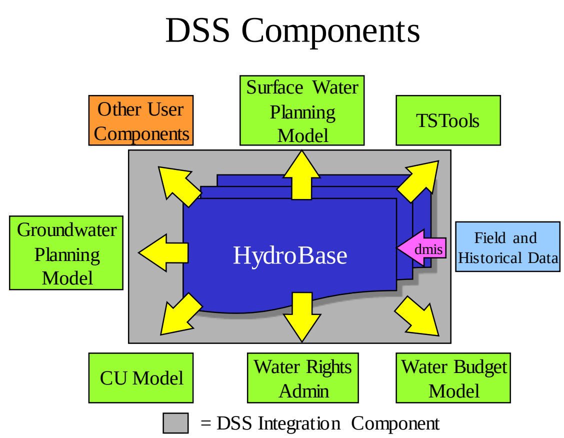


Figure ES-2. Data Centered Approach

Because of the importance of the data centered approach, the first major tasks completed during the development of the SPDSS were a review, evaluation, and supplementation of the existing CDSS data centered modeling process in order to best accommodate the SPDSS groundwater modeling needs. Refinements and supplementation included development of the following:

- Significant additions to groundwater related data, including water level and aquifer properties.
  - Over 29,000 groundwater wells were identified for inclusion in HydroBase.
  - Water levels were compiled extending back to the 1950s; 108,843 alluvial groundwater level measurements were taken from 6,754 wells.
  - Information from 1,241 aquifer tests on aquifer properties (hydraulic conductivity and specific capacity) was compiled.
  - Surface elevations were surveyed at all new wells installed by the program, and at numerous existing wells.
  - Alluvial bedrock elevations were obtained at over 1,500 locations.
- An ArcGIS geodatabase for spatial groundwater data was developed that was not included in HydroBase.
- Custom ArcGIS tools were developed to facilitate the development of modeling packages.
- Custom applications were developed to facilitate the development of modeling packages.
- Modifications were made to existing modeling related data preprocessing tools.

As noted earlier, numerous TMs were developed to document the above efforts and to complete additional analysis required to construct the SPDSS Alluvial Groundwater Model. Please see **Table 1-1**, which summarizes this information and provides the reader with an outline of where to obtain additional information utilized to develop the model. The data centered modeling approach will be further described throughout the remainder of this report.

The SPDSS Alluvial Groundwater Model was developed in MODFLOW-2000 (Harbaugh et al. 2000), a widely used groundwater modeling program developed by the USGS and adopted by the State as one of the CDSS modeling tools. MODFLOW input files were created using the data centered tools developed as part of CDSS and the third-party Groundwater Modeling Software (GMS). GMS and its graphical user interface were used to create specific MODFLOW input files such as the discretization file and to visualize head observations and the potentiometric surface, the ground surface and base of alluvium, and the model active area array. GMS is a valuable visualization tool but is not required to run the model or to evaluate model results. Sections 2 and 3 of the report describe the alluvial groundwater model development and configuration process.

SPDSS Model Calibration Results

To ensure that the SPDSS model reasonably represents real-world aquifer conditions, the model was refined and tested using what is called a "calibration process." The purpose of calibration is to establish that the model can reproduce field-measured heads and flows (Anderson and Woessner 1992). Model calibration is the process where model parameters are adjusted within their range of uncertainty to obtain acceptable agreement between observed flows and heads, and their simulated equivalents in the model. Calibration of the SPDSS model was performed using a combination of trial and error adjustment of parameters and an automated parameter estimation method.

The SPDSS Alluvial Groundwater Model has been developed and calibrated using the data and processes described in this report. The model was calibrated under transient conditions for the calibration period (1999 to 2005) and then results were verified for the validation period (1950 to 2006). Model calibration was an iterative process that included varying within a reasonable range selected model inputs such as aquifer hydraulic conductivity and streambed conductance. Model calibration included the comparison of observed and simulated water levels and flows. The calibrated model met the majority of the goals for the calibration period with the following results:

1. Model simulated heads at observation wells with surveyed elevations (of which there were 104 wells with 16,041 measurements) were within ±5 feet for 83 percent of the observations. For all 513 observation wells with 20,244 measurements, simulated heads were within ±5 feet for 75 percent of the observations.
2. The seasonal changes in heads at all wells were within ±5 feet at 90 percent of the observations.
3. Historical surface water diversions were met 97 percent of the time in the calibrated model.
4. Average annual modeled streamflow was within 25 percent of the observed flow for 89 percent of the stations with annual flows exceeding 25,000 acre-feet per year (AFY).
5. Stream gains and losses in the model were comparable to the estimated targets with both generally showing gaining reaches in the model domain; however, in some cases, the magnitudes were significantly different, with the estimated targets showing larger seasonal fluctuations and the model results showing more damped variations.

6. Evapotranspiration from phreatophytes simulated by the model was 101 percent of the estimated value for the one-year calibration time period (2001).

Overall the results from the SPDSS Alluvial Groundwater Model calibration achieved the goals for the project. Development of the alluvial model did identify a small number of issues during the calibration process. These issues include some instances of model cells with streambed elevations lower than the bottom of the aquifer; inaccurate delineation of the areal extent of the alluvial aquifer on two small tributaries; flooded cells in some locations, especially locations with thin alluvium and/or areas of probable excessive recharge; dry cells along portions of the perimeter of the active model domain; the need to reduce agricultural well pumping during the final stages of calibration due to excessive depletion of the alluvial aquifer compared to observed water level data; and the need to adjust selected tributary surface water flows to their historical values, to facilitate flow calibration in the mainstem of the South Platte River. The occurrence and location of these issues do not have a significant impact on the utility of the model, but they should be noted when utilizing the model for individual planning efforts, and should be considered during future enhancements to the alluvial groundwater model. The surface water-related issues should be revisited after the SPDSS surface water model is completed.

For more information on the model calibration criteria and targets please see Section 4 of this report and Task 48.2 Development of Calibration Targets and Criteria Technical Memorandum (Appendix K).

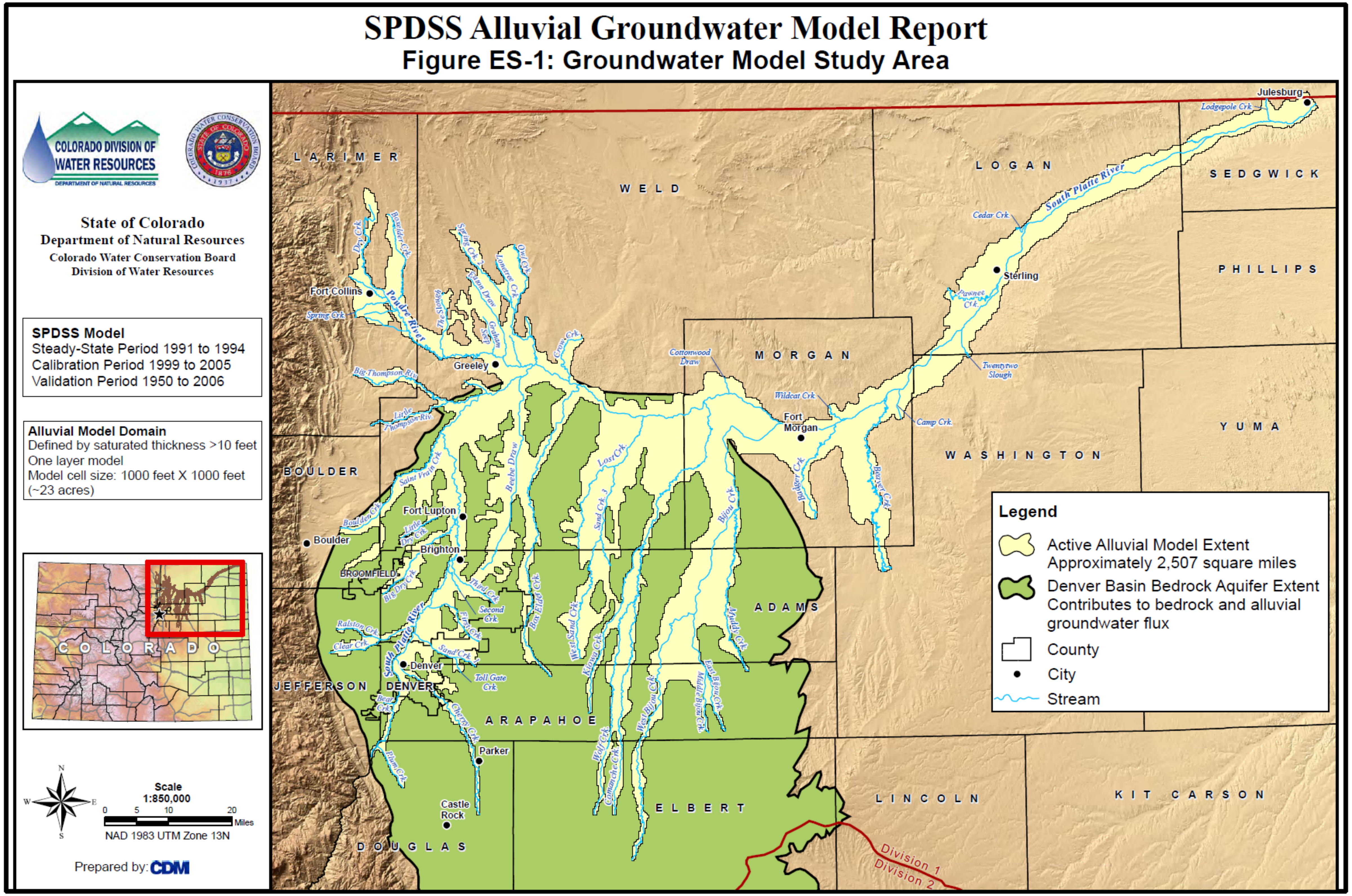
Summary and Recommendations for Ongoing SPDSS Alluvial Groundwater Model Improvement and Enhancements

The SPDSS Alluvial Groundwater Model is a significant step forward in understanding the regional groundwater flow in the South Platte Basin. Databases and tools have been developed throughout this project that will be beneficial to water planners, scientists, engineers, and policy makers. Going forward it is important to note the SPDSS surface water model is under development and slated for completion in 2014. The alluvial groundwater model will continue to be improved upon as new information is collected and as both groundwater and surface water models are applied under different planning scenarios. Based on what has been learned from this first round of alluvial groundwater model development and calibration, a short list of recommendations for potential future enhancements of the SPDSS Alluvial Groundwater Model are provided below:

- Refine the surface water inputs (e.g., estimates of ungaged surface water inflows and stream gains and losses) with results from the surface water model of the South Platte and its tributaries.
- Develop and include a more detailed understanding of reservoir and canal seepage to the alluvial aquifer; in some areas of the South Platte (e.g., from Greeley to Sterling), the seepage can be very high.
- Continue to collect water levels from the existing alluvial wells in the study area using continuously recording data-loggers when possible.
- Add additional wells and water level data (e.g., in the areas of the confluence of Kiowa and Bijou Creeks with the South Platte, and Pawnee Creek near Sterling) to HydroBase allowing for refinement of the model calibration in areas where water level data is currently unavailable.

- Continue to collect and add aquifer property data to HydroBase as it becomes available through new wells or testing of existing wells to enhance the existing hydraulic conductivity distribution in the model.
- Continue to collect well pumping data from municipal, industrial, agricultural, and augmentation wells for inclusion in HydroBase.
- Continue to identify publicly available groundwater data from USGS, State, and consulting reports to include in HydroBase.
- Consider periodic updates (~5 year intervals) of the SPDSS Alluvial Groundwater Model with the latest data to account for changes in hydrology and basin operations.

This page intentionally left blank.


SPDSS Alluvial Groundwater Model Report
Figure ES-1: Groundwater Model Study Area
COLORADO DIVISION OF WATER RESOURCES
DEPARTMENT OF NATURAL RESOURCES
State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources
SPDSS Model
Steady-State Period 1991 to 1994
Calibration Period 1999 to 2005
Validation Period 1950 to 2006
Alluvial Model Domain
Defined by saturated thickness >10 feet
One layer model
Model cell size: 1000 feet X 1000 feet
(~23 acres)
COLORADO
Scale
1:850,000
0 5 10 20
Miles
NAD 1983 UTM Zone 13N
Prepared by: CDM
LARIMER
WELD
LOGAN
SEDGWICK
PHILLIPS
MORGAN
WASHINGTON
YUMA
BOULDER
ADAMS
JEFFERSON
DENVER
ARAPAHOE
DOUGLAS
ELBERT
LINCOLN
KIT CARSON
Julesburg
Sterling
Fort Collins
Greeley
Fort Morgan
Fort Lupton
Boulder
Brighton
BROOMFIELD
Denver
Parker
Castle Rock
South Platte River
Poudre River
Division 1
Division 2
Legend
Active Alluvial Model Extent
Approximately 2,507 square miles
Denver Basin Bedrock Aquifer Extent
Contributes to bedrock and alluvial groundwater flux
County
City
Stream

This page intentionally left blank.

Section 1

Introduction

The South Platte River Basin in northeastern Colorado is an area where both the surface water and groundwater resources are used intensively. One way to better understand the basin's water use and to evaluate the effects of various water resources strategies is to simulate the basin hydrology in a model. This section provides an introduction to the alluvial groundwater model developed as part of the South Platte Decision Support System (SPDSS) project. The SPDSS is one of four decision support systems within Colorado's Decision Support Systems (CDSS), initiated and managed by the Colorado Water Conservation Board (CWCB) and Division of Water Resources (DWR) of the Colorado Department of Natural Resources (DNR).

The SPDSS Alluvial Groundwater Model included developing both a steady-state and transient model. A steady-state model was developed to verify model inputs and determine reasonable hydraulic heads. A monthly transient model was developed and calibrated for the calibration period (January 1999 to December 2005). Finally, the model was verified using the validation period (January 1950 to December 2006). Details of the development of the model and the calibration process and results are provided in the following sections of this report.

The purpose and overall objectives of the SPDSS alluvial groundwater modeling are described in Section 1.1. Section 1.2 describes the area within the South Platte River Basin where the groundwater model was developed. Section 1.3 provides a brief background on the water use and water development within the study area and provides an overview of the general characteristics of the South Platte Basin.

1.1 Purpose and Objectives

The South Platte Alluvial Groundwater Model was developed under a series of technical tasks over a multi-year period. The early work focused on data collection; data analysis and presentation; and the later work focused on developing the conceptual model, calibration, and documentation. The SPDSS Feasibility Study (Feasibility Study) (SPDSS 2001) provided the framework and road map for the development of the SPDSS Alluvial Groundwater Model. The Feasibility Study identified several items that should be accomplished using the CDSS hallmark "data centered approach." The data centered approach establishes a primary focus on existing data and empirical information to drive CDSS models and analytical tools.

The groundwater component of the SPDSS started by gathering available groundwater data and publications on the South Platte Basin. Groundwater data related to water level measurements, aquifer properties, and aquifer configuration was integrated into HydroBase, the State of Colorado's (State's) central water resources database. This data was reviewed and analyzed to identify gaps in the data that could be filled via the SPDSS field program. The SPDSS field program installed new water level monitoring wells, performed aquifer performance tests, and measured wells in areas where data was previously unavailable and added this information to HydroBase.

Using analytical tools developed for the CDSS, in addition to other analytical tools developed specifically for the SPDSS, the data gathered from earlier efforts was used to develop a groundwater model for the South Platte Alluvium in MODFLOW -2000 (Harbaugh et al. 2000), a widely used groundwater modeling program developed by the USGS and adopted by the State as one of the CDSS modeling tools. These tools and databases include HydroBase, StateCU, StateDGI, StatePP, a groundwater geospatial database, and several other tools developed to process data and prepare inputs for a MODFLOW groundwater model using a data centered approach. These tools are discussed in further detail in Task 50 Data Centered Modeling Tools Technical Memoranda (TM) (SPDSS 2007a) and in Appendix J of this Model Report. During the early work tasks, approximately 50 TMs were completed to support the model development. The majority of these are referenced or incorporated in the appendices of this report. All TMs are available via the CDSS website (http://cdss.state.co.us/); a listing of the TMs is summarized in **Table 1-1** located at the end of the body of this report. Please refer to the TMs and the respective appendices for additional information on the SPDSS Alluvial Groundwater Model development and documentation.

The overall objective of the SPDSS Alluvial Groundwater Model is to create a planning level tool for the alluvial aquifer of the South Platte River and selected tributaries to the South Platte. This model was designed to provide water users, policy makers, and other interested stakeholders with a regional model that can be used to evaluate current and future trends in the South Platte alluvial groundwater system and to continue to improve our understanding of groundwater and surface water interactions.

Modeling activities were undertaken with the following goals:

- Enhance the understanding of regional groundwater system in the study area.
- Create a tool to support informed regional water resource decision-making.
- Establish an extensive groundwater database containing well information, aquifer property data, and water level data.
- Develop utilities to assist the data centered process in migrating data from the groundwater database and HydroBase into a groundwater model consistent with other utilities developed for the CDSS.

It is the vision of the CWCB and DWR that the development and enhancement of SPDSS be an ongoing process in order to improve the components when possible and to better understand and evaluate potential changes in the use and management of water resources in the South Platte Basin. The groundwater model and data developed as part of the SPDSS is a significant step toward achieving this vision. The existing databases and current model configuration are designed to allow preparation of model files that can be updated efficiently without having to start from scratch. As noted above, the SPDSS alluvial model is a regional planning model but also provides the framework for local planners to undertake more specific analysis in their areas of interest.

1.2 Study Area Description

The alluvial groundwater modeling component of the SPDSS focuses on the South Platte Alluvium Region. This study area consists of the unconsolidated deposits of the South Platte River mainstem, extending downstream from Chatfield Reservoir to Julesburg near the Colorado-Nebraska state line, and the unconsolidated deposits of selected major tributaries to the South Platte River. **Figure ES-1** identifies the alluvial groundwater modeling extent, which is also referred to as modeling domain. As noted earlier, the active model domain covers an area of approximately 2,507 square miles.

Key tributaries to the South Platte mainstem in the South Platte Alluvium Region represented in the alluvial groundwater model include the following, listed in upstream to downstream order (underlined tributaries denote tributaries that had available gaged flows):

1. Plum Creek
2. Bear Creek
3. Cherry Creek
4. Sand Creek
5. Clear Creek
6. Big Dry Creek
7. St. Vrain Creek (includes Boulder Creek and Coal Creek)
8. Big Thompson River (includes Little Thompson)
9. Beebe Draw
10. Cache la Poudre River
11. Lonetree Creek
12. Crow Creek
13. Box Elder Creek
14. Lost Creek
15. Kiowa Creek
16. Bijou Creek
17. Badger Creek
18. Beaver Creek

The tributaries that drain into the South Platte River from the west, including Clear Creek, Big Dry Creek, St. Vrain Creek, Big Thompson River, and the Cache la Poudre River, are simulated in their lower portions, from approximately where these tributaries flow out of the Front Range canyons.

1.3 Water Resource Development and General Characteristics of the South Platte Basin

The South Platte River Basin is approximately 22,000 square miles and in 2008 contained about 69 percent of the State's residents. With a 2008 population of 3.5 million people and 830,000 irrigated acres of farmland, the South Platte River, its tributaries, and groundwater resources are heavily relied upon to meet the social and economic needs of the basin. The entire South Platte Basin alluvial groundwater system covers about 4,000 square miles (Colorado Geological Survey 2003) and the SPDSS Alluvial Groundwater Model includes approximately 2,507 square miles of modeled alluvium. The development of water resources in the region was critical to support both the urban and agricultural growth of the region. Much of the South Platte Basin, especially in the study area, receives less than 19 inches of precipitation annually. Consequently, water resource development has been extensive and complex. The development history involved development of native in-basin groundwater (both tributary and nontributary) and surface water, as well as the importation of transbasin surface water supplies from the Colorado River Basin.

The alluvial deposits of the South Platte River Basin in the study area consist primarily of sand and gravel with finer grain floodplain deposits present in valley floor areas. The alluvium in the major tributaries and the mainstem comprises a continuously connected aquifer system. The alluvial aquifer is in hydraulic communication with the surface water system throughout most of the study area. The extensive development of irrigation with surface water diversions and groundwater pumping results in gaining conditions for the majority of streams, since percolation of applied irrigation water raises water levels. The maximum thickness of alluvial deposits increases in a downstream direction on the mainstem, with saturated aquifer thickness of 20 to 40 feet at the upstream extent near Denver, to more than 200 feet near Julesburg. Saturated aquifer thickness is typically lower in tributary streams. The hydraulic characteristics of the alluvial aquifer allow development of high yield groundwater wells, with yields as high as 1,500 to 2,000 gallons per minute (gpm) in some areas with thick alluvial deposits. Hydraulic conductivity values range from 100 to 2,000 feet per day, depending on the degree of sorting and the amount of fine grain material present.

Agricultural irrigation is the dominant water use in the South Platte River Basin. Agricultural activity in the basin has led to an extensive network of reservoirs, irrigation canals and ditches, and over 26,300 total groundwater wells, over 9,100 of which are high capacity (>50 gpm). In recent decades rapid urban growth along the northern Front Range of Colorado has led to the acquisitions and transfer of some agricultural water to urban/municipal uses.

Water development in the South Platte Basin generally proceeded in an upstream to downstream progression. The first significant diversion of the South Platte occurred in 1870 in the vicinity of present day Greeley when the Union Colony constructed two canals for irrigation. Development proceeded at a rapid pace and by 1910 irrigated crops included alfalfa, potatoes, and beets, which require irrigation for longer periods than hay and small grain crops. As water was developed, including both direct flow water rights and reservoir storage, a more reliable pattern of return flows allowed for use and reuse of the limited water resources in the basin. Nevertheless, by the 1930s, water shortages and the extreme drought of the 1930s led water users to seek additional/ supplemental water supplies. This effort culminated in the authorization and construction of the Colorado-Big Thompson Project, which imports 285,000 acre-feet (AF) to the South Platte Basin annually (Dennehy et al. 1993).

Wells have been used to obtain irrigation water in the basin since 1900 (Hurr et al. 1975). However, it was not until the 1930s, with electrical driven pumps and modern drilling technology, when well yields were sufficient for large-scale crop irrigation and groundwater began to play an important role in South Platte River Basin agriculture. By 1950 there were approximately 1,500 high capacity (>50 gpm) wells withdrawing water from the alluvial aquifer. Groundwater development grew rapidly in the mid-1950s due to drought conditions in the basin and again in the 1960s in anticipation of pending groundwater use regulations (Hurr et al. 1975). By the 1970s there were approximately 3,200 large capacity wells on file with the DWR.

Groundwater use has been administered in Colorado under the Prior Appropriation System since the 1960s, with the 1965 Groundwater Management Act requiring well permits, and the 1969 Water Rights Determination and Administration Act that integrated wells into the priority system (DWR 2007b). The Colorado DWR, also known as the Office of the State Engineer, administers surface and tributary groundwater under the Prior Appropriation System. This system gives the right to the water users to develop and apply previously unappropriated water for beneficial uses. During times of shortage, the Prior Appropriation System allows the older and more senior water rights to be satisfied before the junior water rights receive any of their water right.

Groundwater in most locations is presumed to be hydraulically connected to a nearby stream and subject to the Prior Appropriation System unless proven otherwise. Groundwater development in the basin has slowed since the early 1970s due to its administration under the Prior Appropriation System along with senior surface water uses (Dennehy et al. 1993).

The Denver Basin bedrock aquifers and groundwater within areas called Designated Basins, including the Ogallala (High Plains) aquifers, are administered under different criteria, based on land ownership and specified rates of aquifer depletion (Colorado Foundation for Water Education [CFWE] 2004). The SPDSS Alluvial Groundwater Model uses results from the U.S. Geological Survey (USGS) Denver Basin Model (USGS 2011) to represent groundwater fluxes between the bedrock and the alluvium.

Designated Groundwater Basins are established by the Colorado Groundwater Commission (CGWC). The CGWC is a regulatory and an adjudicatory body authorized by the General Assembly to manage and control groundwater resources within eight Designated Groundwater Basins in eastern Colorado. Designated basins are areas in the eastern plains with very little surface water where users rely primarily on groundwater as their source of water supply (DWR 2013). These designated basins are considered nontributary and regulated under specific designated basin rules (CFWE 2007). Two designated basins, Lost Creek and Kiowa-Bijou, are located within the SPDSS alluvial study area and are included in the SPDSS Alluvial Groundwater Model.

The drought of early 2000 brought significant changes in groundwater use in the South Platte Basin. In the 2002 to 2006 time period there was a significant reduction in alluvial well pumping in the basin, with over 440 irrigation wells shut down (DWR 2007a). This reduction in well pumping was associated with the lack of available augmentation water during these extreme drought years and with a State Supreme Court decision that changed the procedures and requirements for adjudicating and administering out-of-priority depletions associated with groundwater pumping. This reduction in pumping is expected to have important effects on the alluvial aquifer flow regime in the vicinity of these wells.

Water resource development, management, and administration in the basin have changed significantly over the last 150 years. Throughout all these changes the basin has remained a significant economic engine for Colorado. According to the 2007 United States Census, 7 of the 10 top value agricultural producing counties in Colorado are within the South Platte Basin. The combined value of urban and agricultural development in the basin stresses the importance of optimizing and maximizing the beneficial uses of both ground and surface water. The completion of the SPDSS Alluvial Groundwater Model provides Colorado with a new tool to help achieve this goal.

This page intentionally left blank.

Section 2

Model Development

The first major decision in the development of the SPDSS Alluvial Groundwater Model was the selection of a representative study period that would include both sufficient data and resource variability. The study period identified for the SPDSS project is 1950 through 2006. A number of factors governed the selection of the 1950 to 2006 study period, including streamflow, diversion and other data availability, key climate events, and significant water development and administration events. Selection of the study period was primarily constrained by the availability of diversion and climate data, both of which are available electronically only from 1950 to present. This period includes a wide range of hydrologic conditions over which to evaluate the South Platte water supplies and is a cost-effective choice given the availability of electronic data.

Within that overall study period, the SPDSS groundwater modeling effort includes three modeling study periods: (1) the steady-state period (average annual 1991-1994), (2) the transient calibration period (monthly 1999-2005), and (3) the validation period (monthly 1950-2006). The three modeling study periods were evaluated in order to gain better understanding of groundwater conditions and flow in the South Platte Alluvium. Each period builds on the previous period results.

This section provides the basis and general process used to develop the SPDSS Alluvial Groundwater Model. Information on the model development and the study area water balance are discussed at a more conceptual level in this section and then described in greater detail in Section 3. An initial list of potential modeling applications for the calibrated model is presented in Section 2.1. Existing groundwater models that have been developed within the model study area are described briefly in Section 2.2. The conceptual model for inflow and outflow within the alluvial aquifer system is described in Section 2.3. The data centered modeling approach, developed under the CDSS and enhanced under Task 50 of SPDSS, is discussed in Section 2.4. Section 2 concludes with a presentation of the file naming conventions used for data, simulation, and output files associated with the modeling process.

2.1 Potential Groundwater Modeling Applications

The SPDSS Alluvial Groundwater Model is being developed to:

- Help improve our understanding and management of regional groundwater conditions in the alluvial aquifer of the South Platte River and its key tributaries
- Improve our planning, management, and evaluation of water resource needs and activities
- Identify, prioritize, and begin to fill data gaps

It is anticipated the SPDSS Alluvial Groundwater Model may be used to evaluate regional water resources planning and management activities by the CWCB, DWR, and other stakeholders. These activities could include but are not limited to the following:

- Analyze the effects of pumping, recharge, water transfers, and/or changes in irrigation efficiency on the location, magnitude, and timing of stream depletions (at a more regional not well-specific level)
- Assess the impact of changes in discharge from the bedrock aquifers to the alluvial aquifers
- Identify areas where additional data and analysis is needed to improve our understanding of short- and long-term groundwater trends
- Provide a basis for development of more detailed sub-regional groundwater models

In addition, the calibrated model can provide a starting point to characterize projected groundwater conditions via investigations under varying modeling assumptions and/or resource management scenarios including:

- Evaluating regional trends in groundwater levels based under hypothetical use and recharge assumptions
- Evaluating regional gains and losses under different hypothetical management scenarios
- Evaluating long-term sustainable use of the alluvial aquifers
- Quantifying impacts of climate change on groundwater levels and return flows

Finally, it is anticipated that the calibrated groundwater model and data collected as part of the SPDSS will be used by other entities as a basis for their own groundwater investigations, or to complete regional planning activities or to conduct finer scale analysis and site-specific investigations. Going forward as additional data is collected, this information can be incorporated into HydroBase and/or the SPDSS Alluvial Groundwater Model. This will allow for a continued improvement of the data centered process and enhanced decision-making.

2.2 Prior Groundwater Modeling

Over the past few decades a number of groundwater flow models have been developed for portions of the SPDSS study area. These models were reviewed to understand the methods and process utilized, and to develop the SPDSS in a manner that would be as complementary as possible to these previous modeling efforts. The results of the review showed a large diversity in modeling approaches and modeling boundaries. This result is not surprising given the large number of water interests operating in the basin, but it also means that there will be diversity in both approaches and results, especially when one goes to a smaller geographic scale.

The models identified included analytical models, which focus on stream depletions due to pumping; and numerical models, which employ MODFLOW or similar tools to examine a variety of water supply issues.

The Feasibility Study describes the principal analytical models, which include SDFView and DWR's Stream Depletion Model (Brown and Caldwell et al. 2001, Section 4.4.2). DWR's Stream Depletion Model is no longer available and has been replaced by the Colorado State University (CSU) Integrated Decision Support Group's Alluvial Water Accounting System (AWAS), which is available on their website at www.ids.colostate.edu/.

The Feasibility Study also describes two sets of numerical models. One of these is for the Denver Basin bedrock aquifers, developed by the State under Senate Bill 96-74 (SB 96-74) in 1996. The other is a series of models developed by the USGS in the 1980s for portions of the lower South Platte River downstream of Greeley. The reader is referred to the Feasibility Study for a description of these older models. The Feasibility Study is available via the CDSS website (ftp://dwrftp.state.co.us/cdss/ovw/fs/SPDSSFeasibility_20011001.pdf).

Other groundwater models of the region have been developed for the following areas or subregions: Adams County in the Commerce City area (HRS 2003), upper Cherry Creek (BBA 2006), the Cache la Poudre River (RMC 1990), Tamarack Ranch State Wildlife Area (Colorado Division of Wildlife [CDOW] 2003), Lost Creek (Arnold 2010 and HRS 1995), an updated Denver Basin bedrock model (Black and Veatch et al. 2003) and an updated analytical Stream Depletion Model (CSU 2006). In addition, the USGS, in coordination with the CWCB and DWR, has developed an updated model for the Denver Basin bedrock aquifers that includes an alluvial aquifer layer (USGS 2011). The USGS also has developed a model for the alluvial aquifer along the South Platte River near Brighton to examine wetlands (Arnold 2006). Each of these models was developed to address specific questions regarding changes in groundwater levels and the effect on streamflow due to well pumping. The conceptual model development, boundary condition assignments, and inputs for the numerical models listed above have been reviewed. The relevant aspects of these prior modeling efforts were considered and included in the SPDSS Alluvial Groundwater Model development.

2.3 Conceptual Model

A conceptual model of the alluvial groundwater study area is a prerequisite to development of a numerical model (Anderson and Woessner 1992). The conceptual model of the South Platte alluvial groundwater system included a narrative and graphical description of the aquifer configuration and of its significant inflows and outflows for both surface water and other hydraulically connected groundwater (SPDSS 2008b). The conceptual model was used to design the model grid and determine the best approach to simulate the aquifer system. The following section includes a summary of the conceptual model for the alluvial groundwater system of the South Platte River Basin, followed by descriptions and estimates where available of each of the inflows and outflows to the alluvial aquifer. The estimated inflows and outflows for the model are used to develop a preliminary model water budget as described in Section 4 of this report.

2.3.1 Conceptual Water Balance for the Model Domain

As discussed earlier in this report, the South Platte River Basin supports a significant amount of irrigated agriculture. Consequently, agricultural water use exerts a large influence on groundwater flow and conditions of the alluvial aquifers. Over a century of irrigation activity in the basin has resulted in an extensive network of diversion ditches, canals, and reservoirs. More recently, especially in the last 20 years, there has been extensive development of groundwater recharge projects that are utilized to augment out-of-priority groundwater withdrawals.

Water that is diverted and applied to farms experiences losses as a result of seepage that can contribute flow into the underlying alluvial aquifers, as well as to evaporation, nonbeneficial evapotranspiration (ET) (due in part to the presence of phreatophytes), and irrigation tail water returns. Flood irrigation is a common technique to apply diverted water to agricultural lands in the basin. This irrigation method results in about 60 percent efficiency with the majority of the remaining water (40 percent) percolating below the root zone of the crops and recharging the groundwater system. Sprinkler irrigation is also common in the basin and this method of irrigation also affects groundwater; however, since sprinkler systems are about 80 percent efficient, their impact on return flows is less that flood irrigation. Groundwater typically flows downgradient toward streams, and, if aquifer water levels are high enough, discharges to the streams as return flow.

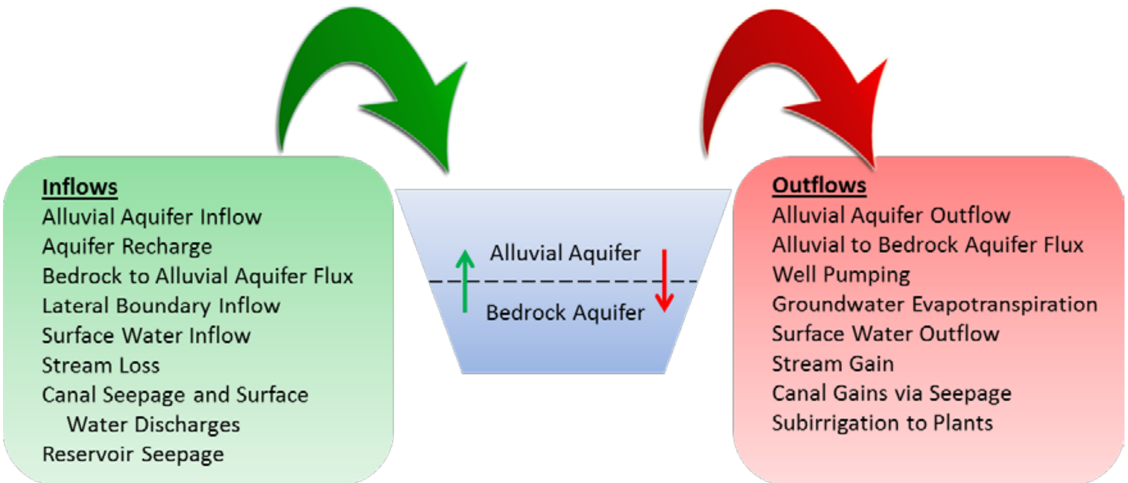
Prior to widespread irrigation most of the streams and rivers in the basin flowed only during the spring and early summer months when snowmelt runoff was at its peak. Irrigation and water development activities in the basin has, over time, increased available water supplies via storage, increased surface water return flows, and increased the volume and/or levels of groundwater. These factors have combined to create a more stable and positive water balance and most of the larger rivers in the basin are now perennial. Hurr (1975) reported that surface water flow increased during the late 1800s and early 1900s as a result of widespread irrigation in the basin and increased return flows. However, water levels appear to have stabilized since at least the 1950s, as shown by the consistency of hydrographs from year to year. For more information on groundwater trends in the South Platte Alluvium please see the Task 44.3 TM (SPDSS 2006f), which is included in Appendix A to this report.

Wells used for irrigation withdraw water from the alluvial aquifer and, depending on the rate of withdrawal and rate of recharge, can lower the water table surface locally. The wells can also reduce streamflow, either by intercepting some of the groundwater that would have discharged to the river, or by inducing infiltration from the streams to the aquifer. The amount, timing, and location of stream depletion due to pumping depends on the proximity of a well to a stream, the pumping rate and duration, the direction and rate of groundwater flow, the amount of groundwater recharge, and hydraulic properties of the aquifer.

The South Platte Basin is a highly dynamic hydrologic system, with return flows dependent on the location, timing, and amount of irrigation water applied, the effects of irrigation wells, the distance to a receiving stream, the hydraulic properties of the underlying aquifer, stream stage, and streambed properties. The Prior Appropriation System of water rights administration makes this an even more dynamic system, because the locations of stream diversions in priority can change dramatically on a daily basis depending on the water needs and rights of the senior appropriators. While the system is very complex, the overall alluvial aquifer water balance can be represented by the following simplified equation:

Conceptual Block Diagram of Hydrologic System

The individual components that contribute to outflows and inflows were delineated and simulated in the SPDSS Alluvial Groundwater Model. The figure below summarized the outflow and inflow components to the alluvial groundwater model and they are described in more detail in the following sections and in the appendices.



2.3.2 Inflows to the Alluvial Aquifer Model Domain

The following describes each of the key inflows into the modeled portion of the South Platte Basin.

Alluvial Aquifer Inflow

Alluvial groundwater inflow enters the model domain at the upgradient extent of the major tributaries summarized in Section 3 as well as the mainstem of the South Platte River. The quantity of groundwater entering the model domain was estimated based on Darcy's Law, using estimates of the cross-sectional area, hydraulic conductivity, and groundwater gradient at the upstream extent of each of the significant tributary valleys. The estimates used available aquifer properties and water level data gathered under Tasks 42-44 during the early part of the project and are summarized in Appendix D. The data required to estimate alluvial groundwater inflow at the model boundary was limited to the South Platte mainstem and the larger tributaries. These tributaries include Plum Creek, Bear Creek, Cherry Creek, Clear Creek, Big Dry Creek, South Boulder Creek, Boulder Creek, St. Vrain River, Little Thompson River, Big Thompson River, and Cache la Poudre River, which are shown in Figure D-1 in Appendix D.

Aquifer Recharge

Recharge is defined as the flux of water that percolates below the evapotranspiration zone to the groundwater system. Recharge to the alluvial aquifer consists of both irrigation-based contributions, which were described earlier in this report, and precipitation.

Irrigation-based contributions to aquifer recharge are determined via the consumptive use analysis using StateCU consumptive use model and then translated into recharge for the groundwater model using StatePP. StatePP is a program developed for the CDSS used to prepare MODFLOW input files for recharge, wells, ET, and drain packages (Rio Grande Decision Support System [RGDSS] 2003). The irrigation-based recharge is the portion of water applied to irrigated parcels of land that makes it to the aquifer after runoff and ET are taken into account.

Precipitation-based recharge is the deep percolation that occurs due to precipitation on irrigated and nonirrigated lands, after runoff and ET are accounted for. Estimates of precipitation-based recharge were documented in Appendix B (see Tables B-2 and B-3) and incorporated into the model. The consumptive use studies completed for the SPDSS determined that approximately 3 percent (originally estimated to be 1 percent and revised based on literature and scientific judgment) of precipitation that falls on native vegetation percolates below the root zone and becomes recharge to the alluvial aquifer system on lands. Higher percentages of precipitation infiltrate on irrigated lands during the irrigation season.

Precipitation data was obtained for monitoring stations within the SPDSS study area, and interpolated to a regular grid over the area of interest. The average annual recharge rate for the native vegetation areas is 0.43 inches per year based upon available climate station data in the region. The model area where recharge is applied consists of approximately 2,536 square miles. The recharge varies spatially, with higher recharge rates in the western portion of the study area where rainfall is higher.

Bedrock and Alluvial Aquifer Interactions

Groundwater flow interactions, also referred to as flux, exist between the alluvial aquifer and the bedrock aquifers of the Denver Basin, which lies beneath the alluvial deposits in the western portion of the model domain. Estimates of the interchange of groundwater between the bedrock and alluvial aquifers were obtained from results from the transient Denver Basin Model developed by the USGS (2011). The USGS developed a utility called GRID2GRIDFLOW to translate groundwater flow between the bedrock and alluvial aquifers simulated by the Denver Basin Model for use as input to the SPDSS Alluvial Groundwater Model (Banta et al. 2008). The Denver Basin Model predicts a substantial flow from bedrock to the alluvium in areas outside of the SPDSS alluvial aquifer model area (see Figure D-6). The input values for the model domain from these bedrock groundwater contributions to the alluvial aquifer are incorporated either in the surface water inflow or the alluvial aquifer inflow components at the upgradient reaches of tributary valleys.

Lateral Boundary Inflows

Subsurface inflows along the edges of the alluvial valley system were accounted for in the model as lateral boundary inflows. These flows originate largely from deep percolation of precipitation, irrigation water on fields, or as seepage from canals and reservoirs located on upland areas that lie outside of the alluvial aquifer model domain. This percolating water migrates along the alluvial – bedrock interface, or in the upper fractured and weathered bedrock material, and flows downgradient and into the alluvial aquifer at widespread locations along its boundaries. The method used to develop lateral boundary inflows in the model is discussed in additional detail in Appendix D.

Surface Water Inflow

Surface water inflow to the model area is the largest component of the model water budget. Surface water is the primary source of water for diversions for irrigation, a portion of which returns to the aquifer as recharge.

Inflow was determined for the principal surface water sources based on stream gaging records for the following locations:

1. South Platte mainstem at the Chatfield Reservoir outlet
2. Plum Creek
3. Cherry Creek
4. Bear Creek
5. Clear Creek
6. Big Dry Creek
7. Boulder Creek
8. Coal Creek
9. Saint Vrain Creek
10. Little Thompson River
11. Big Thompson River
12. Cache la Poudre River

The inflow from these streams was based on the nearest gaging station, correcting where necessary for diversions between the gage and the inflow point to the model.

For ungaged surface water inflows, estimates of these values were developed based on monthly precipitation and runoff factors. This runoff is calculated on a cell by cell basis, and routed to the nearest stream that was included in the model. This ungaged runoff includes a 3-mile buffer area outside of the active model domain for drainages that do not have their inflows already accounted for by surface water inflow or alluvial underflow.

Stream Loss

Stream gains and losses between the surface water and groundwater system occur, depending on hydraulic properties of the alluvial aquifer and streambed deposits, and the relative difference between stream stage and groundwater levels at the corresponding location. This interchange between the surface water system and the alluvial aquifer is calculated by the model. Stream loss from the surface water system provides inflow to the alluvial aquifer.

Canal Seepage and Surface Water Discharges

Surface water is diverted for agricultural, municipal, and industrial use. A portion of the diverted water recharges the alluvial aquifer through several mechanisms, including deep percolation in irrigated areas, and seepage from canals that overlie the alluvial aquifer. Canal seepage is calculated by StateCU based upon the amount of water conveyed by a ditch system, StateCU calculates the portion of the canal flows lost to canal seepage to the alluvial aquifer using specified values that ranged from 10-50 percent, averaging of 23 percent (SPDSS 2008d). The canal seepage calculated by StateCU is used in StatePP to prepare MODFLOW inputs via the recharge package to be included in the model. The portion of surface water diverted for municipal and industrial (M&I) purposes that is not consumptively used returns to the stream after treatment and via lawn irrigation return flows. Key surface water discharges and surface water inflows have been included in the model to account for these return flows. These return flows are incorporated into the Streamflow-Routing (SFR2) package using model enhancement tools; this method is described in more detail in Appendices F and G.

Reservoir Seepage

Surface reservoirs lose water through evaporation and seepage. The portion of water percolating from reservoirs as seepage becomes recharge water to the alluvial aquifer system. Detailed water balance of reservoirs in the South Platte Basin has not been performed so estimates of the amount of reservoir seepage were calculated based on surface area and soil types. The groundwater model incorporates seepage losses from key reservoirs in the South Platte Basin; this method is described in more detail in Appendix B.

2.3.3 Outflows from the Alluvial Aquifer Model Domain

The following describes each of the key outflows from the model.

Alluvial Aquifer Outflow

Groundwater outflow occurs where the South Platte River alluvial aquifer flows beyond the downgradient model extent near the Colorado-Nebraska state line. This outflow is simulated in the model as a general head boundary.

Lateral Boundary Outflow

It is estimated that there is no groundwater outflow along the margins of the alluvial aquifer. Data available during model development did not indicate lateral boundary outflow although some lateral boundary outflow may exist at specific locations in the study area.

Alluvial and Bedrock Aquifer Interactions

The interaction between the alluvial and bedrock aquifers of the Denver Basin was estimated by the USGS in their model of the Denver Basin (USGS 2011). These flows are incorporated into the alluvial groundwater model. Locally, there are both inflows and outflows between the alluvium and bedrock aquifers, but overall there is a net discharge from the bedrock aquifers to the alluvium.

Well Pumping

As previously discussed, groundwater in the SPDSS study area has been extensively developed, with thousands of alluvial aquifer water wells producing water for agricultural, M&I, and residential purposes. The vast majority of alluvial groundwater use is for agricultural purposes and is calculated based on crop consumptive use requirements on a monthly basis and used in the model. M&I pumping is minor compared to the amount of surface water diversion and agricultural pumping, but an M&I well may have a significant effect on the groundwater system in its immediate vicinity. Unlike agricultural use of water, M&I pumping occurs throughout the year but also has a seasonal variation with higher use during the summer months. Industrial pumping was treated as a constant rate.

Groundwater Evapotranspiration

This outflow component describes the flow of groundwater out of the alluvial aquifer due to plant transpiration and direct evaporation of shallow groundwater. ET will occur when the water table rises to within the root zone of phreatophyte plants and when groundwater is exposed to the surface. There are also subirrigated crop areas that evapotranspire groundwater. (See below for more information on subirrigation in the water balance.)

Surface Water Outflow

Surface water outflow from the model domain occurs in the South Platte River as it flows across the state line into Nebraska at the model boundary. Stream outflow at the downstream portion of the model domain is used to assist in model calibration, so stream outflow is an indirect but important component of the aquifer water balance. This outflow quantity is calculated in the model and compared to the gage data during the calibration process.

Stream Gain

Gain to the surface streams represents an outflow of water from the alluvial aquifer system. Based on maps of the groundwater surface from Hurr et al. (1972a-f) and from the SPDSS Task 46 Stream Gain/Loss Estimates TM (SPDSS 2008c), stream gains occur along most of the South Platte River within the study area (see Appendix E for more detail).

Canal Gains via Seepage

It is likely that some shallow groundwater is intercepted by canals within the study area. Some of this water returns back to the alluvial aquifer system through canal seepage. Both the amount of groundwater outflow to canals and portion of canal seepage associated with the groundwater outflow to canals back into the alluvial aquifer are unknown. Although canal losses are represented in the model, canals are not explicitly simulated in the streamflow-routing portion of the groundwater model that allows stream gains to occur; consequently, the model does not include any outflow from the alluvial aquifer into canals.

Subirrigation

In areas where the groundwater table is high, there is a potential for part of the consumptive use demand to be supplied by direct ET from groundwater (SPDSS 2010). StateCU identifies the total consumptive use demand for the areas that have been identified as having the potential for subirrigation. The total consumptive use demand is reduced, taking into account the amount of applied water, and the remaining quantity of water needed to meet this demand is identified. StatePP uses this residual demand to modify ET parameters such that the full demand will be met if groundwater is at the land surface. The quantity of ET is reduced as the depth to water increases. Subirrigation is calculated in the model based on the simulated water table for areas identified as having the potential for subirrigation.

2.3.4 Summary of Inflow and Outflow Sources

In summary for the SPDSS Alluvial Groundwater Model, the following inflows and outflows are directly or indirectly provided as input into the model.

Inflow Sources:

- Alluvial aquifer inflow that enters the alluvial aquifer at the upgradient model extent of key tributaries as well as the mainstem of the South Platte River
- Lateral boundary inflow from upland areas located outside of the tributary alluvial channels
- Bedrock aquifer inflow from the Denver Basin aquifers, which lie beneath the alluvial deposits
- Recharge inflow from precipitation, irrigation, reservoir seepage, and canal seepage
- Stream inflows and surface water discharges
- Stream losses

Outflow Sources:

- Alluvial aquifer outflow where the South Platte River alluvial aquifer flows beyond the downgradient model extent near the Colorado-Nebraska state line.
- Alluvial aquifer outflow into the Denver Basin aquifers, which lie beneath the alluvial deposits
- Surface water outflow at the downgradient extent near the Colorado-Nebraska state line
- Stream gains from groundwater outflows to streams
- Well pumping from agricultural and M&I wells
- Groundwater ET from subirrigated and phreatophyte plants

Additional details on each of the inflows and outflows listed above are provided in Section 3. In addition, a detailed water balance for each modeled time step is provided in Appendix H.

2.4 Data Centered Groundwater Modeling Approach

The CDSS utilizes a data centered approach to groundwater modeling. A data centered approach employs processes and tools that provide a dynamic linkage between data sources, such as HydroBase and State geographic information system (GIS) coverages, and numerical models and analytical tools. This approach facilitates updating of numerical models when changes to underlying datasets occur, when model simulation periods change, or if additional processes need to be incorporated. This data centered approach has been refined and enhanced for the SPDSS modeling efforts. Under Task 50 of the SPDSS, the existing CDSS data centered modeling process was evaluated and refined to best accommodate the SPDSS groundwater modeling needs. This refinement included the development of databases for measured data and engineering control data, creation of an ArcGIS geodatabase for groundwater spatial data, development of customized ArcGIS tools and other software programs to facilitate the preparation of modeling packages, and the modification of existing modeling related data management interface (DMI) tools.

The SPDSS Alluvial Groundwater Model was developed using a double precision version of MODFLOW-2000, Version 1.18 (Harbaugh et al. 2000) and Groundwater Modeling Software (GMS), version 6.0 (BYU 2005). GMS was used to assist in developing some of the model input packages and to facilitate the data centered modeling process, but it is not required to conduct the model simulations. The SPDSS Alluvial Groundwater Model requires a specifically compiled version of MODFLOW-2000 for the model to run correctly. This version of MODFLOW-2000 is based on version 1.18 but includes modifications to improve model function during times when dewatering occurs (Doherty 2001). This modification utilizes an algorithm that prevents drying of cells by maintaining a minimal transmissivity and saturated thickness (3 feet) during times when the water level may go below the base of the cell during iterations. This prevents oscillations and numerical instability that occur as stresses such as recharge and pumping fluctuate significantly during the transient model simulation. GMS and its graphical user interface were used to create specific MODFLOW input files such as the discretization file and to visualize head observations and the potentiometric surface, the ground surface and base of alluvium, and the model active area array. GMS is a valuable visualization tool but is not required to run the model or to evaluate model results.

2.5 File and Directory Naming Conventions

The applications and tools in the groundwater modeling process are directory independent and no specific directory structure is necessary. See Appendix I for details on naming conventions.

2.6 Tool and Database Development

During the early parts of the project and under Task 50 of the SPDSS, the existing CDSS data centered modeling process was evaluated and refined to best accommodate the SPDSS groundwater modeling needs. Refinements included development of the following:

- Significant additions to groundwater related data, including water level and aquifer properties data.
    - Over 29,000 groundwater wells were identified for inclusion in HydroBase.
    - Water levels were compiled extending back to the 1950s; 108,843 alluvial groundwater level measurements were taken from 6,754 wells.

  - Information from 1,241 aquifer tests on aquifer properties (hydraulic conductivity and specific capacity) was compiled.
  - Surface elevations were surveyed at all new wells installed by the program, and at numerous existing wells.
  - Alluvial bedrock elevations were obtained at over 1,500 locations.
- An ArcGIS geodatabase for spatial groundwater data was developed that was not included in HydroBase.
- Custom ArcGIS tools were developed to facilitate the development of modeling packages.
- Custom applications were developed to facilitate the development of modeling packages.
- Modifications were made to existing modeling related data preprocessing tools.

As noted earlier, numerous TMs were also developed to document the model development process and to complete additional analysis required to construct the SPDSS Alluvial Groundwater Model. Please see **Table 1-1** at the end of this report, which summarizes this information and provides the reader with an outline of where to obtain additional information utilized to develop the model.

This page intentionally left blank.

Section 3

Model Configuration and Inputs

The previous section of this report conceptually summarizes the major inflows and outflows for the SPDSS Alluvial Groundwater Model. This section describes the model configuration and includes more detailed information on the model inflows and outflows as inputs to the model. The model grid and geometry are described in Sections 3.1 through 3.3. The initial aquifer properties assigned to the model cells are described in Sections 3.4 and 3.5. The initial water levels and boundary conditions are discussed in Sections 3.6 and 3.7. Aquifer stresses including inflows and outflows are described in Sections 3.8 through 3.12. Model output control and solver parameters are presented in Sections 3.13 and 3.14, respectively.

3.1 Model Domain and Grid

The SPDSS Alluvial Groundwater Model includes the alluvial aquifer system within the South Platte River Basin located east of the Front Range of the Rocky Mountains and extending downstream to the Colorado-Nebraska state line (**Figure ES-1**). The alluvial aquifers of the South Platte mainstem and key tributaries are included (see Section 1.2 for a list of the tributaries). The model covers an alluvial area of approximately 2,500 square miles.

The alluvial groundwater model is constructed with a uniform 1,000-foot by 1,000-foot grid cell size. This cell size was selected to provide a balance between characterizing the complexity of the alluvial system and minimizing model processing due to large file sizes. The model grid contains 655 rows and 848 columns and is oriented on a north-south alignment.

The northeast trend of the alluvial aquifer along the mainstem of the South Platte River combined with the orientation and generally narrow extents of tributary alluvial aquifers result in a complex configuration of saturated alluvial materials. Upland areas exist between the saturated alluviums of the tributaries. The upland areas are not simulated in the active domain of the SPDSS groundwater model; however, they are included when appropriate in the contribution of lateral boundary inflows and ungaged surface water inflows to the active model area. In many cases, model cells were split between saturated alluvial areas and areas outside the alluvium. The model cells to be included in the active portion of the model domain were determined using a combination of the aquifer saturated thickness, width of saturated alluvium, consistency with the USGS Denver Basin groundwater model (USGS 2011), and cell interconnection.

The saturated thickness map and associated data [see Appendix A – Task 42.3 TM (SPDSS 2006b) for additional information] were used as the basis to identify saturated alluvial materials and define the active model domain. First, the saturated thickness grid was converted to a polygon shapefile and all areas with greater than 10 feet of saturated thickness were selected to represent the active model domain. The active model domain includes all areas with a high density of wells with decreed yields greater than 50 gpm (DWR 2006).

In addition to the saturated thickness criterion, the model domain was truncated in any tributaries of the alluvial aquifer system where the saturated thickness of 10 feet or greater extended less than

2,000 feet across the width of the alluvial channel. This criterion was selected so that the active model domain would be at least two model cells wide, to allow flow to occur along model faces.

To facilitate communication between the SPDSS alluvial and USGS Denver Basin bedrock models, the SPDSS active model domain was compared to the USGS model's alluvial layer active domain. The USGS model has an active domain that extends farther up some of the western tributaries of the South Platte River, on the South Platte River near Chatfield Reservoir, Plum Creek, Cherry Creek, Kiowa and Bijou Creeks, and near Jackson Reservoir. To achieve greater consistency the SPDSS model domain was expanded to include the areas covered by the USGS model. However, the USGS model grid is much larger (square mile) than the SPDSS model so there are minor differences in simulated area between these models due to differences in model gridding. A utility program called GRID2GRIDFLOW was developed to translate results from the USGS Denver Basin Model into inputs for the SPDSS Alluvial Groundwater Model (Banta et al. 2008).

The SPDSS active model domain was also expanded to include the mainstem alluvial aquifer several miles into Nebraska, to just past the Western (Canal) Irrigation District. The model domain in Nebraska was defined based on the extent of saturated thickness reported by Bjorklund and Brown (1957). This model extension into Nebraska was completed so the downgradient edge of the model domain would be oriented perpendicular to the predominant direction of groundwater flow, rather than being truncated at an oblique angle at the state line due to the orientation of the alluvial aquifer as it crosses into Nebraska.

The model domain was then compared to the streams within the project area. In some cases the streams meandered outside of the model domain and then returned to the domain. In these cases, the domain was expanded by a few model cells so the streams are primarily contained within the domain. Shapefiles of the model grid and alluvial saturated thickness were imported into GMS and used to activate the grid cells. After activating the model domain it was inspected to verify that all active cells had at least one side connected with other active cells. If an active cell was only connected at the corners with another active cell, then the domain was modified to create connection between cells along a row or column. This was done because MODFLOW allows flow to occur only through model faces. **Figure 3-1** presents the active model domain.

3.2 Ground Surface Elevations

The ground surface is used in the SPDSS Alluvial Groundwater Model to define several model input parameters, to calculate outflow due to groundwater ET, and to establish a datum for model calibration. The USGS 30-meter National Elevation Dataset (NED) was used as the source of information to define ground surface. The 30-meter NED data were interpolated onto the 1,000-foot model grid and then used to produce an average elevation for each grid cell. The grid-averaged elevation data were then imported to GMS and applied as the model top layer. The model ground surface is also the alluvial aquifer top and is presented in **Figure 3-2**.

3.3 Model Layering and Stratigraphy

The South Platte alluvial aquifer model is represented using a single layer. The aquifer is primarily sand and gravel with interbedded and discontinuous layers of silt and clay. Drilling logs indicate that deposits near the base of the alluvium are the coarsest and become finer grained towards the surface. In addition, the aquifer grades from coarser material in the west to finer material in the east, consistent with a higher energy environment near the mountain front and a lower energy environment on the plains. Despite this vertical and lateral variation, the aquifer materials are considered to be similar enough at the scale of the model to be represented with a single layer.

The top of the model is represented by the ground surface, generated from the USGS 30-meter NED discussed in Section 3.2.

The bottom of the model layer represents the base of the alluvial aquifer. The configuration of this bottom surface was developed primarily from the alluvial aquifer configuration completed in Task 42.3 (SPDSS 2006b, see Appendix A), and expanded with data from Bjorklund and Brown (1957). In addition, the USGS provided data on the bottom elevations from the alluvial aquifer layer of the USGS Denver Basin model (USGS 2011). The data from the USGS model was used to refine or add to the existing base of alluvium data in the areas of Plum Creek, Upper Cherry Creek, Wolf Creek, Jackson Reservoir, and along the western edge of the confluence of the Lost Creek drainage with the South Platte River. Data from Robson (1996, 2000a-d) were used to extend the base of alluvium surface upstream in Boulder and Coal Creeks. Finally, data from Bjorklund and Brown (1957) were digitized to create an electronic dataset for the base of alluvium into Nebraska. The data sources were merged and used to create the model bottom. **Figure 3-3** shows the elevations for the base of the alluvium.

3.4 Hydraulic Conductivity

Hydraulic conductivity (K) is the main physical parameter that governs the rate of groundwater flow. Aquifer K values were initially estimated from the dataset collected, analyzed, and presented in the Task 43.3 South Platte Alluvium Region Aquifer Property TM (SPDSS 2006d, see Appendix A). A detailed account of the development of K model inputs can be found in that document. A brief discussion of the initial K inputs is presented below.

Data used to develop the K inputs was compiled into a database of aquifer property measurements from 15 historical reports and numerous unpublished sources of data, totaling 1,241 aquifer property measurements. Many of these data were presented for the first time in a publicly accessible report and electronic database (HydroBase) in the Task 43.3 South Platte Alluvium Region Aquifer Property TM (SPDSS 2006d).

Pumping test based K values are regarded as the most representative of bulk aquifer properties and were used as a baseline for comparison with other testing types. A total of 167 pumping test based K values were collected and used in further analysis.

Specific capacity data are readily available from driller's logs and well permit information. These data were converted to transmissivity (T) using linear regression techniques on pumping tests where both T and specific capacity data were available. Transmissivity was divided by aquifer saturated thickness to obtain a value for K. A total of 566 specific capacity tests were used in further analysis.

Specific capacity data is generally considered less reliable than aquifer pumping test data, since this characteristic is impacted by factors such as well losses. Therefore, additional analysis was performed to substantiate the usefulness of the specific capacity dataset. The analysis performed under Task 43.3 (SPDSS 2006d) determined that specific capacity tests from 360 high capacity wells (flow >50 gpm) have K values similar to those derived from aquifer pumping tests. The specific capacity based K values derived from low capacity wells were determined to not be representative of bulk aquifer characteristics and were excluded from the data set used to contour K. A list of these tests can be found in Appendix A of the Task 43.3 TM (SPDSS 2006d).

Laboratory and previously contoured data were also collected under the alluvial aquifer properties Task 43.3, but were not used in generating the K contours used for model inputs. Laboratory data represents the K value at a point location and is not a good indicator of bulk aquifer conditions. Underlying methods and data used to generate contours, such as in the Hurr and Schneider (1972a-f) reports, are unknown and were therefore not used to generate K contours. Further discussion of the exclusion of laboratory data and a comparison of the Hurr and Schneider (1972) T contours with the SPDSS T contours can be found in Appendix A of the Task 43.3 TM (SPDSS 2006d).

Engineering control points were introduced to the data set in areas where little or no data exist and also along key alluvial boundaries. Engineering control points constrain the contouring process to reasonable values and reduce errors caused by the numerical algorithms involved in contouring. In the future, if new data becomes available, these engineering control points can be replaced with relevant data. A total of 320 engineering control points were added to the K data set prior to contouring. Values for the control points were determined by calculating the median value of K from available data for each specific basin or from averages presented in published reports. A summary of these values, counts, and locations is presented in Appendix A of the Task 43.3 TM (SPDSS 2006d).

The aquifer K data were contoured onto a regular grid with a 1,000-meter spacing using a kriging algorithm. The individual data points were smoothed as part of the contouring process to emphasize regional trends in K data. **Figure 3-7** is a K map of the entire model domain. The K values presented in this figure are used in the model as initial K values, which are refined during the calibration process.

Additional refinement of the hydraulic conductivity information was facilitated by discretizing the model area into zones. **Figure 3-8** shows the zonation that was defined for the analysis. Zones were incorporated to constrain interpolation of K values during the calibration process, because interpolation of K values in the mainstem valley into some tributary valleys was not considered appropriate (e.g., alluvium in the plains tributaries tends to be finer grained, leading to a lower K).

3.5 Storage Coefficient and Specific Yield

The storage properties are another key aquifer parameter. For confined and semi-confined aquifers, the volume of water released from storage under a unit decline in hydraulic head per unit area of aquifer is defined by the aquifer storage coefficient (S). For unconfined aquifers, the volumetric fraction of water that will drain by gravity from a unit volume of aquifer is defined by the specific yield (Sy). Since the model utilizes a single layer, only the specific yield is relevant, since the alluvium is treated as an unconfined aquifer. S and Sy data are less abundant than K data within the study area. A constant value of 0.17, the median of all Sy values collected, was used throughout the alluvial aquifer for the initial model input in the model simulations (see Appendices A and K for additional details).

3.6 Initial Aquifer Heads

Initial heads for simulations were developed using a transient approach, where conditions prior to the simulation period were run for multiple time steps to obtain a stable water table surface to assist in model convergence for the period of interest. This transient warm-up period included a 10-year period using 1950 conditions, followed by conditions from 1950 to the period of interest. This approach proved necessary to accommodate the dynamic nature of the aquifer system, particularly in the designated basins included in the model. This approach was incorporated during model calibration, since changes to model parameters are impacted by the history prior to the period of interest. **Figure 3-4** shows the initial heads.

3.7 Boundary Conditions

Boundary conditions are used to represent groundwater flow entering and leaving the model domain from various sources. The SPDSS boundary conditions include:

- Flow entering the domain as groundwater from alluvial tributaries and flow leaving the model at the downstream boundary
- Lateral flows from precipitation and irrigation activities located outside the active domain
- Groundwater flow to and from the underlying bedrock aquifers

The model utilizes these boundary conditions as described below and additional information can also be found in Appendix D. The boundary conditions were developed using a variety of data and inputs developed as part of the SPDSS project.

3.7.1 Alluvial Aquifer Flow

Groundwater enters the alluvial aquifer at the modeled upgradient extent of many of the tributaries as well as the mainstem of the South Platte River. Two categories of alluvial aquifer inflow were considered:

1. Alluvial valleys with perennial streams at the upstream model boundary.
2. Alluvial valleys without perennial streams at the upstream model boundary.

The estimates used available aquifer properties and water level data gathered under Tasks 42-44 (see Appendix A). The alluvial aquifer underflow into the model area was estimated at about 11,850 acre-feet per year (AFY) and is used directly as a model input.

Groundwater underflow into and out of the model domain through saturated alluvium was estimated using the Darcy equation:

Q=KIA

where:

Q = Groundwater underflow (ft^3/day)
K = Aquifer hydraulic conductivity (ft/day)
I = Water table gradient in the vicinity of the transect (ft/ft)
A = Cross-sectional area of the tributary aquifer (ft^2)

Data used in the groundwater flow calculations include the saturated thickness, aquifer hydraulic conductivity, and hydraulic gradients evaluated and reported in the Task 42.3, 43.3, and 44.3 Technical Memoranda (SPDSS 2006b-d, Appendix A). Cross-sectional area was calculated using the saturated thickness data across a transect of the alluvial valley. The transect was chosen as a line perpendicular to the direction of groundwater flow, extending across the alluvial aquifer and defining the location for which groundwater flow is calculated. Hydraulic conductivity data used for the underflow calculations were obtained from aquifer pumping tests located near the transects, if available, or estimated based on lithologic characteristics. The groundwater hydraulic gradients were measured from mapped water level data at the transect locations. This groundwater flow calculation method is recommended in groundwater underflow evaluations (Freeze and Cherry 1979; Fetter 2001) and has been used in local studies (Duke and Longenbaugh 1966).

At locations where stream systems enter the model domain, but data for water levels, hydraulic conductivity, and/or aquifer configuration were either very limited or unavailable, representative values for hydraulic conductivity from similar areas and a hydraulic gradient equal to the stream gradient were used to estimate groundwater fluxes for the model.

The boundary inflows are input in the model as specified flux values using the well package of MODFLOW. The flow values remained constant during all simulation periods. **Figure 3-5** presents the alluvial aquifer inflow locations which are located at the edge of the active model domain.

3.7.2 Lateral Boundary Flows

Lateral boundary flow represents the groundwater inflow along the active model boundary from recharge sources located outside of the active model domain. These inflows can be significant, as there are extensive irrigated upland areas outside of the alluvium, especially in the lower South Platte valley. The amounts of recharge in areas outside of the model were quantified using the same method as within the model, principally using StatePP. These components included recharge from precipitation and irrigation, infiltration of runoff, and canal and reservoir seepage. The recharge flows were then accumulated and lagged to assess when they would accumulate to the active model boundary. These flows varied over time. This inflow component was included within the MODFLOW well package. These inflows average 456,900 AFY during the calibration period. Details of this tool are documented in Appendix J, Data Centered Groundwater Modeling Enhancements.

3.7.3 Bedrock and Alluvial Aquifer Flux

The Denver Basin bedrock aquifers discharge to the overlying alluvial aquifer in some areas and are recharged by the alluvial aquifer in other areas, with a net discharge to the alluvial aquifer. Results from the USGS's model for the Denver Basin (USGS 2011), which includes both bedrock and alluvial aquifers, were used to quantify these bedrock aquifer fluxes to the SPDSS Alluvial Groundwater Model. The simulated bedrock-alluvial aquifer fluxes from the Denver Basin Model were interpolated onto the SPDSS Alluvial Groundwater Model grid using the USGS GRID2GRIDFLOW Modeling Utility (Banta et al. 2008). The simulated fluxes within the SPDSS model active domain were included using the MODFLOW well package. **Figure 3-6** shows the location of these wells used to represent the bedrock flux and whether the bedrock aquifers contribute to or receive flow from the alluvial aquifer system. The average annual bedrock groundwater flow into the alluvial aquifer during the calibration period is 12,473 AFY.

3.8 Well Pumping

Well pumping is the largest stress on the alluvial aquifer system and a key input to the SPDSS Alluvial Groundwater Model. In the South Platte Basin there are alluvial wells that supply water for agricultural use (irrigation), municipal use, commercial use, and for augmentation. The estimates of pumping rates for each of these well types were specified as an input to the model. The average annual pumping for these well types during the calibration period is:

- Agricultural wells: 498,00 AFY
- Augmentation and Recharge wells: 10,700 AFY
- M&I wells: 45,080 AFY

Agricultural wells are used within the SPDSS study area to provide irrigation water to a variety of crops. They are one of the key sources of groundwater outflow in the alluvial groundwater flow model. Indirect methods based on crop irrigation water requirements were used to estimate agricultural pumping by irrigation structure (i.e., ditch system), since no direct monitoring of well production was available (SPDSS 2010).

In order to locate agricultural well pumping locations, data is preprocessed (StatePP) using data from the State Data Graphic Interface (StateDGI) to allocate the pumping within a structure to individual wells, up to the decreed maximum permitted volume. StateDGI uses the GIS database to determine individual parcels within a structure that are served by wells; or in the case where specific records are not available, geographic proximity to the structure area is used to select wells that are pumped to meet the demand. The total groundwater demand for a structure is then allocated to wells based on the decreed yield (truncated to 2,000 gpm, if necessary) and the proportion of time the well is available. The total pumping for each model cell containing a well is summed and a properly formatted MODFLOW well package file is produced. More information on well pumping can be found in Appendix C.

Augmentation wells are wells that pump alluvial groundwater directly to surface water to replace out of priority groundwater depletions. These wells typically have long stream depletion factors. These wells are described in more detail in Appendix M. Recharge wells are wells that supply groundwater to recharge basins that retime groundwater flow back to surface water and are timed to replace out of priority depletions. These wells are described in more detail in Appendix M. This information is available in HydroBase and is translated to the MODFLOW well package format. The datasets used to develop these model inputs were obtained via queries of HydroBase and are described in Appendix M.

M&I pumping information used as input to the alluvial groundwater model is taken largely from results presented in the SPDSS Task 41.3 TM (SPDSS 2007). As reported in this TM, M&I users that pump alluvial groundwater in the study area were identified from a query of the HydroBase water rights database based on the 'use type' code and linking this to a GIS shapefile of Division 1 decreed wells. Only wells that pump more than 50 gpm or M&I entities that have a total permitted pumping rate of at least 1,000 gpm were considered. This resulted in 49 M&I entities, shown below, each of whom were contacted to obtain pumping data.

- Fort Morgan
- Public Service (also listed as Xcel Corp)
- Fort Lupton
- Brighton
- Aurora
- Monfort Finance Co Inc (now Five Rivers Ranch)
- Thornton
- Englewood
- South Adams County Water & Sanitation District Sterling
- Cherry Creek Gallery
- Golden Eagle Ranch (also listed as R. McAtee)
- Great Western Sugar Co
- Monfort Packing Co. (now Swift & Co.)
- Brush
- Greeley

- Piney Creek (ECCV Wellfield)
- Sterling E W
- Sterling Colorado Beef CO/ Cargill (now Trinidad Bean Co.)
- Julesburg
- LaSalle
- Klausner, James T.
- Packaging Corporation of America/ Republic Paperboard
- SUNCOR / Conoco Phillips Commerce City Refinery
- Carey, E K
- Parker Water & Sanitation District (also listed as Williamson Well)
- Wiggins
- Reddy Ice (Formerly City Ice)
- Grand Mesa Eggs, Inc (listed as Dekalb Wells)
- Cherry Creek Country Club (formerly Holland Marcus/Los Verdes Golf Club)
- Centennial Water & Sanitation District (also listed as Cent. Turf Club)
- Lauck/Knievel D.A. & M. A.
- Platteville
- Walker Well 4-2498-F/Beauprez R.L. JR. & T. M.
- Cushman Bros./Cushman S.E. & D.W.
- Log Lane Village
- Colorado State Land Board
- K&B Packing/High Plains A & M, LLC
- Kersey
- Ovid
- Morgan County Quality Water Co.
- Krueger Martin (Lower Platte & Beaver)
- Hibbs W. D.
- Mathews/Emerald Sod Farms Ltd/TESODCO
- Valencia Wells
- Lousberg G.W. 1-13083
- Sedgwick
- Hillrose
- N. Colorado Water Association
- Merino

3.9 Streamflows and Diversions

Streamflow and stream-aquifer interactions are simulated using the SFR2 (Niswonger and Prudic 2006). This package defines the characteristics of the streams and points for diversion simulated in the study area. Inputs to the SFR2 package include stream locations, stream cross-section geometry, stream inflows, and physical properties of the streambed, as well as locations and amounts for points of diversion. A description of this package and a relatively detailed discussion of the data sources and process used to develop the SFR2 package are provided in Appendix G. The custom tools created in Task 50, documented in Appendix J, were utilized to develop the SFR2 package file.

The following sections provide an overview of streamflow-routing package inputs (including the stream network, stream properties and segmentation, stream inflows, and diversions) and streamflow-routing package development.

3.9.1 Streamflow-Routing Package Inputs

Stream Network

The CDOW shapefile of the hydrography of Colorado was used to define the stream network. This shapefile was used because it contains stream order information, which was needed by the SFR2 package generator. Features from the shapefile were selected to ensure that at least one tributary covered each drainage area within the modeled domain. The stream features were truncated at the extent of the model domain. Information on diversion locations and amounts within the South Platte study area were developed from other studies and are incorporated into the model.

The stream network was preprocessed using the tools developed under Task 50 so that the network could be split into segments with the appropriate properties discussed in the following paragraphs. The modeled stream network is depicted in **Figure 3-9**.

Stream Properties and Segmentation

To characterize stream segments, information was developed for stream depth, streambed width, streambed thickness, roughness coefficient, vertical hydraulic conductivity, streambed elevation, and for determining stream segmentation points. This section describes the development of these stream segment properties. The Task 50 tools used to generate the SFR2 package require the stream segment properties to be specified at the most upstream end of every stream, at locations where there is a non-linear change in the property, at the confluence of streams, and at the downstream end of the stream.

Stream Depth Calculation Method

The SFR2 package allows multiple methods for calculating the stream depth. The stream depth was estimated dynamically within the model based on the flow, gradient, and width using Manning's equation. The method can vary from one segment to the next. In the model, a depth-discharge relationship method was used in the SFR2 package for all segments. This method calculates the depth of flow for a given stream discharge for a constant width channel using Manning's equation. Model cross-sections for the South Platte River and 12 tributary locations were developed based on cross-sections surveyed in the field during SPDSS Task 34 Streambed Conductance Testing (SPDSS 2006g). Locations of these cross-sections are shown on **Figure 3-10**. A depth-discharge relationship was developed for each of the Task 34 cross-sections and included the SFR2 package. **Figure 3-11** represents an example Task 34 streambed cross-section on the South Platte River and **Figure 3-12** illustrates an example cross-section for a tributary. For locations where no stream geometry data were collected for Task 34, a generalized cross-section was used, as shown in **Figure 3-13**. The generalized depth-discharge relationship was developed using representative data from tributaries where Task 34 cross-sections exist—Beebe Draw, Box Elder Creek, and Lonetree Creek. Appendix G identifies whether a Task 34 location or the generalized cross-section was used for each modeled stream (SPDSS 2006g).

Streambed Width

A constant width based on stream cross-sections was developed for the stream segments. In areas where no data were available, a suitable width was estimated based on the nature of the stream.

Streambed Thickness

During Task 34 field activities, sediments were collected up to 3 feet below the streambed, the maximum penetration of the sediment coring device, at several locations along the South Platte River and contributing tributaries. The similarity of sediments throughout the entire cored interval at all sites indicated that no distinctive streambed is present to a depth of 3 feet below the top of the streambed at the locations evaluated. Due to the lack of more definitive information and the nature of the usage of this parameter (see Section 4.3.3), an assumed constant streambed thickness of 3 feet was used for the mainstem and tributaries in the SFR2 input.

Roughness Coefficient

Manning's 'n' roughness coefficients, model inputs needed by SFR2 to calculate stream stage, were estimated using various sources such as Prudic (1989), Chow (1959), Gingery (1979, 1980), Engineering Professionals, Inc. (1987), Soil Conservation Service (1982), and various surface water hydraulic models of South Platte tributaries provided by the Urban Drainage and Flood Control District (UDFCD 2001; URS 2003). Average n values were estimated for three categories of streams in the model:

- Mainstem South Platte River
- Mountain tributaries
- Other tributaries

Table 3-1 lists the values of Manning's roughness coefficients used. Appendix G provides more detail on this input parameter.

Table 3-1. Summary of Manning's Roughness Coefficient Values

Location	Manning's n Value	Streambed k' Value (ft/day)
Mainstem	0.035	5
Mountain tributary	0.040	10
Other tributary	0.038	.5

Vertical Hydraulic Conductivity

The model requires a vertical hydraulic conductivity, from which a streambed conductance term is derived in the model. This parameter is highly scale dependent, since the proportion of a finite difference cell that is occupied by the stream is relatively small (Mehl and Hill 2010). Initial estimates of vertical hydraulic conductivity used results from the Task 34 Streambed Conductance Testing TM (SPDSS 2006g) and were applied to tributaries and mainstem streams. These field based values resulted in instabilities in the model due to the scale dependence issues and lower values were required for stable model solutions. As shown in Table 3-1, separate values were applied to stream segments in the mainstem of the South Platte, to tributaries draining the foothills on the western side of the model domain, and to other tributaries whose headwaters overlie the Denver Basin or other locations. The k' values were revised as part of the calibration process, which is described in more detail in Section 4.3.3.2.

Streambed Elevation

Streambed elevations were obtained from the USGS 30-meter NED and SPDSS Task 34 survey results (SPDSS 2006g). Elevation values were specified for the SFR2 package input at stream confluences and at Task 34 testing locations and other locations with elevation information. The SFR2 package requires stream properties to either vary linearly or be constant for each segment. Therefore, elevation profiles along the stream network were generated and reviewed to identify locations where control points were required for the stream channel to maintain a simulated linear slope within each segment. The points identified are referred to as segmentation points. Sixty-five elevation segmentation points were identified and added to the SFR2 input. **Figure 3-14** shows an example stream elevation profile of the Spring Creek in the model.

Segmentation Points

Once the above information was compiled the streams were discretized into segments, each of which consists of a number of individual model cells or reaches. Within each segment, all stream properties remain the same. In addition to changes in stream properties, the following were used also to define segments: streamflow gaging stations, diversion locations, and confluence locations. The seven main gage locations on the South Platte River (Henderson, Kersey, Weldona, Fort Morgan, Balzac, Atwood, and Julesburg) were added as segmentation points in the SFR2 package. A total of 774 segments were used to define the surface water system in the model.

Reaches

After the stream network was established and the physical properties of the streams were used to segment the streams, stream segments were intersected with the model grid to split the segments into multiple reaches (individual cells), accomplished in an automated process using tools developed in Task 50. Each reach, as defined in MODFLOW, represents the presence of a stream within a model cell. Each reach was numbered in the downstream direction and its length within a model cell was calculated. A total of 10,207 cells are included in the stream network.

Stream Inflows

Historical streamflows were determined on an average monthly basis for each stream that enters the model boundary at the locations shown in **Figure 3-15**. Streamflow data were gathered from HydroBase from 1950 to 2006. The CDSS time series data processor, TSTool, was used to fill gaps in the streamflow time series for locations with isolated missing records and then an average monthly value was computed for all streams. In cases where the gaging station was in the model and downstream of the model boundary, drainage areas above and below the gage were used to estimate the amount of stream inflow at the model boundary. Streamflow estimates were made for streams with no recorded data by using published reports on the stream basins, data from nearby gaging stations, and engineering judgment.

Many of the streams originate near the model boundary, and for those streams, the streamflow at the model boundary was estimated to be zero. The relative average annual streamflow for each modeled stream is shown in Figure 3-15. Additional detail on the development of stream inflows/inputs can be found in Appendix F.

Ungaged Surface Water Inflows

In addition to specifying the stream inflows at the model boundary there was a need to account for ungaged surface water inflows that occur within the model. For ungaged surface water inflows, estimates of these values were developed based on monthly precipitation and runoff factors. This runoff is calculated on a cell by cell basis, and routed to the nearest stream that was included in the model. This ungaged runoff includes a 3-mile buffer area outside of the active model domain for drainages that do not have their inflows already accounted for by surface water inflow or alluvial aquifer inflow. The average ungaged surface water inflow during the calibration period is 121,600 AFY as determined using precipitation runoff for each land use and soil type.

Diversions

Historical surface water diversions for key diversion structures were included in the model to better represent streamflows on the South Platte and associated tributaries. The key diversion structures in the model were identified in the SPDSS Task 3 Key Diversion Structures TM (SPDSS 2007c). These diversions account for approximately 85 percent of the net absolute decreed surface water rights in Water Division 1. Due to the large amounts of water leaving various stream segments through stream diversions, it was integral to account for these effects in order to properly calibrate to streamflow in the groundwater model.

A data file (DDH) created in SPDSS Task 3 (SPDSS 2007) containing filled monthly diversion records for all key diversions was used to represent historical diversions for the 1950-2006 study period. The data were imported into Excel and filtered by the diverting structure Water District ID (WDID) number. The data were then reformatted and uploaded to the SPDSS groundwater geodatabase. The SPDSS groundwater geodatabase is an ArcGIS geodatabase developed specifically to store groundwater information for the model. In addition, diversion locations that were used to assign diversions to a specific reach of the SFR2 stream network were added to the SPDSS groundwater geodatabase. This geodatabase is used by the ArcGIS SFR2 tools and SFR2 package generator to prepare the MODFLOW SFR2 package used in the groundwater model. Additional detail on the development of diversion inputs can be found in Appendix F.

3.9.2 Streamflow-Routing Package Development

The SFR2 package input file was created using the modeling geodatabase, the custom ArcGIS SFR2 tools, and the SFR2 package generator. These are discussed in more detail in Appendix J. In general terms the geodatabase was populated with the stream network, the physical properties of the streams, additional segmentation points, and the model grid. The ArcGIS SFR2 tools were utilized to split the stream network into segments based on the location of segmentation points (locations of tributaries, diversions, streamflow gages, and changes in stream physical properties). The ArcGIS tools were then used to divide the segments into reaches using the model grid, and the SFR2 tools assigned the physical properties of the streams to the upstream and downstream point of every segment. The SFR2 generator then reformatted the geodatabase data and combined the table of streamflows to generate the SFR2 package. Additional details on the use of the Task 50 tools can be found in Appendices G and J.

3.10 Groundwater Evapotranspiration via Phreatophytes

Groundwater ET is an outflow term in the water budget representing the removal of water from the aquifer by either direct evaporation from soils or the consumption of groundwater by plants. In the context of the SPDSS model, this is the ET by phreatophytes within riparian areas. The subirrigation component will be discussed in a later section of this report. This process is considered to be a significant component of outflow in the hydrologic budget of the SPDSS alluvial model domain.

ET varies as a function of the water table depth below ground surface with maximum ET occurring when the water table is at the ground surface and decreasing to zero when the water table drops below where plant roots can make use of it, also referred to as the "extinction depth."

For the SPDSS Alluvial Groundwater Model, the State's consumptive use contractor provided an ET curve and land use information where phreatophytes are present (**Figure 3-16**) (SPDSS 2007b). The ET curve for the study area is based on one developed for the San Luis Valley and modified for the South Platte River Basin using data from field stations in Fort Lupton, Fort Collins, Greeley, and

Holyoke. Field studies have shown that the relationship between phreatophyte ET and depth below ground surface in northeastern Colorado can be portrayed graphically with a four-segment curve that generally declines steeply between ground surface and a depth of 4.0 feet and declines more gradually below that to a depth of 8.0 feet and then declines more gradually still to an extinction depth of 15 feet (**Table 3-2** and **Figure 3-17**). The maximum phreatophyte ET is approximately 3 feet of water per year when the water table is at ground surface. The geometry of the four-segment ET curve was used to create a seven-segment curve used in the MODFLOW ET Segments (ETS) package model input file. A seven-segment curve was used in the ETS package to allow for the discretization necessary to represent the curves for phreatophyte ET, sub-irrigated meadow and sub-irrigated alfalfa.

Table 3-2. Segments for ET by Depth to Water

Segment	Depth Interval	Formula
1	Surface to 2 ft.	ET = (-0.187 * depth + 1.000) * ETo
2	2 to 4 ft	ET = (-0.203 * depth + 1.031) * ETo
3	4 to 8 ft.	ET = (-0.0367 * depth + 0.367) * ETo
4	8 to 15 ft.	ET = (-0.0103 * depth + 0.154) * ETo

Phreatophyte ET inputs for the alluvial groundwater model were developed using StatePP. StatePP creates a composite ET function for each cell by accounting for the portion of the cell area covered by each sub-irrigated crop and combines it with the phreatophyte group and the shape of the function for each vegetative group. A detailed description of how the monthly ET is determined is presented Appendix B.

An independent check on phreatophyte ET using satellite imagery was conducted by an independent contractor. Additional details on the check are provided under the Calibration Section 4.3.2.3. The estimated ET from groundwater in phreatophyte areas using satellite imagery analysis within the active model domain for 2001 is 163,200 AF. A summary of the methodology is presented in the Task 65 Estimating South Platte Phreatophyte Groundwater Evapotranspiration (SPDSS 2007b)

3.11 Recharge

Recharge is that portion of water applied to the surface that infiltrates to the saturated zone of the aquifer. The model recharge components include precipitation and irrigation-based recharge, and reservoir and canal seepage. Example distributions of annual average recharge from all sources for January to December in the calibration period (1999 to 2005) are shown in **Figures 3-18 to 3-29**. Compilation of these various recharge sources is done within StatePP and several other data management packages, as documented in Appendix J. Each of the major components of recharge is described in the following sections and additional details can also be found in Appendix B.

3.11.1 Precipitation-Based Recharge

Precipitation is developed on a monthly basis for the modeling period for each of the 21 climate stations utilized in the study area. These monthly values are interpolated onto each model cell (both active and inactive) using kriging weights developed by other contractors (Brown and Caldwell, undated Software manual, "State DGI Database and Graphical User Interface"). The land use and irrigation status are then used to develop recharge quantities from precipitation that are used as an input to StatePP for merging with other components of recharge. The recharge on native vegetation areas in all seasons was estimated at 3 percent of the precipitation, while the recharge on irrigated areas during the irrigation season reached a maximum of 23 percent in some irrigated crop areas (Soil Class A – 23 percent; Soil Class B - 14 percent, and Soil Class C - 4 percent with all percentiles express as percent of total precipitation). The average annual precipitation-based recharge is 101,000 AF for the calibration period.

3.11.2 Irrigation-Based Recharge

Water applied during the irrigation process that is not consumed by crops or evaporation provides a significant amount of water to the alluvial aquifer. A historical consumptive use analysis was applied using StateCU to determine the amount of irrigation-related recharge within the model domain (SPDSS 2010). For areas that are flood irrigated, 40 percent of the applied water is estimated to infiltrate to groundwater, while for sprinkler irrigated areas, 20 percent is estimated to percolate to groundwater (SPDSS Task 56 Memorandum; SPDSS 2008d). The average annual recharge from irrigation is 840,000 AF during the calibration period.

3.11.3 Reservoir Seepage

Reservoir seepage involves percolation of water from reservoirs to the alluvial groundwater system. Key reservoirs in the study area were identified based upon the SPDSS Task 5 memorandum (SPDSS 2006h) and incorporated into the model. In the case where a reservoir is located within the active domain, seepage from the reservoir was included in the MODFLOW Recharge package. In the case where either a portion or the entire area of the reservoir area is located outside the active model domain, the reservoir seepage was used to compute lateral boundary inflows. There are no direct measurements of reservoir seepage, so it was estimated for use in the model. For each of the cells with an overlying reservoir, the area and soil class were used to develop the recharge rate within the cell. This rate was assumed to be constant across all stress periods. Reservoir seepage in the active model area is implemented as a specified flux condition using the MODFLOW Recharge package and more information on reservoir seepage can be found in Appendix B.

3.11.4 Canal Seepage

Canal conveyance efficiencies are estimated in the Task 56 Memorandum (SPDSS 2008b) and are used in StateCU to calculate the amount of canal seepage by ditch system. Canal seepage is included in the model as recharge to the aquifer in model cells where the canals are located. Canal seepage ranged from 10-50 percent (average of 23 percent) and is evenly distributed within StatePP along the length of the canal (SPDSS 2008d). Additional information can be found in the Historic Crop Consumptive Use Analysis report (SPDSS 2010).

3.12 Subirrigation

Subirrigation can occur in the model in irrigated meadows and alfalfa in the study area when the depth to groundwater is shallow and the consumptive use demand for these crops has not been met. If the full consumptive use demand is not fulfilled by surface water or groundwater pumping, groundwater ET is allowed to fulfill this demand, depending on the depth to groundwater.

For the SPDSS Alluvial Groundwater Model, the State's consumptive use contractor provided CDM Smith with ET curves for subirrigated meadows and alfalfa (**Table 3-3** and **Figure 3-17**).

Table 3-3. Subirrigation ET Rates by Depth to Water

Depth to Water (ft)	Subirrigated Meadows Rate (ft/day)	Subirrigated Alfalfa Rate (ft/day)
0	0.009035	0.00794
2	0.009035	0.00794
3.3	0.002033	0.00763
3.4	0.002033	0.007527
4	0.001848	0.006836
8	0.000614	0.002279
10	0	0
15	0	0

Subirrigation inputs for the alluvial groundwater model were developed using StatePP. StatePP creates a composite ET function for each cell by accounting for the portion of the cell area covered by each sub-irrigated crop and combines it with the phreatophyte group and the shape of the function for each vegetative group. A detailed description of how the monthly ET is determined is presented Appendix B.

3.13 Output Control

Model output can be specified by model stress period for a variety of inflow and outflow information. Typical model output for the SPDSS alluvial groundwater model will include simulated head and drawdown, and cell-by-cell flows for constant heads, wells, drains, and streams.

3.14 Solver Parameters

The PCG2, PCGN, and GMG solvers have been used in the model at various times, with the GMG solver being used most of the time, since head convergence and volumetric mass balance were obtained with reasonable computational efforts. A head closure criterion of 0.2 feet with use of adaptive damping was successful in obtaining a solution that converges and has a volumetric mass balance of less than one percent discrepancy. The head closure criterion is set by the modeler and can be adjusted within a reasonable range to obtain model convergence with an acceptable volumetric mass balance while balancing model simulation times. Other solvers may be used with the model, provided that acceptable head closure and volumetric mass balance criteria are met.

This page intentionally left blank.

Section 4
Calibration and Model Results

The next major step in the development of the SPDSS Alluvial Groundwater Model was the calibration and validation process. The following study periods were used.

- Steady-state period (average 1991-1994): This was an initial calibration period designed to provide reasonable water budget, starting water level elevations and initial aquifer property values.

- Transient calibration period (monthly 1999-2005): This was the main calibration period where significant time was spent in refining the aquifer properties and surface water interactions.

- Validation period (monthly 1950-2006): This period was used to verify that the calibration determined during in the 1999-2005 period was robust.

Model results were evaluated primarily in the ability to simulate observed heads and seasonal head changes during the calibration period, as well as in terms of differences between estimated and simulated inflows and outflows. The primary water budget components that were assessed included streamflows at gage locations and diversions. The estimated streamflow gains and losses were compared to the modeled gains and losses; however, this component is considered as qualitative, due to significant uncertainties.

4.1 Model Water Budget

Prior to performing model simulations, a preliminary water budget was developed for the steady-state model simulation based on the conceptual model and inflows and outflows discussed in Sections 2 and 3. This water budget was used to validate the significant inflows and outflows of the model for the selected steady-study period. A water budget allows a rapid comparison of calculated and simulated flows, providing a useful tool to evaluate the conceptual model and model inputs. A water budget describes the sources, quantities, and timing of inflows and outflows to a defined basin. Some of the components of the water budget are directly specified as a model input, including:

- Well pumping
- Recharge components from both precipitation and irrigation
- Denver Basin bedrock inflows
- Upstream alluvial underflow
- Surface water inflow
- Diversions

Other components, including streamflows within the model, evapotranspiration from groundwater, and basin outflow are calculated in the model. The basin considered for the water budget is the alluvial groundwater model domain. The groundwater and surface water budgets are tightly linked in the South Platte River Basin, since the surface water features are in direct communication with the alluvial aquifer. Please see Section 2.3.1 to review a schematic illustration of the water budget components active in the South Platte basin and included in the groundwater model.

4.2 Steady-State Model

A steady-state model was initially developed for the 1991 to 1994 time period to represent average conditions in the mainstem area of the South Platte. The purpose of the steady-state model was to validate the conceptual model and develop preliminary estimates of water budget components and hydraulic characteristics and obtain starting water elevations for the transient run. Representation of significant areas in the model with steady-state conditions was not possible due to pumping rates exceeding recharge rates, mainly in the designated basins. Under these pumping conditions, a steady-state model would deplete these areas, since a steady-state simulation represents equilibrium conditions after an infinite time period. The simulations were facilitated by reducing net pumping in the designated basins to a rate that would allow them to remain saturated. Some initial refinements to hydraulic conductivity and streambed conductance were made using both heuristic calibration and parameter estimation to provide a reasonable starting point for the transient calibration. Based on these refinements and adjustments, model calibration proceeded to the transient period for additional calibration.

4.3 Transient Model

The transient model was configured based on the steady-state model, with incorporation of monthly values for the time-variable stresses, including recharge, well pumping and streamflow. The calibration process, goals, and results are described in following sections.

4.3.1 Calibration Process

Model calibration is the process where model parameters are adjusted within their range of uncertainty to obtain acceptable agreement between observed flows and heads and their simulated equivalents in the model. Estimates of each of the significant model inflows and outflows were developed, as previously described, and specified in the model. Characteristics that were varied during the calibration process included hydraulic conductivity in the aquifer, streambed conductance, which is controlled by the specified vertical hydraulic conductivity of the streambed materials, specific yield, and, to a limited extent, pumping rates in localized areas.

The transient calibration process involved using the steady-state model configuration and parameters as a basis. The transient input datasets were prepared, and initial heuristic model runs were performed to verify the transient model converged and found a solution within the specified criteria. Once a stable transient model was achieved, model calibration was undertaken by varying model parameters. Automated calibration was used to vary hydraulic conductivity within the model using a pilot point approach. Once a reasonable calibration was achieved for hydraulic conductivity other model parameters were varied heuristically until model calibration was achieved. The parameter modifications focused on areas where large magnitude residuals were consistently present.

The pilot point approach was implemented during the calibration process to facilitate development of a relatively smoothly varying hydraulic conductivity field within the model. In this approach, the distribution of hydraulic conductivity is described by a series of points distributed across the model, each of which specifies a point value for the hydraulic conductivity. In addition, a series of zones were defined to control interpolation of the point hydraulic conductivity values onto the model grid cells. Only pilot points within a zone are used to interpolate hydraulic conductivity onto grid cells within that zone, using kriging techniques. A total of 270 pilot points were defined within 16 zones. The largest zone includes the South Platte mainstem alluvium, its major western tributaries, and the former valley of the ancestral South Platte River. Individual zones were defined for other tributaries to allow independent estimation of properties within each zone. Paired pilot points were typically included at the boundary between zones to allow for a smooth transition in properties during the interpolation process. This process was achieved using a groundwater data utility called "PPK2FAC3" developed by John Doherty (Doherty 2009). **Figure 4-1** shows the zones, along with the pilot points used to define the hydraulic conductivity.

The initial estimates of hydraulic conductivity were defined based on the analysis in Task 43.3 South Platte Alluvium Region Aquifer Property TM (SPDSS 2006d; Appendix A). Preliminary calibration efforts during the steady-state modeling resulted in modifications to the hydraulic conductivity field that served as the starting point for the transient calibration. The hydraulic conductivity modifications were implemented by changing the value of individual pilot points, then interpolating hydraulic conductivity onto the model grid and running the model. These changes were focused on areas where the largest differences between observed and modeled heads occurred.

The initial conditions used in the model during the calibration process have a significant impact on the simulations. Due to this factor, the initial conditions were developed using an equilibrium period (January 1950 hydrology ran for 3000 days) to obtain a stable mathematical condition to use for the start of the 1950 to 2006 simulation period. The full simulation period was run and then the 1999 to 2005 simulated conditions were compared to observed field data for the same period to assess the calibration.

As a result of the initial calibration there were several model parameters which required adjustments to achieve model calibration. The adjustments to these parameters are discussed in greater detail in Section 4.3.3 Model Calibration Results.

4.3.2 Calibration Goals

A series of calibration goals were defined during earlier phases of the project that were used to assess the model calibration. These goals or criteria are set based on comparisons between model simulation results and field measurements, observations, and estimated values. These goals address various targets with numerical criteria, including heads, seasonal variability in heads, and streamflows in the model. Other targets with qualitative goals have also been defined for factors such as the presence of dry and flooded cells and the ability to meet diversions. Each of the categories of calibration targets and goals are addressed below and additional details can be found in Appendix K.

Head Targets

Comparison of observed water level measurements and their modeled equivalent for both individual measurements and seasonal variation provide one important measure of model calibration. In order to supplement existing water level information in the study area, numerous monitoring wells were installed and instrumented with data recorders as part of the SPDSS project, and other existing monitoring wells were surveyed under Task 39 (SPDSS 2008e) to obtain accurate elevations. Water level measurements were compiled and summarized in the Task 44 TM provided in Appendix A.

The difference between the field observation and the modeled equivalent is referred to as the "residual." The water level observations available in the study area include measurements in three categories. The first category consists of the wells installed as part of the SPDSS field program, and includes frequent automated water level measurements with accurate survey information. The second category of wells includes pre-existing monitoring wells with accurate survey information; these wells have manual water level measurements rather than automated pressure transducer measurements. A number of wells in critical locations were surveyed during the SPDSS program. The third category of wells includes a large number of wells with manual water level measurements, but with elevations estimated from topographic maps. Two types of criteria for head targets were included in the calibration, incorporating the three categories of water level measurements. The first type includes residuals using individual measurements from monitoring wells in the first two categories, i.e., wells with surveyed elevations. The first two bullets in the list below include criteria for this type. The second type of criteria includes residuals using the relative change in water levels at a monitoring well, also referred to as delta heads. Comparisons of the change in head over time are not sensitive to the surveyed elevation, so residuals from both surveyed and unsurveyed wells were used. The last two bullets in the list below include criteria for this second type.

- The absolute value of the *mean* residual at wells with surveyed elevations across the calibration period should be less than 5 feet.
- The absolute value of the residuals at wells with surveyed elevations across the calibration period should be less than 5 feet for 75 percent of the observations.
- The absolute value of the *mean* change in head residuals from observation points across the calibration period should be less than 5 feet.
- The absolute value of the change in head residuals at wells across the calibration period should be less than 5 feet.

Flow Targets

Flow targets include streamflow, stream gains and losses, and surface water diversions. Extensive data are available for streamflows at gaging stations and for surface water diversions. However, little direct data are available on stream gains and losses from groundwater; therefore, estimates were made in Task 46 (Appendix E) for numerous stream reaches in the model. Flow targets are an important complement to head targets in obtaining a robust calibration.

Each of the calibration goals for flow targets is described below:

- The principal quantitative goal for the flow related targets is associated with streamflows, where the goal was to match the average annual streamflow within 25 percent for those gages with flows greater than 25,000 AFY. Originally, as described in Appendix K, the goal was to match average annual streamflows within *10 percent* for gages with flows greater than 25,000 AFY. This criterion was modified to 25 percent, when it was recognized during the calibration process to be unreasonably stringent. Reasons for this change are due to the uncertainty of some aspects of the surface water domain, including the lack of accurate estimates of ungaged surface water inflows within the model area. Once completed, the SPDSS surface water model should help reduce some of these uncertainties.
- The original goal for stream gains and losses was that estimated and modeled average annual stream gain/loss within a given reach should be within 10 percent for all flows greater than 25,000 AFY. Subsequently, this criterion was also found to be unrealistic. Stream gains and losses were estimated for use as model targets using hydrographic data (see Appendix E for details); however, due to the uncertainty in the approximations (e.g., the potentially large magnitude of unknown factors such as ungaged surface water flows), it was decided that this

parameter should be compared on a qualitative basis with respect to seasonal variability and relative magnitude.

- The model is also capable of tracking the ability of the stream to support monthly historical diversions. This is an important indicator of the degree of calibration with respect to the surface water component, as it shows that there is adequate flow in the surface stream both in amount and timing. The goal for the diversions target is that the simulated diversions should be within 10 percent of observed diversions across all time periods.

Groundwater Evapotranspiration via Phreatophytes

Phreatophyte ET from groundwater along the South Platte mainstem and tributaries was estimated using satellite imagery for 2001 (SPDSS 2007b). The difference between these estimates and the simulated groundwater ET from phreatophytes should be less than 10 percent when examined at the end of the transient simulations.

Other Calibration Targets

Other calibration goals have also been set to judge the representativeness of the model.

- Head residuals should be randomly distributed on a geographic and temporal scale to the degree possible.
- The model must have volumetric mass balance of less than one percent for the steady-state calibration simulation and within 5 percent at the end of the transient simulations. The residual for each of the components of the groundwater budget will be less than 10 percent for 75 percent of the budget components. These groundwater budget components were specified to ensure that all appropriate input parameters were included in the model at their proper magnitude.
- The number of dry and flooded cells will be less than 1 percent of the model cells in the active model domain and will be randomly distributed; this criterion was changed to a qualitative criterion of "minimize" as discussed in Section 4.4.
- Qualitative assessment of water level contours.

4.3.3 Model Calibration Results

This section summarizes the results of the model calibration, including comparisons of model results with the calibration goals. The calibration results address the head and streamflow comparisons and other qualitative calibration goals. Model calibration is a non-unique process, since many combinations of parameters may result in a similar ability to meet calibration goals. The calibrated model represents the set of parameters produce results that are reasonably consistent with field data and the calibration goals. Calibration results are presented below for the hydraulic properties in the model, tributary streamflow, pumping, heads, streamflows, stream gains and losses, diversions, groundwater ET from phreatophytes, and other non-numeric calibration targets.

Hydraulic Properties

Hydraulic parameters, including aquifer hydraulic conductivity, specific yield, and streambed vertical hydraulic conductivity, were modified during the calibration process. The initial estimates of hydraulic conductivity were modified in the steady-state model for the South Platte valley alluvium. These values and those in areas outside of the South Platte mainstem were refined during the transient calibration process by examining areas exhibiting the highest head residuals and modifying individual pilot points to reduce these residuals. **Figure 4-2** shows the distribution of hydraulic conductivity values in the calibrated model. The hydraulic conductivity values within the model area range from about 115 to 700 feet per day. The highest hydraulic conductivity values occur in the upper reaches of the South Platte alluvium and in the valleys of western tributaries. Hydraulic conductivity values were typically lower in tributary valleys originating on the plains, where sediment source areas consist of finer grain materials. The area of the South Platte where several of these major plains tributaries discharge, including the confluences of the mainstem with Kiowa Creek, Bijou Creek, and Wolf Creek, also exhibited lower hydraulic conductivity, based on the calibration. In areas where few calibration target wells were present, hydraulic conductivity was not modified from the initial estimates.

The specific yield was also modified from the original estimates during the calibration process. The seasonal variation in water levels was used as the measure of calibration for specific yield, since this parameter is the primary control on the seasonal fluctuation in water level. The final selected value for specific yield was 0.20, which was applied to the entire model area.

One of the other hydraulic parameters that were modified during the calibration process was the streambed vertical hydraulic conductivity that is used in the SFR2 package in MODFLOW. This parameter is used to calculate a conductance term in the model used in calculating stream gains and losses. The conductance term that is calculated in the model is a function of streambed area and thickness of streambed materials. The conductance term in the SFR2 package is calculated using the following equation.

$$C = \frac{k' \bullet w \bullet L}{m}$$

C – Conductance
k' - Streambed vertical hydraulic conductivity
w – Channel width
L – Length of channel in grid cell
m – Streambed thickness

The conductance term is used within the model to calculate the flux of water into or out of the stream, based on the groundwater elevation and stream elevation, including consideration of the potential for the groundwater elevation falling below the base of the streambed material. This parameter should be considered an approximation of the physical parameters that control stream seepage, since the complexities of the three dimensional flow proximal to the streambed are difficult to represent when the stream dimension is small compared to the dimension of the grid cells. A refined streambed conductance term should be considered if local or smaller regional models with a smaller grid dimension are developed from the SPDSS model, since the streambed conductance will typically increase as the grid dimension approaches the stream width (Mehl and Hill, 2010). **Table 4-1** summarizes the stream parameters in the calibrated model.

Table 4-1 Streambed Vertical Hydraulic Conductivity in Model

Tributary Name	Streambed Vertical Hydraulic Conductivity (ft/day)
Ashcroft Draw	0.5
Badger Creek	0.5
Bear Creek	0.5
Beaver Creek	5
Beebe Draw	5
Big Dry Creek	5
Big Thompson River	5
Bijou Creek	5
Boulder Creek	10
Box Elder Creek	5
Boxelder Creek	5
Camp Creek	0.5
Cedar Creek	0.5
Cherry Creek	0.5
Clear Creek	5
Coal Creek	5
Comanche Creek	0.5
Cottonwood Draw	0.5
Crow Creek	5
Dry Creek	5
East Bijou Creek	5
Eaton Draw	5
First Creek	0.5
Graham Seep	5
Kiowa Creek	0.5
Little Dry Creek	5
Little Thompson River	5
Lodgepole Creek	0.5
Lonetree Creek	5
Lost Creek	4
Middle Bijou Creek	0.5
Muddy Creek	0.5
Owl Creek	5
Pawnee Creek	0.5
Plum Creek	0.5
Poudre River	0.5
PR1	2
PR2	2
Ralston Creek	5
Saint Vrain Creek	5
Sand Creek 1	0.5
Sand Creek 2	5
Sand Creek 3	5
Sand Creek 4	0.5
Second Creek	5
Sheep Draw	0.5
South Platte River	0.5
South Platte River NE	0.5
South Platte River: Balzac to Julesburg Reach	5
South Platte River: Denver to Henderson Reach	5
South Platte River: Fort Lupton to Kersey Reach	5
South Platte River: Henderson to Fort Lupton Reach	5
South Platte River: Kersey to Weldona Reach	5

Table 4-1 Streambed Vertical Hydraulic Conductivity in Model

Tributary Name	Streambed Vertical Hydraulic Conductivity (ft/day)
South Platte River: Waterton to Denver Reach	5
South Platte River: Weldona to Balzac Reach	5
Spring Creek	0.5
Spring Creek 2	0.5
The Slough	5
Third Creek	5
Toll Gate Creek	0.5
Trib 1	0.5
Trib 4	0.5
Twentytwo Slough	0.5
West Bijou Creek	0.5
West Sand Creek	0.5
Wildcat Creek	0.5
Wolf Creek	0.5

Heads

There are three aspects of the model calibration that consider heads:

- Qualitative assessment of the water table contours
- Comparison of individual observed and simulated heads
- Comparison of the seasonal change in heads

A qualitative visual assessment of the simulated head contours was performed first to verify general flow directions and gradients within the model domain. **Figures 4-3** and **4-4** show the simulated water table surface for August 2004 and February 2005, respectively. These periods represent the range of water levels, with the August values showing the effect of pumping during the irrigation season, while the winter water levels reflect recovery from this pumping. These water table maps are similar to those based on contouring of observed water levels, and generally reflect the gaining nature of the South Platte River.

One of the principal quantitative measures of calibration is the comparison of observed and modeled heads. During the calibration period, a total of 20,244 head observations at 513 individual wells were used to assess the calibration during the 1999 to 2005 period. This included 111 wells with surveyed elevations available and 402 wells with estimated elevations. There were 16,041 individual observations at the surveyed wells and 4,203 observations at wells with estimated elevations.

A significant number of the surveyed wells had transducers and dataloggers installed, resulting in a large number of observations. In order to avoid a bias toward these wells, the residuals were assessed both by calculating an average residual at each individual surveyed well, and calculating an average residual across all observations at surveyed wells. One measure of the calibration quality is to assess the absolute value of residuals at all wells and also determine the overall mean residual at the surveyed wells. The calibration goals included obtaining residuals of less than an absolute value of 5 feet at 75 percent of surveyed well locations. When only surveyed wells were considered, 83 percent of these observations had residuals with an absolute value of less than 5 feet. The absolute value of the mean difference of the head residuals for wells with surveyed elevations was 3.36 feet. In order to assess seasonal and longer term head changes, which allow use of the unsurveyed wells, the relative changes in the observed and simulated head data were compared. The mean absolute value of residuals for these head changes was 2.95 feet, with 90 percent of the residuals within ± 5 feet.

Figure 4-5 shows the statistical distribution of the mean residuals at surveyed wells for the calibration period. **Figure 4-6** shows the distribution of residuals for all observations at surveyed wells. Comparisons were also made for the pooled set of observations, including both surveyed and unsurveyed wells. It should be noted that since the reference elevation for the unsurveyed wells is uncertain, no formal calibration goal was set for these wells. **Figure 4-7** is a map showing the distribution of the mean residuals by well during the calibration period and the results show the goal of achieving random distribution was achieved. This map includes both the surveyed and unsurveyed wells. **Figure 4-8** shows the distribution of residuals for all observations during the calibration period for surveyed and unsurveyed wells. Seventy-five percent of all observations showed residuals between -5 and +5 feet.

The calibration also considered the seasonal variability in heads at all wells. Many of the wells had multiple water level measurements. The delta head is defined as the change in head from observation to observation at an individual well. This change in head is independent of the elevation of the datum, so all wells were utilized in this analysis. The wells with the most data on temporal variation were the SPDSS observation wells with transducers installed. The corresponding change in head in the model over a corresponding time period was calculated for the comparison using internal MODFLOW tools. This change in head over time is useful for assessing the specific yield of the aquifer, because of its influence on the magnitude of seasonal variation in heads. **Figure 4-9** shows the distribution of head change residuals at all wells, indicating that 90.5 percent of the residuals were between -5 and +5 feet.

Graphical comparisons of observed and simulated heads provide an additional view of the model calibration. **Figure 4-10** show a cross-plot of simulated and observed heads for all observations during the calibration period. These observations cluster around the 1:1 slope, which is the line that describes a perfect correlation between the model and field data. The scatter around this line represents the residuals.

Hydrographs at individual wells during the calibration period are presented in Appendix L. These hydrographs include all wells with more than 10 observations. **Figure 4-11** shows several hydrographs superimposed on the model area map. The correspondence between modeled and observed hydrographs is variable, with some wells in very good agreement both in water table elevation and temporal variation. The presence of nearby pumping wells will have a strong impact on the water table elevation and degree of seasonal variation in the observation well. MODFLOW treats pumping wells as being located at the center of a model cell. Since the actual well locations are distributed throughout a given cell, the comparisons of modeled versus observed water level elevations will be affected when the actual distance between a monitoring well and a pumping well (or other model stress) is different from the model representation.

Streamflows

Streamflow is calculated within the model, accounting for inflows, diversions, reported discharges, and interactions with groundwater. The calibration goal was to simulate average annual streamflows in the model within 25 percent for the following gaging stations which exceed 25,000 AFY in streamflows.

- Cherry Creek at Denver
- South Platte River at Denver
- South Platte River at Henderson
- South Platte River at Fort Lupton
- Cache la Poudre near Greeley

- South Platte River near Kersey
- South Platte River near Weldona
- South Platte River at Balzac
- South Platte River at Julesburg (combined)

Figure 4-12 shows a comparison of the observed and simulated average annual streamflows at these stations for the calibration period. All of the stations showed an average annual modeled flow over the calibration period lower than the observed flow, with the exception of Cherry Creek, the Cache la Poudre near Greeley, and the South Platte River at Balzac, where the modeled flows were higher than the observed flows. Overall, the average modeled annual flows over the calibration period are typically within 15 percent of the observed flows, with three exceptions.

- Cherry Creek at Denver, where the flow was 30 percent higher in the model (average modeled flow of 36,188 AFY with an observed flow of 27,741 AFY, a difference of 8,446 AFY).

- South Platte River at Henderson, where the average modeled flow was 17 percent below the observed flow (average modeled flow of 271,897 AFY and an observed flow of 327,444 AFY, a difference of 55,547 AFY).

- Cache la Poudre at Greeley, where the average modeled flow was 91 percent higher than the observed flow (average modeled annual flow 174,292 AFY, while the observed flow was 91,133 AFY, a difference of 83,159 AFY).

Figures 4-13 through **4-21** provide a comparison of the simulated and observed annual streamflow during the calibration period for each of the above gages. Most of the gages show a reasonable comparison from year to year. For about half of the gages, the largest difference between modeled and observed flows occurs in 1999, which was a high runoff year. Cherry Creek and the Cache la Poudre show the most notable differences between the modeled and observed streamflows, with the modeled flow always higher than the observed flow, indicating there likely are processes occurring in those drainages that are not accurately represented in the model.

Stream Gains and Losses

Stream gains and losses were originally identified as a calibration target with a quantitative criterion, but this was modified to a qualitative criterion during model calibration based on engineering judgment and available data. The South Platte River is a highly developed, complex system with numerous inflows and outflows, including measured inflows and diversions, ungaged surface water inflows, and stream/groundwater interactions. Due to uncertainties involved in the estimation of stream gains and losses to be used as the model targets, primarily related to ungaged surface water inflows, it was deemed appropriate to change this criterion to qualitative. The revised criterion was to use the stream gain/loss estimates as a guide to the magnitude of modeled stream gain/loss, if a reach was gaining or losing, and whether similar seasonal variations were seen in a particular reach over time.

Stream gains and losses estimates are further documented in the SPDSS Task 46 TM (SPDSS 2007), which is included as Appendix E to this report. The Task 46 analysis estimated gains and losses by stream reach on a monthly basis. The analysis did not include an explicit input for ungaged surface water inflows (i.e., they are part of the gain/loss estimated value), so the target estimates were modified for this comparison by correcting for the estimated ungaged surface water inflow inputs that are used in the model.

Figure 4-22 provides an overall summary of the average monthly gains and losses over the calibration period. Note in this and other gain/loss figures that a negative flow occurs when discharge occurs from the aquifer to the stream (gaining reach). The model results and the estimated targets are in good agreement on whether a stream reach is gaining or losing overall, with both indicating that each of the reaches evaluated gains flow on an average annual basis, with the exception of Cherry Creek, where overall the stream loses flow to the aquifer. The modeled and observed magnitude of average monthly gains and losses is reasonable in most cases. The most significant difference between the modeled and observed stream gains was for the reach between the Kersey and Weldona gages. In this reach, the modeled stream gain from groundwater was 66 percent larger than the observed, a difference of 7,200 AF/month. A large percentage difference also occurred at Cherry Creek, where the model showed a larger loss to the aquifer. However, the actual magnitude of the difference was small, at about 550 AF/month.

The magnitude of estimated and modeled gains and losses varies during the year, generally with larger gains during the summer months. **Figures 4-23 to 4-31** show the estimated and modeled monthly stream gains and losses for each of the reaches. The Waterton to Denver reach shows good agreement in magnitude of the stream gain, with the largest differences during the winter months, where the gain is higher in the model. The Cherry Creek reach shows the greatest percentage difference between the estimated gains and losses and the modeled equivalent. The model shows relatively small stream losses for Cherry Creek throughout the year, while the estimated targets show more variability, with frequent large gains and even larger losses. Note that this may indicate larger uncertainty in the estimated Cherry Creek targets, compared to estimated gain/loss targets for other reaches.

The Denver to Henderson reach is primarily a gaining reach in the Task 46 analysis, except during some summer months. The model simulates this reach as gaining during the entire calibration period. Generally, the magnitude of the stream gains is lower in the model compared to the estimates during the non-irrigation season.

The Task 46 estimates indicated the Henderson to Fort Lupton Reach is a losing reach during the winter and early spring months. The model predicts this reach to be gaining throughout the year. The magnitude of the gain during the irrigation season in the model is about half the estimated value.

The Cache la Poudre is also estimated to be principally a gaining reach, with the exception of short periods during the irrigation season in several years. The model also indicates this reach is gaining; however, in several years the magnitude of the gain is greater in the model than the estimates.

The Fort Lupton to Kersey reach of the model shows very good correspondence between the estimates and the modeled values. This reach is gaining throughout the year.

The Kersey to Weldona reach is estimated to be primarily a gaining reach, except for occasional periods during the non-irrigation season. The model simulations indicate stream gains during the entire calibration period. The magnitude of simulated stream gains is greater than the estimates during the non-irrigation season.

The Weldona to Balzac reach shows relatively good agreement between the estimated and modeled gains and losses. Both the Task 46 analysis and the model indicate this reach is gaining at all times.

The Balzac to Julesburg reach is shown by both the model and the estimates to be a gaining reach at most times during the calibration period. In most months, the modeled gains are lower than the estimated gains.

The overall agreement between the estimated gains and losses and those calculated in the model is reasonable, considering the uncertainty with some of the parameters included in the estimation of the targets, e.g., ungaged surface water inflows. In the majority of cases, both the estimated targets and the model show the stream reaches as gaining. The estimates and the model results also follow generally similar trends in seasonal variations, but the estimated values show larger seasonal fluctuations with the model showing more damped variations.

Diversions

The SFR2 package used in the model simulates historical diversions that are provided as an input parameter. The SFR2 package tracks inflows and outflows from the stream, and if flow is available in the stream the historical diversion amount is removed. If a specified diversion exceeds the flow in the stream at the location, then the available flow is removed from the stream and the stream is dried up at that point. Tracking the model's ability to meet the observed diversion quantities is an additional means of assessing the ability of the calibrated model to match field data. During the calibration period, diversion quantities were met 97 percent of the time. **Figure 4-32** shows the percentage of time by monthly stress period that diversions were met in the calibrated model. The lowest percentages of historical diversions met in the model are typically in the summer months.

Tributary Streamflow

During model calibration the modeled surface flow for several tributaries at the confluence with the South Platte River differed from observed flows. The South Platte River and its tributaries are highly developed and include diversions, wastewater treatment plant discharges, and ungaged surface water inflows, which would be more thoroughly identified with a surface water model of the tributary. Due to the lack of information for some of the tributaries, it was determined during model calibration that the focus of the calibration of the surface water flows would be in the mainstem of the South Platte River. To allow the major tributary surface water flows entering the mainstem to be used in the model for groundwater/surface water interaction it was decided to adjust the surface water flows at the confluence of seven tributaries to their historical flow values. These tributaries are Big Dry Creek, Big Thompson River, Boulder Creek, Cache la Poudre River, Cherry Creek, Clear Creek, and Saint Vrain Creek. Once a surface water model is developed for these tributaries, it will reduce the uncertainty of the surface water contributions in these creeks.

Well Pumping

Well pumping was reduced during the final stages of calibration due to excessive depletion of the alluvial aquifer compared to observed water level data. This depletion issue could only be addressed by either increases in recharge or reductions in pumping. As a result of this, all agricultural pumping was reduced to 80 percent of the demand based estimates. In addition, pumping in Beaver and Bijou Creek tributary alluvial aquifers was reduced to 70 and 65 percent, respectively, of the demand based pumping rates. The additional pumping reductions in the Beaver and Bijou aquifers was done to be consistent with the water level declines observed in these areas.

Groundwater Evapotranspiration via Phreatophytes

As noted in Section 3, an independent assessment of phreatophyte ET of groundwater was made for 2001 (SPDSS 2007b). These estimates were allocated to the mapped phreatophyte areas within the active model domain to allow a comparison of the prior estimates and the modeled ET. The estimated 2001 groundwater ET from vegetation is 245,427 AF (SPDSS 2007b). Only a portion of that ET occurs within the active model area. GIS coverages were used to calculate the amount of ET from groundwater within the model area. The ET from groundwater in the model area is 163,200 AF. The corresponding calculated phreatophyte ET in the calibrated model is 165,262 AF, within about 1 percent of the estimated quantity.

During the final stage of calibration, checks of the model calculated ET of groundwater by phreatophytes in simulation year 2001 was lower than the rate reported by Groeneveld (SPDSS 2007b). Since there is significant variation in land surface elevation, which is the reference elevation used for calculation of ET, this parameter was adjusted to obtain a match in this important water budget component. The surface elevations were estimated in the model by averaging 30 meter resolution digital elevation model information for each 1,000-foot cell, so the model elevation is the average of about 103 individual elevations. This surface elevation was used for the initial estimate of the ET reference surface. Since much of the land covered by phreatophytes is located in the inner floodplain of streams, the average elevations may include some upland areas, resulting in an elevation that is above the floodplain elevation. A uniform adjustment to the ET surface was made to match the 2001 estimated and modeled phreatophyte groundwater ET rate by decreasing the reference surface by 2.5 feet.

Non-Numeric Goals

Several additional calibration goals were also set for the model. These included assessing the percentage of dry and flooded cells. In initial model calibration runs it was determined that the 1 percent criterion originally established was not realistic due to the large and intricate active model domain. As a result a goal of minimizing dry and flooded cells was adopted. **Figures 4-33** and **4-34** show the location of dry and flooded cells in February and August of 2001. During the calibration period, an average of 1,997 cells were flooded and 8,750 cells were dry, which is about 15 percent of the total active cells (69,895) in the model. The flooded cells occur principally along the inner floodplain of the South Platte, the Cache la Poudre, and St. Vrain Creek, while dry cells occur mainly in the upper reaches of tributaries and along the valley sides where saturated thickness is thin.

4.4 Calibration Summary

The SPDSS Alluvial Groundwater Model calibration process utilized an iterative approach where selected sensitive model parameters were adjusted within predetermined ranges until the simulation results match observed data to an acceptable degree. The process involved simulating historical conditions within an acceptable range of uncertainty, thus representing the effects of past inflows and outflows. Calibrated models that adequately simulate the validation period are considered to be even more robust in their ability to reproduce the processes that have occurred historically in the area modeled. Models are most commonly used for evaluating future conditions and "what-if" scenarios. A calibrated model may be used to estimate future and past conditions with confidence if the stresses imposed on the model are comparable to those imposed during the calibration and validation periods. The goal for the calibration of the SPDSS was to achieve calibration targets to allow use of the model for estimating past and future conditions and this goal was achieved for regional scale analysis.

Overall, the calibrated SPDSS model met most of the calibration goals. Selection of reasonable calibration goals was based on review of the data and engineering judgment, and some criteria were revised based on the initial model calibration efforts and review of available data sets. The calibration criteria and specified criteria target values define the acceptable differences between the measured and simulated values. Specific calibration criteria, targets, and results from the calibration are summarized in **Table 4-2** and the text below.

Table 4-2. Model Quantitative Calibration Target Summary

Calibration Criteria	Model Results	Calibration Target Value	Criteria Met
Cumulative % mass balance	0.01%	Minimize	Yes
Absolute mean of the head residuals (surveyed)	3.36 ft	5 ft	Yes
Head residuals (all) +/- 5 ft	75%	NA[2]	NA
Head residuals (all) +/- 10 ft	88%	NA[2]	NA
Head residuals (surveyed) +/- 5 ft	83%	75%	Yes
Head residuals (surveyed) +/- 10 ft	95%	NA[2]	NA
Absolute mean of the change in head residuals	2.95 ft	5 ft	Yes
Delta head residuals +/- 5 ft	90%	75%	Yes
Delta head residuals +/- 10 ft	98%	NA[2]	NA
Annual Streamflow +/- 25%	89%	100%	No
Annual Streamflow +/- 40%	95%	NA[2]	NA
Annual Streamflow Gains and Losses +/- 10%[1]	NA	100%	Changed to qualitative and criterion met
# of flooded cells 1%[1]	NA	Minimize	Changed to qualitative and criterion met
# of dry cells 1%[1]	NA	Minimize	Changed to qualitative and criterion met
% diversions met	97%	90%	Yes
Phreatophyte Evapotranspiration	101%	90%	Yes

[1] Target revised to qualitative criterion based on initial calibration. See report text below for additional detail.
[2] No calibration target value set; this criterion was used to indicate if model calibration was moving toward achievement of the calibration target.
NA Not applicable

The quantitative calibration goals for the SPDSS Alluvial Groundwater Model included both head and flow targets, which provide a basis for a robust model calibration. The results of the calibration showed simulated heads at surveyed wells within ±5 feet for 83 percent of the observations, which exceeds the goal of 75 percent. When all heads at observation points, including those at wells that were not surveyed, are included in the results, 75 percent of the observations fall within the ±5 foot goal. The seasonal change in head targets also met the goal, with 90 percent of the values within the ±5 foot criteria. The average annual streamflow target (100 percent) was not met, with 89 percent of the stations showing simulated flows within ±25 percent of the observed value. The surface water diversions were met 97 percent of the time, exceeding the 90 percent goal that was set.

The evapotranspiration by phreatophytes was within about 1 percent of the rate estimated for 2001, exceeding the calibration goal of 90 percent.

As previously noted, model calibration is an iterative process. During this iterative process qualitative criteria or non-numeric goals are often used and these criteria may also be judged to be more realistic indicators of calibration, based on available data and model specific applications. More specifically, for the South Platte Alluvial Groundwater Model three quantitative criteria were modified to qualitative criteria during the model calibration process. These include the stream gain/loss criterion, described in the first bullet below, and the flooded and dry cell criteria, described in the second bullet.

- At the onset of the model development, an aggressive quantitative calibration target was established for streamflow gains and losses. During data collection, the complexities of tributary and mainstem diversions and returns, coupled with significant ungaged flows, led to a revision of this criterion from quantitative to qualitative. Stream gains and losses in the model were comparable to the estimated targets with both generally showing gaining reaches in the model domain; however, in some cases, the magnitudes were significantly different, with the estimated targets showing larger seasonal fluctuations and the model results showing more damped variations.

- In regard to the number of flooded and dry cells, it was determined that the 1 percent criterion originally established was not realistic due to the large and intricate active model domain. As a result a goal of minimizing dry and flooded cells was adopted. The calibrated model results did show 3 percent of the cells flooded and 12 percent of the cells dry. To more fully examine if these criteria were qualitatively met, a more detailed analysis of flooded and dry cells was completed.

  Overall flooded cells occurred primarily within the inner floodplain of the South Platte, and dry cells occurred primarily in peripheral areas of the model where saturated thickness was low. Two major causes for cell flooding were identified. First, in areas near Beebe Draw and Big Dry Creek, anomalous bedrock elevations were identified that lead to cell flooding. This issue can be addressed in future model updates by modifying the active model extent to exclude these areas because the alluvial system may not be contiguous with the active model domain as currently defined. Second, the additional review of flooded cells in the active model domain identified eight other areas that showed "grouped" cells with flooding. These cells are located in areas of the model where there is either thin alluvium or probable excessive recharge. These areas of thin alluvium are a challenge in model calibration. Minimizing flooded cells in these areas would require localized revisions to the data centered recharge estimates, or revisions to the alluvial thickness, and it was determined that additional information should be gathered before additional revisions are made to the model. For this first major SPDSS Alluvial Groundwater Model development effort, these results do not have significant negative implications for regional planning efforts. However, these results should be noted when evaluating groundwater conditions in these areas and interpreting results from the model output in areas near the edge of valley boundaries.

Finally, during model calibration two additional topics were identified that warrant reiteration and further discussion. The first relates to the well pumping that was reduced during the final stages of calibration due to excessive depletion of the alluvial aquifer compared to observed water level data. This depletion issue could only be addressed by either increases in recharge or reductions in pumping. As a result of this, all agricultural pumping was reduced to 80 percent of the demand based estimates. In addition, pumping in Beaver and Bijou Creek tributary alluvial aquifers was reduced to 70 and 65 percent, respectively, of the demand based pumping rates. The second relates to the streambed elevation in relation to the aquifer configuration a review of streambed elevations revealed a small number (241 of 10, 207) of Streamflow-Routing cells where the streambed elevations were below the base of alluvium. Although this results in virtually no difference in the numeric solution of the model, it is recognized that these portions of the model do not provide an accurate representation of the physical environment.

4.5 Model Comparison with Validation Period

The SPDSS Alluvial Groundwater Model calibration was compared to water level observations available over the entire study period of 1950 to 2006 to assess the model calibration. Water level observations were selected as the primary indicator of model validation because they are the most direct calibration parameters associated with assessing groundwater conditions. All available water level records were included in the data set; however, this comparison was limited to wells that had surveyed elevations, due to the uncertainties with elevations at unsurveyed wells. During the 1950 to 2006 time period, a total of 30,600 observations were available from wells with surveyed elevations, of which about half are from the 1950 to 1998 time period. The calibrated model was run over the entire period of record and residuals (differences between observed data and the simulated water level elevation) were calculated for the observations for comparison. The residuals were assessed to determine the level of agreement between the simulated and observed data. The absolute of the mean head residual (surveyed) for the entire comparison period was 4.36 feet, which compares well with 3.36 feet for the calibration period. This increase in the absolute mean head residual is expected since the model was not calibrated using data for the 1950 to 1998 time period. The modeled head residuals for the calibration period (1999 to 2005) are the same for both runs. Seventy seven percent of the head residuals were less than 5 feet, while 89 percent were less than 10 feet which again compares well with the head residuals during the calibration period. Based upon these results the model provides a reasonable approximation of the groundwater conditions over the entire period, especially considering the significant changes in surface water and groundwater use and changes in land use from the pre-calibration period to the calibration period.

Section 5

Sensitivity Analysis

The final steps in the SPDSS Alluvial Groundwater Model calibration process were to evaluate the sensitivity of the model to changes in selected parameters and to identify possible modeling uncertainties. This section presents the results of these efforts.

5.1 Sensitivity Analysis

A sensitivity analysis was conducted to assess how the difference between observed and modeled results changed as a function of changes in selected parameters. During the calibration efforts, three parameters that were estimated were found to have the most effect on the model residuals. These were hydraulic conductivity, specific yield and, to a lesser extent, streambed conductance.

5.1.1 Hydraulic Conductivity Sensitivity

The hydraulic conductivity field in the calibrated model varies continuously through the domain, since it is based on interpolation of values at a large number of pilot points to the model grid using kriging. In order to assess the sensitivity of the model to overall changes in hydraulic conductivity, a percentage change was applied to the entire field and the change in the overall head residual was assessed. The hydraulic conductivity was increased uniformly by 10 percent throughout the model domain and the weighted residual sum of squares error recalculated for heads and delta heads. This 10 percent increase in hydraulic conductivity resulted in a change in the weighted residual sum of squares of 8.7 percent, indicating that the model is very sensitive to the hydraulic conductivity. This is consistent with the finding during calibration that supported using this parameter as the principal one to vary during the calibration process.

5.1.2 Specific Yield Sensitivity

The specific yield of the aquifer impacts the magnitude of the seasonal variation in heads due to changes in aquifer stresses, such as irrigation pumping and recharge. The specific yield is set at a value of 0.20 throughout the model. The sensitivity analysis compared the head and delta head residuals by decreasing the specific yield by 10 percent. This 10 percent reduction in the specific yield resulted in an increase in the sum of squares residual of 0.4 percent. This indicates that the model is not very sensitive to this parameter.

5.1.3 Streambed Conductance Sensitivity

The streambed conductance controls the vertical gradient that develops in the vicinity of the stream and will have an impact on head and the timing of discharge of groundwater to the river. The final calibrated streambed conductance was decreased by 50 percent for the sensitivity analysis; however, this decrease made no significant difference in the sum of squares residual error for heads and delta heads. The impact of this change was also assessed by comparing stream gains and losses between model simulations. The decrease in streambed conductance resulted in very slight decreases in stream gains in all reaches except Cherry Creek, which is predominantly a losing stream in the model. The maximum observed difference was in the Fort Lupton to Kersey reach, where the decrease in average monthly stream gain was 1.9 percent. The gains in other reaches changed by less than one percent. The decrease in streambed conductance by 50 percent resulted in insignificant changes in heads, and less than 1.9 percent decrease in stream gain in the most impacted reach. This parameter has limited sensitivity in the model.

5.2 Model Uncertainty and Limitations

The overall objective of the SPDSS Alluvial Groundwater Model is to provide a planning level tool for the alluvial aquifer system of the South Platte River and its tributaries downstream of Chatfield Reservoir that can be used to better understand and manage water resources in the basin. Since all models such as this are a simplification of complex natural systems, they should be considered an approximation of these systems. The SPDSS alluvial model provides a reasonable representation of the alluvial aquifer system at a regional scale. Given the scale and complexity of the SPDSS model, there is of course some uncertainty in many of the parameters that are used in the model. Recognizing these uncertainties and the limitations of the model is critical in application of the model and interpretation of the results. Although the model is best suited for regional-scale analysis, it can also be utilized to identify areas of refinement and to design site-specific modeling at a more local scale. In order to reduce uncertainty in the model and understand model limitations, the following factors should be considered in future model refinement and to guide more local modeling efforts.

- **Hydraulic Conductivity.** The distribution of hydraulic conductivity in the calibrated model is one realization of many potential distributions that can explain the field data. As additional data become available, these estimates should be refined. Also, since these hydraulic conductivity estimates were obtained through calibration at a regional scale, they should be revisited if the scale of the model changes.

- **Streambed Conductance.** The model has limited sensitivity to the value specified for streambed vertical hydraulic conductivity; however, as noted previously, this parameter is scale dependent. If the grid size changes, revisions to this parameter will be required, using calibration techniques. Direct estimation of this parameter using field data on vertical hydraulic conductivity of streambed materials is not possible unless very small grid cells are utilized.

- **Specific Yield.** Limited data are available on the specific yield of the aquifer, due to the small number of long-term aquifer performance tests with observation wells. One value of specific yield (0.20) was utilized for the entire model. This value appears reasonable for the majority of the aquifer but localized variability is expected. The model value should be reevaluated in a smaller scale model application and if any additional data or information becomes available.

- **Pumping Rates.** The pumping rates in the model are largely based on estimates of the consumptive use demand of crops (also referred to as irrigation water requirement), rather than direct measurements. Actual pumping rates vary and are likely to be less than needed to meet the irrigation water requirements in some cases. In the future, measured pumping records may become more readily available throughout the basin. The incorporation of these data in the model will greatly reduce the uncertainty of this parameter.

- **Ungaged Surface Water Inflows.** Estimates of ungaged surface water inflows that have been included in the modeling contain a significant amount of uncertainty. The SPDSS surface water model that is currently under development may provide better estimates of this parameter. This groundwater model input should be revisited when the surface water model is completed. Additionally, estimates of stream gains and losses as calibration targets should be refined as appropriate.

- **Tributary Surface Water Flows.** During model calibration it was discovered that there was uncertainty in the tributary surface water flows relating to diversions, return flows and ungaged surface water inflows. These all contribute to the ability to accurately represent surface water flows in these tributaries. This uncertainty should be reduced once a surface water model is developed for these tributaries as a part of ongoing SPDSS activities.

- **Reservoir Seepage.** Reservoirs whose seepage is represented in the model are often located in areas of moderately to highly permeable soils, with resultant high seepage values. There is significant uncertainty in the reservoir seepage values in the model, but improved estimates may be available once the SPDSS surface water model is completed.

- **Lateral Boundary Inflow.** Estimates of the subsurface inflow into the model due to recharge outside the model boundary are included in the model input. Given the large size of the model extent and the large inactive portion of the model grid that contributes to this parameter's magnitude, this is an important parameter with significant uncertainty. This parameter should be reevaluated with additional information, especially in the case of site-specific modeling applications.

- **Discretization.** The model is most suitable for use as a regional planning tool, and as a basis for developing refined local models. The level of spatial discretization is appropriate for a regional-scale model; however, for use in more local scale applications, a finer degree of both vertical and horizontal discretization may be appropriate.

This page intentionally left blank.

Section 6

Summary and Recommendations

6.1 Summary

A calibrated alluvial groundwater model was developed for the alluvial aquifer of the South Platte River and its key tributaries. The model area extends downstream from the foothills at Chatfield Reservoir to the Nebraska state line. The alluvial model area simulated is approximately 2,507 square miles. The groundwater model includes a detailed representation of the alluvial aquifer extent and geometry and includes the interaction with a detailed network of rivers and streams. It includes representative values for inflows at the upper reaches of each stream valley, including both surface water and alluvial groundwater.

The SPDSS Alluvial Groundwater Model was simulated using the USGS program MODFLOW-2000 (version 1.18). The model uses a uniform grid with cells 1,000 feet on each side for a total of 655 rows and 848 columns. The model was developed using a data centered approach using the data collected and developed for the SPDSS. These datasets include aquifer configuration, aquifer properties, well pumping, aquifer recharge, stream diversions, and ET discussed in Section 3. In addition, the model enhancement tools developed under Task 50 were implemented and found to correctly translate data into the appropriate model input formats. Model calibration was achieved using heuristic and automated parameter calibration methods. The results were evaluated by comparing estimated to simulated values for each major category of inflows and outflows, by comparing the water balance of inflows and outflows, and by examining the number and location of both dry and flooded model cells. The SPDSS Alluvial Groundwater Model provides reasonable results based on these evaluation criteria.

The SPDSS has significantly improved the understanding of groundwater conditions in the South Platte alluvium. Specific accomplishments include:

- Developed a detailed database that can be used as a source of information for continued use and refinement of the SPDSS and other groundwater studies
- Developed additional data centered tools for CDSS to facilitate future model updates
- Achieved a calibrated alluvial groundwater model of the South Platte alluvium that can be used for water resource planning at a regional scale
- Developed a model that can be used as a basis for localized modeling of specific tributaries or sections of the South Platte alluvium

As stated in Section 1 of this report, the SPDSS is an ongoing process. The SPDSS Alluvial Groundwater Model is a significant step forward in understanding the regional groundwater flow in the South Platte Basin. Databases and tools have been developed throughout this project that will be beneficial to water planners, scientists, engineers, and policy makers.

In summary, the SPDSS Alluvial Groundwater Model provides a foundation for future groundwater and surface water modeling efforts in the South Platte Basin. The model uses a rigorous and well documented data centered process to prepare model input files. The model preprocessors facilitate the updating of the model domain, grid, and inputs as modeling needs change and as new data become available.

6.2 Recommendations

During the development of the SPDSS, extensive groundwater data for the South Platte alluvium was collected and incorporated into the State's centralized water resources database, HydroBase. These data were used to develop and calibrate an alluvial groundwater model of the South Platte River and its key tributaries to better understand regional groundwater flow. Through this effort several items that would further enhance the understanding of regional groundwater flow and groundwater-surface water interactions in the South Platte alluvium were identified.

The following is a list of recommendations for potential future enhancements to the alluvial groundwater model that would build upon the existing knowledge and groundwater related data collected in the South Platte Basin.

- Refine the surface water inputs (e.g., estimates of ungaged surface water inflows and stream gains and losses) with results from the South Platte Basin surface water model that is currently under development.
- Develop and include a more detailed understanding of reservoir and canal seepage to the alluvial aquifer; in some areas, seepage can be very high.
- Continue to monitor water levels from the existing alluvial wells in the study area using continuously recording data-loggers when possible.
- Add additional wells and water level data to HydroBase (e.g., in the areas of the confluence of Kiowa and Bijou Creeks with the South Platte, and Pawnee Creek near Sterling), allowing for refinement of the model calibration in areas where water level data is currently unavailable.
- Continue to collect and add aquifer property data to HydroBase as it becomes available through new wells or testing of existing wells to enhance the existing hydraulic conductivity distribution in the model.
- Continue to collect well pumping data from municipal, industrial, agricultural, and augmentation wells on monthly or daily intervals for ongoing inclusion in HydroBase.
- Continue to identify publicly available groundwater data from USGS, State, and consulting reports to include in HydroBase.
- Consider periodic updates (~ 5 year intervals) of the SPDSS Alluvial Groundwater Model with the latest data to account for changes in hydrology and basin operations.

Several important insights were gained through development of the stress inputs for the SPDSS Alluvial Groundwater Model.

- Although surface water contributions to the groundwater have been developed based upon the best of available information at the time, additional detail on surface water inputs would be beneficial for calibrating streamflows, particularly in the tributaries of the South Platte.
- Historical M&I pumping data was limited, requiring estimates of the amount of water pumped from wells, additional historical pumping records for M&I wells would be beneficial to improve model calibration.
- Several unusually high decreed capacities were observed in the agricultural well data set. Additional investigation into the physical pumping rates or decreed capacities of these wells would eliminate the need to truncate agricultural well pumping at 2,000 gpm.
- When using a data centered approach, a quality control check should be made to assure that independently developed inputs are consistent. For example, the aquifer bottom elevations are developed independently of the streambed elevations, and this combined with model discretization issues can lead to inconsistencies in model elevations.

This page intentionally left blank.

Section 7
References

Anderson, M.P. and Woessner, W.W. 1992. Applied Groundwater Modeling. Academic Press, Inc. San Diego. 381 p.

Arnold, L.R., 2010, Hydrogeology and steady-state numerical simulation of groundwater flow in the Lost Creek Designated Ground Water Basin, Weld, Adams, and Arapahoe Counties, Colorado: U.S. Geological Survey Scientific Investigations Report 2010–5082, 79 p.

Arnold, L.R. 2006. USGS South Platte alluvial groundwater flow model development. Personal communication.

Banta, E.R., Paschke, S.S., and Litke, D.W. 2008. User guide and documentation for five MODFLOW ground-water modeling utility programs: U.S. Geological Survey Techniques and Methods 6–A28, 24 p.

Bishop-Brogden Associates (BBA). 2006. Upper Cherry Creek Groundwater Model. Written communication with Bruce Rindahl. August 2006.

Black & Veatch, Rick Giardina & Associates, Inc., HRS Water Consultants, Inc., Hydrosphere Resource Consultants, and Mulhern MRE, Inc., 2003, South Metro Water Supply Study Executive Summary, South Metro Water Supply Study Board, 19 p.Bjorklund and Brown. 1957. Geology and Ground-Water Resources of the Lower South Platte River Valley between Hardin Colorado, and Paxton, Nebraska. USGS Water Supply Paper 1378.

BYU (Brigham Yong University). 2005. Groundwater Modeling System (GMS), Reference Manual. Version 6.0, Brigham Young University Environmental Modeling Research Laboratory.

Burns, Alan. 1980. Hydrologic Analysis of the Proposed Badger-Beaver Creeks Artificial-Recharge Project, Morgan County, Colorado. USGS Water-Resources Investigations 80-46.

Chow, Ven Te. 1959. Open-Channel Hydraulics. Table 5-6 Values of the Roughness Coefficient n. McGraw-Hill Book Company.

Colorado Division of Wildlife (CDOW). 2003. Tamarack Recharge Project Model. Prepared in conjunction with Northern Colorado Water Conservancy District and Colorado State University. July.

Colorado Geological Survey. 2003. Ground Water Atlas of Colorado. Special Publication 53.

CFWE (Colorado Foundation for Water Education). 2004. Citizens Guide to Colorado Water Law.

CFWE (Colorado Foundation for Water Education). 2007. Citizen's Guide to Denver Basin Groundwater.

CSU (Colorado State University). 2006. Alluvial Water Accounting System (AWAS). July.

DeLorme, 2000. Colorado Atlas and Gazetteer.

Dennehy K.F., Litke D.W., Tate C.M., Heiny J.S. 1993. South Platte River Basin - Colorado, Nebraska, and Wyoming. Water Resources Bulletin 29: 647–683.

Doherty, J, 2009. Groundwater Data Utilities. Watermark Numerical Computing. February.

Doherty, J. 2001. Improved calculation for dewatered cells in MODFLOW, Ground Water, V. 39, No. 6, Pp 863 - 869

Duke, H. R. and Longenbaugh, R. A. 1966. Evaluation of Water Resources in Kiowa and Bijou Creek Basins, Colorado. Prepared by Colorado State University for the Colorado Water Conservation Board. May.

DWR (Division of Water Resources). 2013. Colorado Division of Water Resources. Colorado Ground Water Commission Home (Designated Basins). http://water.state.co.us/groundwater/CGWC/Pages/default.aspx. Accessed March 2013.

DWR. 2007a. Well Regulation in the South Platte River Basin of Colorado. South Platte Task Force Briefing Document, June. http://www.ag.state.co.us/SouthPlatteTF.html. Downloaded August 2007.

________. 2007b. History of Water Rights in Colorado. http://water.state.co.us/org/History.asp. Downloaded in March 2007.

________. 2006. HydroBase. August 24, 2006.Engineering Professionals, Inc. 1987. Manning's N-Value Report-Floodplain Information and Drainage Plan for St. Vrain Creek and North St. Vrain Creek. July 1987.

Fetter, C.W. 2001. Applied Hydrogeology, Fourth Edition. Prentice-Hall, Inc. Upper Saddle River, New Jersey.

Freeze, Allan R., Cherry, John A. 1979. Groundwater. Prentice-Hall, Inc. Englewood Cliffs, New Jersey.

Gingery Associates, Inc. 1980. Spring Creek Major Drainageway Planning Study Manning's N-Value Report. February.

_______. 1979. Hydraulic Roughness Value Analysis-Manning's N-Dry Creek. August.

Halford, K.J. and Hanson R.T., 2002, User Guide for the Drawdown-Limited, Multi-Node Well (MNW) Package for the U.S. Geological Survey's Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, Versions MODFLOW-96 and MODFLOW-2000. U.S. Geological Survey Open-File Report 02-293, 33 p.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G. 2000. MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- User guide to modularization concepts and the Ground-Water Flow Process. USGS Open-File Report 00-92.

Hill, M.P. 1990. Preconditioned Conjugate-gradient 2 (PCG2), a computer program for solving ground-water flow equations. USGS Water-Resources Investigations Report 90-4048.

Hurr, R.T., Schneider Jr. P.A., Minges D.R. 1975. Hydrology of the South Platte River Valley, Northeastern Colorado. Colorado Water Resources Circular 28. Colorado Water Conservation Board, Denver, CO.

Hurr, R.T. and Schneider, P. 1972a. Hydrogeologic Characteristics of the Valley Fill Aquifer in the Brighton Reach of the South Platte River Valley, Colorado. USGS Open File Report 72-332.

_______. 1972b. Hydrogeologic Characteristics of the Valley Fill Aquifer in the Greeley Reach of the South Platte River Valley, Colorado. USGS Open File Report 73-124.

_______. 1972c. Hydrogeologic Characteristics of the Valley Fill Aquifer in the Weldona Reach of the South Platte River Valley, Colorado. USGS Open File Report 73-127.

_______. 1972d. Hydrogeologic Characteristics of the Valley Fill Aquifer in the Brush Reach of the South Platte River Valley, Colorado. USGS Open File Report 73-123.

_______. 1972e. Hydrogeologic Characteristics of the Valley Fill Aquifer in the Sterling Reach of the South Platte River Valley, Colorado. USGS Open File Report 73-126.

_______. 1972f. Hydrogeologic Characteristics of the Valley Fill Aquifer in the Julesburg Reach of the South Platte River Valley, Colorado. USGS Open File Report 73-125.

HRS Water Consultants, Inc. 2003. SACWSD Ground Water Model Documentation. Prepared for South Adams County Water and Sanitation District (SACWSD). December.

HRS Water Consultants, Inc. 1995. Lost Creek Ground Water Model. Written Communication with Bard Ford of HRS Water Consultants, Inc. on March 2005.

Mehl, S. and Hill. M. 2010. Grid-size dependence of Cauchy boundary conditions used to simulate stream-aquifer interaction. Advances in Water Resources. vol 33, pp 430 – 442.

Niswonger, R.G. and Prudic, D.E., 2006. Documentation of the Streamflow-Routing (SFR2) Package to include unsaturated flow beneath streams--A modification to SFR1. USGS Techniques and Methods, Book 6, Chap. A13.

Prudic, David E. 1989. Documentation of a Computer Program to Simulate Stream-Aquifer Relations Using a Modular, Finite-Difference, Ground-Water Flow Model. Table 1 Experimental values of Manning's roughness coefficient. USGS Open-File Report 88-729.

Prudic, David E., Konikow, Leonard F., and Banta, Edward R. 2004. A New Streamflow-Routing (SFR1) Package to Simulate Stream-Aquifer Interaction with MODFLOW-2000. USGS Open-File Report 2004-1042.

RGDSS (Rio Grande Decision Support System). 2003. RGDSS Ground Water, Task 36 – State Pre-Processor Modifications. Prepared for CWCB and DWR by HRS. February 19.

Robson, S.G. 1996. Geohydrology of the shallow aquifers in the Denver metropolitan area, Colorado. U.S. Geological Survey Hydrologic Investigations Atlas HA-736.

Robson, S.G., Heiny, J.S. and Arnold, L.R. 2000a. Geohydrology of the Shallow Aquifers in the Greeley-Nunn area, Colorado. USGS Hydrologic Investigations Atlas HA-746A.

_______. 2000b. Geohydrology of the Shallow Aquifers in the Fort Collins-Loveland area, Colorado. USGS Hydrologic Investigations Atlas HA-746B.

_______. 2000c. Geohydrology of the Shallow Aquifers in the Fort Lupton-Gilcrest area, Colorado. USGS Hydrologic Investigations Atlas HA-746C.

_______. 2000d, Geohydrology of the Shallow Aquifers in the Boulder-Longmont area, Colorado. USGS Hydrologic Investigations Atlas HA-746D.

Rocky Mountain Consultants (RMC). 1990. Groundwater Investigations--Thornton Northern Water Supply Project, Draft Report, Prepared for City of Thornton.

Soil Conservation Service. 1982. Documentation for Selection of Manning's Roughness Coefficient for Boxelder Floodplain Management Study. August.

SPDSS (South Platte Decision Support System). 2010. SPDSS Historic Crop Consumptive Use Analysis. Prepared by LRE for the Colorado Water Conservation Board and Colorado Division of Water Resources. March 2010.

_______.2008. SPDSS Phase 4 Task 48.2 Development of Calibration Targets and Criteria Technical Memorandum. Prepared for CWCB and DWR by CDM Smith (formerly Camp Dresser & McKee Inc.). October.

_______. 2008b. SPDSS Ground Water Component Phase 3, Task 48 Alluvial Groundwater Modeling Report – Draft Final. Prepared for the CWCB and DWR by CDM Smith. January.

_______. 2008c. SPDSS Ground Water Component Phase 4, Task 46 Stream Gain/Loss Estimates Technical Memorandum. Prepared for the CWCB and DWR by CDM Smith. April.

_______. 2008d. Task 56 Conveyance and Application Efficiencies Technical Memorandum. Prepared for the CWCB and DWR by LRE. March.

_______. 2008e. SPDSS Phase 4 Task 39 Water Level Measurement Technical Memorandum. Prepared for the CWCB and DWR by CDM Smith. May 20, 2008.

_______. 2007a. SPDSS Ground Water Component Phase 3, Task 50.4 Denver Basin Region Aquifer Property Technical Memorandum. Prepared for the CWCB and DWR by CDM Smith. February.

_______. 2007b. SPDSS Task 65 Estimating South Platte Phreatophyte Groundwater Evapotranspiration. Prepared for the CWCB and DWR by D. Groeneveld, D. and M. Prescott. January 30, 2007.

_______. 2007c. SPDSS. Key Diversion Structures Task 3 Technical Memorandum. Prepared for the CWCB and DWR by LRE. May 2007.

_______. 2006a. SPDSS Ground Water Component Phase 2, Task 42.2 Denver Basin Region Aquifer Configuration Technical Memorandum. Prepared for the CWCB and DWR by CDM Smith. February.

_______. 2006b. SPDSS Ground Water Component Phase 3, Task 42.3 South Platte Alluvium Region Aquifer Configuration Technical Memorandum. Prepared for the CWCB and DWR by CDM Smith. November.

_______. 2006c. SPDSS Ground Water Component Phase 2, Task 43.2 Denver Basin Region Aquifer Property Technical Memorandum. Prepared for the CWCB and DWR by CDM Smith. February.

_______. 2006d. SPDSS Ground Water Component Phase 3, Task 43.3 South Platte Alluvium Region Aquifer Property Technical Memorandum. Prepared for the CWCB and DWR by CDM Smith. December.

_______. 2006e. SPDSS Ground Water Component Phase 3, Task 44.2 Denver Basin Bedrock Water Level Technical Memorandum. Prepared for the CWCB and DWR by CDM Smith. November.

_______. 2006f. SPDSS Ground Water Component Phase 3, Task 44.3 South Platte Alluvium Region Water Level Technical Memorandum. Prepared for the CWCB and DWR by CDM Smith. November.

_______. 2006g. SPDSS Groundwater Component, Phase 3, Task 34 Streambed Conductance Testing. Prepared for the CWCB and DWR by CDM Smith. June 9, 2006.

_______. 2006h. SPDSS Task 5 Key Reservoirs Technical Memorandum. Prepared for the CWCB and DWR by LRE. December 19, 2006.

_______. 2006i. SPDSS Task 53.3 Assign Key Climate Information to Irrigated Acreage and Reservoirs. Prepared for the CWCB and DWR by LRE. February 1, 2006.

_______. 2001. South Platte Decision Support System Feasibility Study. Prepared for the CWCB and DWR by Brown and Caldwell, CDM Smith, Leonard Rice Consulting Water Engineers, and Riverside Technology. October.

URS. 2003. Cherry Creek to Scott Road Reservoir HEC Model. Prepared for the Urban Drainage and Flood Control District. May 2003.

UDFCD (Urban Drainage and Flood Control District). 2001. Box Elder Creek HEC Model. Box Elder Floodplain Future. Wright Water Engineers. September.

United States Geological Survey (USGS), 2011. Groundwater availability of the Denver Basin aquifer system, Colorado: U.S. Geological Survey Professional Paper 1770. Suzanne Paschke ed. 274 p.

USGS. 2001. USGS 30-meter National Elevation Dataset. http://ned.usgs.gov/ The NED raster was obtained by the CWCB and combined into one Raster for the State of Colorado in 2001.

This page intentionally left blank.

Table 1-1. SPDSS Technical Memoranda and Reference Table

SPDSS Technical Memorandum	Purpose of Technical Memo and Use in Model Development	Section of South Platte DSS Report where information is mentioned or summarized
South Platte Decision Support System Feasibility Study	The South Platte Decision Support System Feasibility Study reviewed the data and feasibility of developing a Decision Support System for the South Platte Basin. It also established goals for the development of the SPDSS.	Section 1 and 2
Historic Crop Consumptive Use Analysis South Platte Decision Support System Final Report	The Consumptive Use Analysis developed a model (Consumptive Use Model) which is used to calculate the Irrigation Water Requirement and subsequent groundwater use. The groundwater use is distributed to wells based on their decreed pumping rates and assigned parcels.	Sections 2, 3 and 5 Appendix B, C and H
Task 2 Identify Key Streamflow Gages and Estimate Streamflows for Missing Records	Identified key streamflow gages to be used for specifying surface water inflow to the groundwater model. Gages with missing records will be filled to generate a complete dataset for the entire period of record.	Sections 2, 3 and 4 Appendix E, F and G
Task 3 Aggregate Non-Key Agricultural Diversion Structures	Identified the aggregate non-key agricultural diversion structures to be included in the groundwater model. Diversions from the river are simulated in the groundwater model via the MODFLOW SFR2 package. The datasets developed in this technical memorandum are used to explicitly define the surface water diversions in the groundwater model.	Sections 2, 3 and 4 Appendix F and G
Task 3 Summary Key Diversion Structures	Identified the key diversion structures to be included in the groundwater model. Diversions from the river are simulated in the groundwater model via the MODFLOW SFR2 package. The datasets developed in this technical memorandum are used to explicitly define the surface water diversions in the groundwater model.	Sections 2, 3 and 4 Appendix E, F and G
Task 5 Identify Key Reservoirs	Identified key reservoirs in the South Platte Basin. The listing of key reservoirs was used to identify the reservoirs to be explicitly included in the model.	Sections 2 and 3 Appendix D
Task 7.2 Well Use and Well Augmentation Plans	Identified modifications to be made to the data used in Consumptive Use Model based on review of augmentation plans for well-parcel combinations.	Section 3 Appendix R
Task 33.2 Field Study Work Plan for Testing and Water Level Measurement	Developed a work plan for installing wells, performing aquifer tests and installing water level data loggers. Wells were sited to fill data gaps for aquifer property and water level data to be used for assessing groundwater in the South Platte Alluvium region and model calibration.	Section 3 Appendix G

Table 1-1. SPDSS Technical Memoranda and Reference Table

SPDSS Technical Memorandum	Purpose of Technical Memo and Use in Model Development	Section of South Platte DSS Report where information is mentioned or summarized
Task 34 Streambed Conductance Testing	Collected the data needed to quantify the groundwater flux across the streambed in the South Platte River and key tributaries. The information collected in this study was used as initial values for streambed hydraulic conductivity and used as a guide during groundwater model calibration.	Section 3, 4 and 5 Appendix G
Task 35 Alluvial Well Construction and Testing	Drilled new alluvial wells in the South Platte Alluvium to collect additional aquifer property and water level data for the groundwater model.	Section 3 Appendix A
Task 37.2 Aquifer Pumping Tests	Performed aquifer pump tests on existing wells to obtain additional aquifer property data in areas where there are data gaps.	Section 3 Appendix A
Task 39 Water Level Measurement Technical Memorandum	This task collected water level data in the South Platte Alluvium Region. Water level data was collected form existing wells as well as wells installed and equipped with water level data loggers as part of the SPDSS under Task 37. This data is summarized in Task 44 and used for model calibration in Task 48.	Sections 2, 3 and 4 Appendix A, L and M
Task 41.3 Estimation of Municipal and Industrial Pumping in the South Platte Alluvium Region	This task collected, analyzed and developed estimates for municipal and industrial pumping in the South Platte Alluvium Region. The data from this task was used to define the municipal and industrial groundwater pumping in the groundwater model.	Sections 3 and 4 Appendix C
Task 42.3 South Platte Alluvium Region Aquifer Configuration Technical Memorandum	Collected, analyzed and summarized the publically available aquifer configuration for the South Platte Alluvium Region. The aquifer configuration data collected under this task was used to define the aquifer top and bottom elevations using a data centered approach.	Sections 2, 3 and 4 Appendix A
Task 43.3 South Platte Alluvium Region Aquifer Property Technical Memorandum	Collected, analyzed and summarized the publically available aquifer property data in the South Platte Alluvium Region. This data was used to develop the initial hydraulic conductivity distribution in the active model domain and define the pilot points used during the groundwater model calibration.	Sections 2, 3 and 4 Appendix A
Task 44.3 South Platte Alluvium Region Water Level Technical Memorandum	Collected, analyzed and summarized the publically available water level data in the South Platte Alluvium Region. Data collected under this task was used to assess aquifer water table, saturated thickness and water level measurements were used for groundwater model calibration.	Sections 2, 3 and 4 Appendix A, L and M

Table 1-1. SPDSS Technical Memoranda and Reference Table

SPDSS Technical Memorandum	Purpose of Technical Memo and Use in Model Development	Section of South Platte DSS Report where information is mentioned or summarized
Task 46.2 Stream Gain/Loss Estimates	Developed estimates of stream gains and losses from groundwater in the main stem of the South Platte River and its tributaries within the study area to be used to help calibrate the SPDSS Alluvial Groundwater Model.	Sections 2, 3 and 4 Appendix E
Task 48.2 Development of Calibration Targets and Criteria Technical Memorandum	Developed and established the calibration targets and criteria to be used in for the calibration of SPDSS Alluvial Groundwater Model.	Sections 4 and 6 Appendix L
Task 50.1 Review of Existing Approaches to Development of a Data Centered Approach for the SPDSS Groundwater Component	This task reviewed the data centered modeling process implemented by the Rio Grande Decision Support System (RGDSS) and identified candidate graphical user interface (GUI) tools for screening and selection in subsequent Task 50 phases. The evaluation focused on groundwater processes, since surface water and consumptive use-related processes are well developed and currently meet the State's needs.	Sections 2, 3 and 4 Appendix J
Task 50.2 Definition of Requirements for an Enhanced Data Centered Modeling Process for the SPDSS Groundwater Component	This task defined and prioritized potential enhancements to the data centered modeling process in relation to the groundwater model. This included identification of data types used in the modeling, where the data reside, a discussion of current processes to move data from the source repository to the models and an identification and prioritization of enhancements. This task also identified needed output types for model development and future model use, as well as prioritizing development activities needed to provide these outputs. Recommendations for a primary GUI were provided, along with recommended tools and processes for implementation in the SPDSS.	Sections 2, 3 and 4 Appendix J
Task 50.3 Implementation Scope of Work for an Enhanced Data Centered Modeling Process for the SPDSS Groundwater Component	This task provided a scope of work for implementing high priority enhancements. The highest priority tasks were selected for implementation. These selected development tasks focused on the elements of the data centered process required during model development activities to be conducted under Task 48.	Sections 2, 3 and 4 Appendix J

Table 1-1. SPDSS Technical Memoranda and Reference Table

SPDSS Technical Memorandum	Purpose of Technical Memo and Use in Model Development	Section of South Platte DSS Report where information is mentioned or summarized
Task 50.4 Technical Memorandum Data Centered Groundwater Modeling Enhancements	This task expands on the data centered approach defines processes and tools that facilitate a linkage between data sources, such as HydroBase and State GIS files, and a numerical groundwater model. This approach facilitates rapid updating of numerical models when changes to underlying data sets occur, model simulation periods change, or additional processes need to be incorporated.	Sections 2, 3 and 4 Appendix J
Task 53.2 Collect and Fill Missing Monthly Climate Data	Collected and filled in missing climate data to be used in the SPDSS modeling efforts. Climate stations were identified and selected to represent the temperature and precipitation in the SPDSS area for modeling. There are several models in the SPDSS which require temperature and/or precipitation data: Consumptive Use Model, Groundwater Model, Surface Water Model and Water Budget Model.	Section 3 Appendix B
Task 53.3 Assign Key Climate Information to Irrigated Acreage and Reservoirs	Assigned key climate stations to geographic areas for the SPDSS modeling efforts according to data identified in Task 53.2. Selected climate stations we used to develop the temperature and precipitation data used in the Consumptive Use Model (used to determine agricultural well pumping in the groundwater model) and the precipitation datasets used to determine the recharge in the groundwater model.	Section 3 Appendix B
Task 64 Review and Develop Precipitation Recharge Estimates	Developed an approach to estimate precipitation recharge for use in the Denver Basin and South Platte Alluvial groundwater models based on key climate stations identified in Task 53.	Section 3 Appendix B
Task 65 Estimating South Platte Phreatophyte Groundwater Evaporation	Identified areas in the South Platte Basin where phreatophyte groundwater evaporation occurs and developed an ET by depth to water relationship to be used in the groundwater model	Sections 3 and 4 Appendix L and M
Task 96 River Network and Key Structure Location Products	Identified the river network and key structures to be used in the groundwater model. This defines the locations of rivers, streams, and tributaries to be included in the groundwater model within the model domain. In addition, this memo defines the location of key structures to be modeled on the rivers within the model domain.	Sections 2 and 3 Appendix L and M

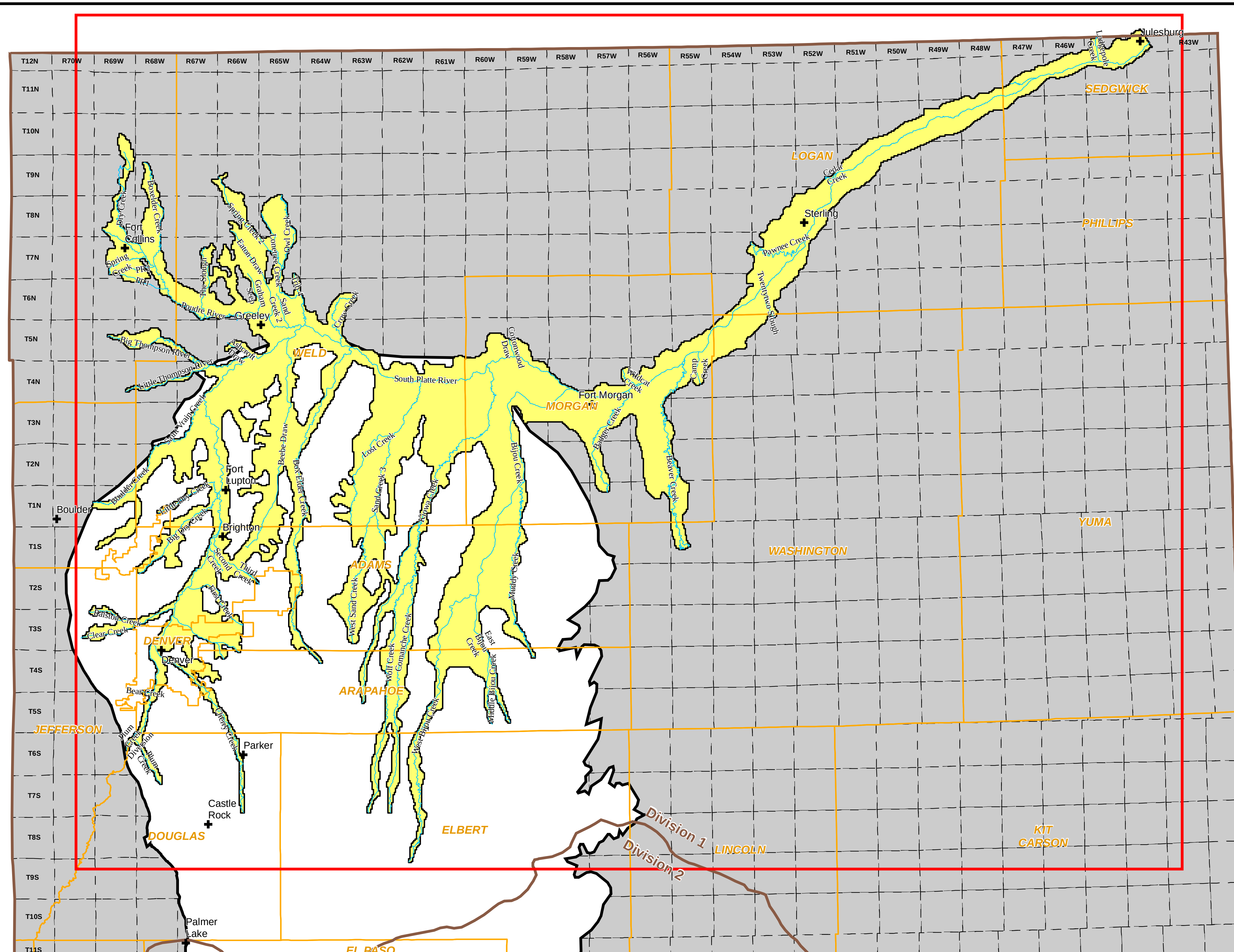
SPDSS Alluvial Groundwater Model Report

Figure 3-1: Model Domain

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

- City
- Stream
- County
- Alluvial Aquifer Extent
- Denver Basin Extent
- Township
- Model Grid Active Area
- Model Grid Outline

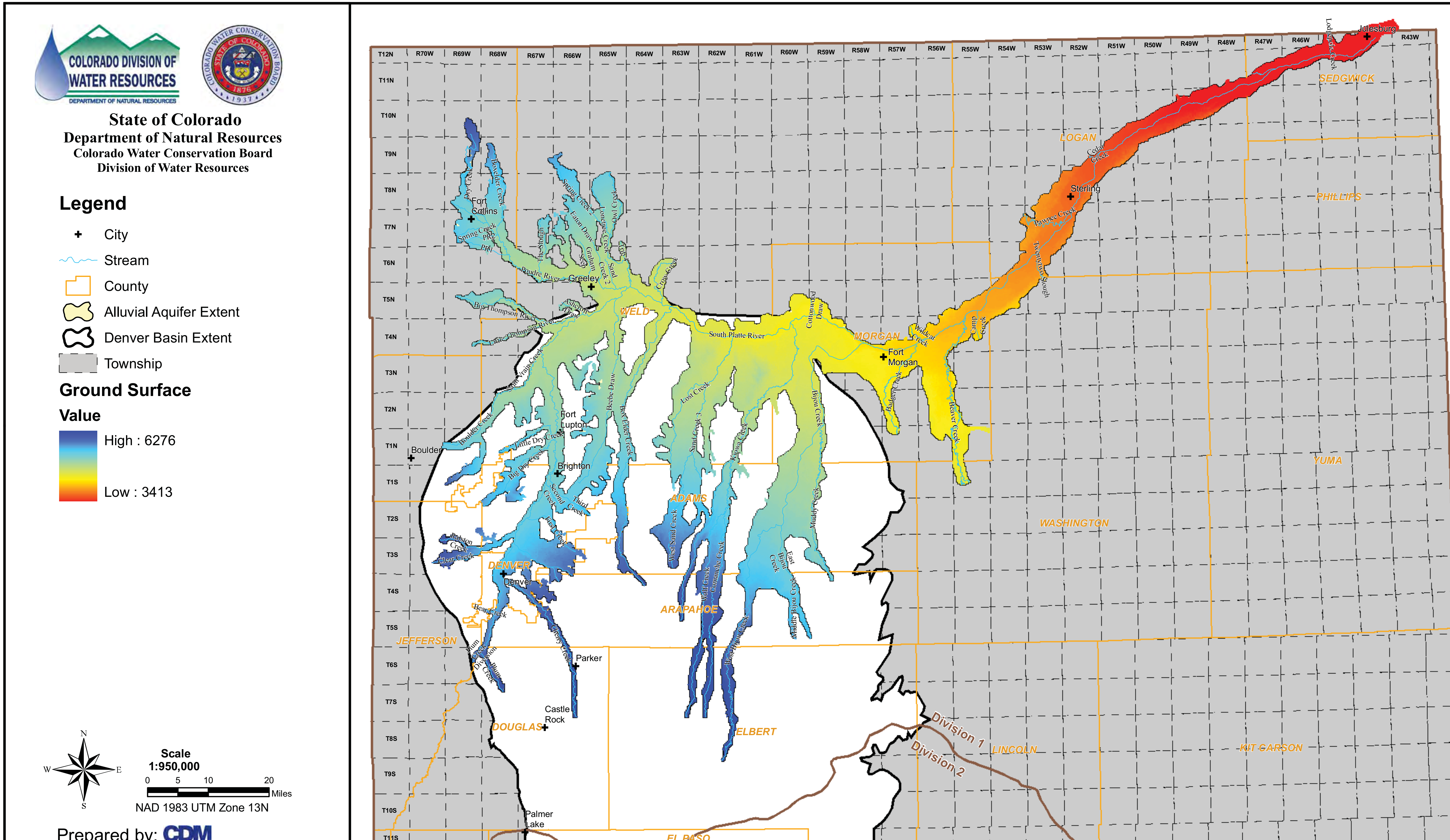


Scale
1:950,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 3-2: Top (Ground Surface)



SPDSS Alluvial Groundwater Model Report

Figure 3-3: Bottom Elevation

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

- City
- Stream
- County
- Alluvial Aquifer Extent
- Denver Basin Extent
- Township

Bottom

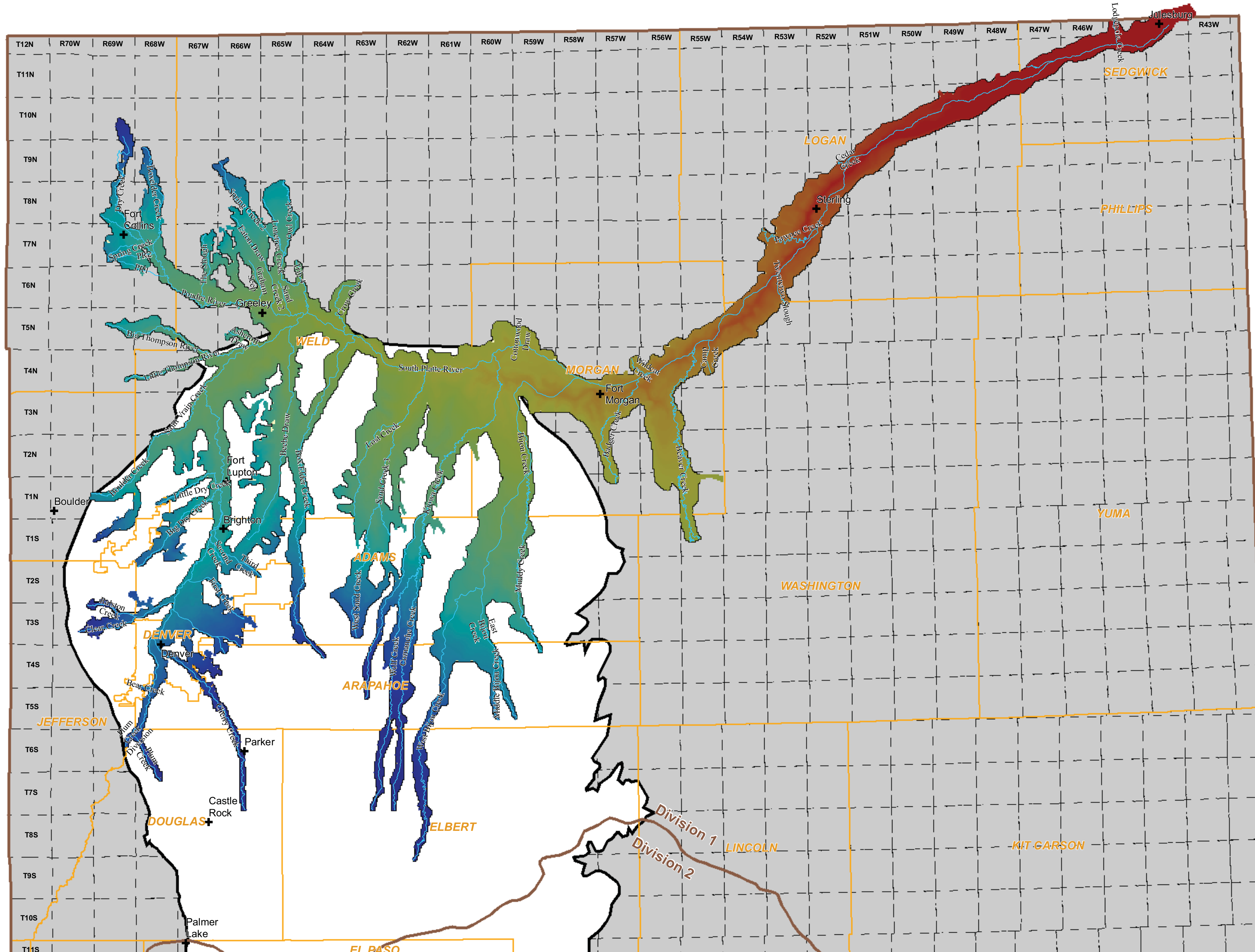
Value

High : 6228

Low : 3235

Scale
1:950,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM



SPDSS Alluvial Groundwater Model Report

Figure 3-4: Initial Heads

COLORADO DIVISION OF WATER RESOURCES
DEPARTMENT OF NATURAL RESOURCES

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

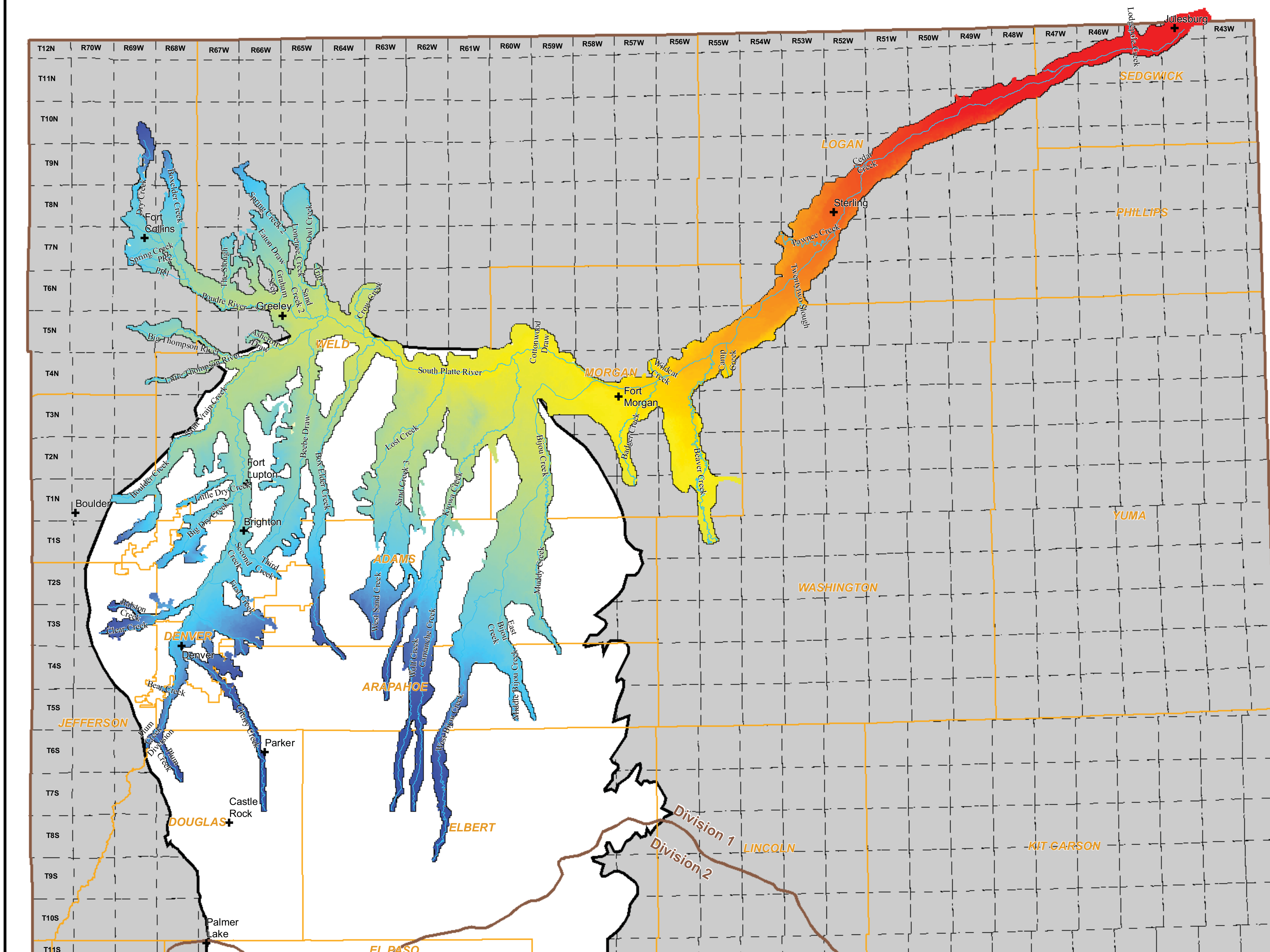
- City
- Stream
- County
- Alluvial Aquifer Extent
- Denver Basin Extent
- Township

Initial Heads

Value

High : 6276

Low : 3413



N
W
E
S

Scale
1:950,000

0 5 10 20 Miles

NAD 1983 UTM Zone 13N

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 3-5: Boundary Conditions - Alluvial Aquifer Inflows

COLORADO DIVISION OF WATER RESOURCES
DEPARTMENT OF NATURAL RESOURCES

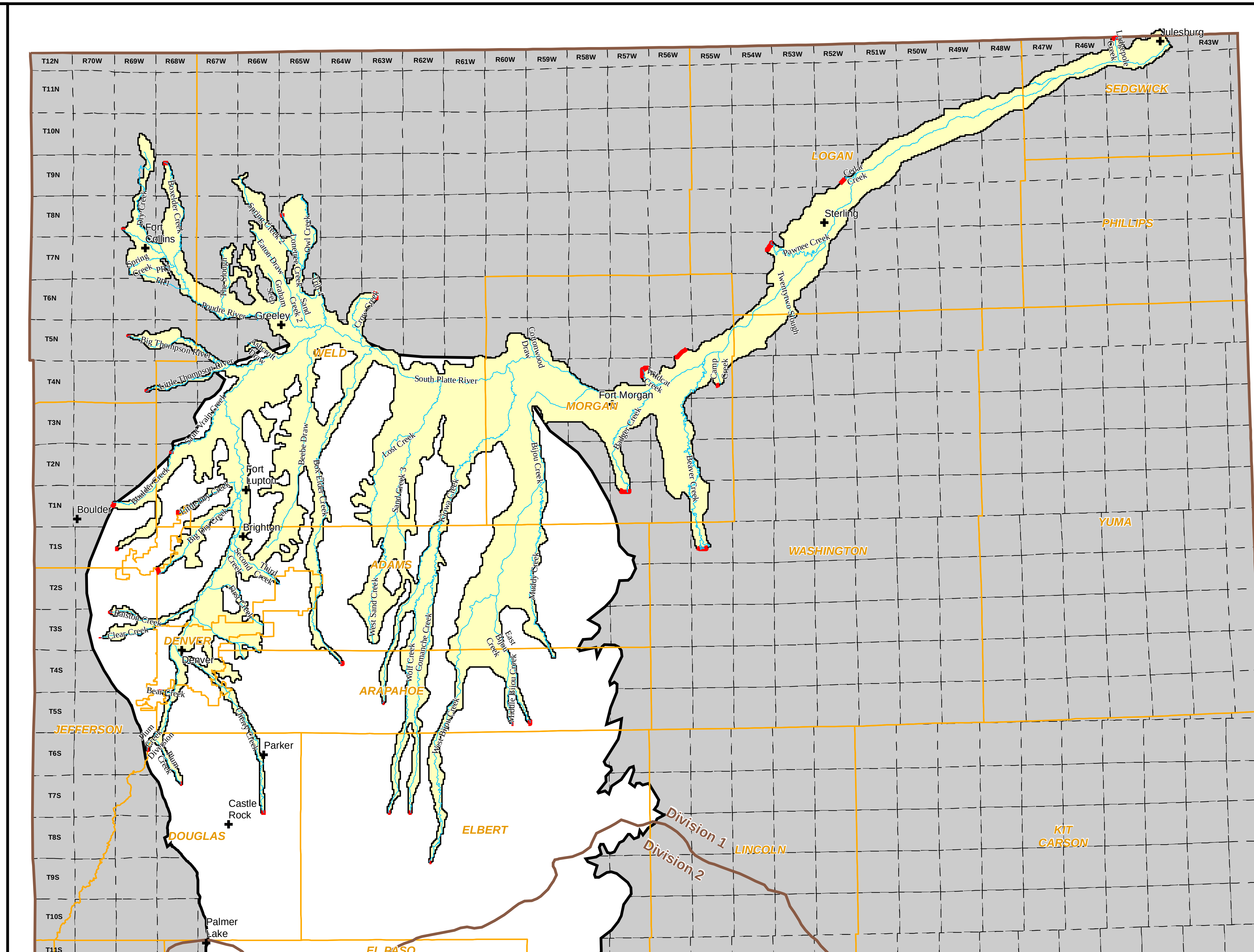
State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

- ✚ City
- Stream
- County
- Alluvial Aquifer Extent
- Denver Basin Extent
- Township
- Boundary Condition

Scale 1:950,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM



N
W E
S

SPDSS Alluvial Groundwater Model Report

Figure 3-6: Bedrock Flux

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

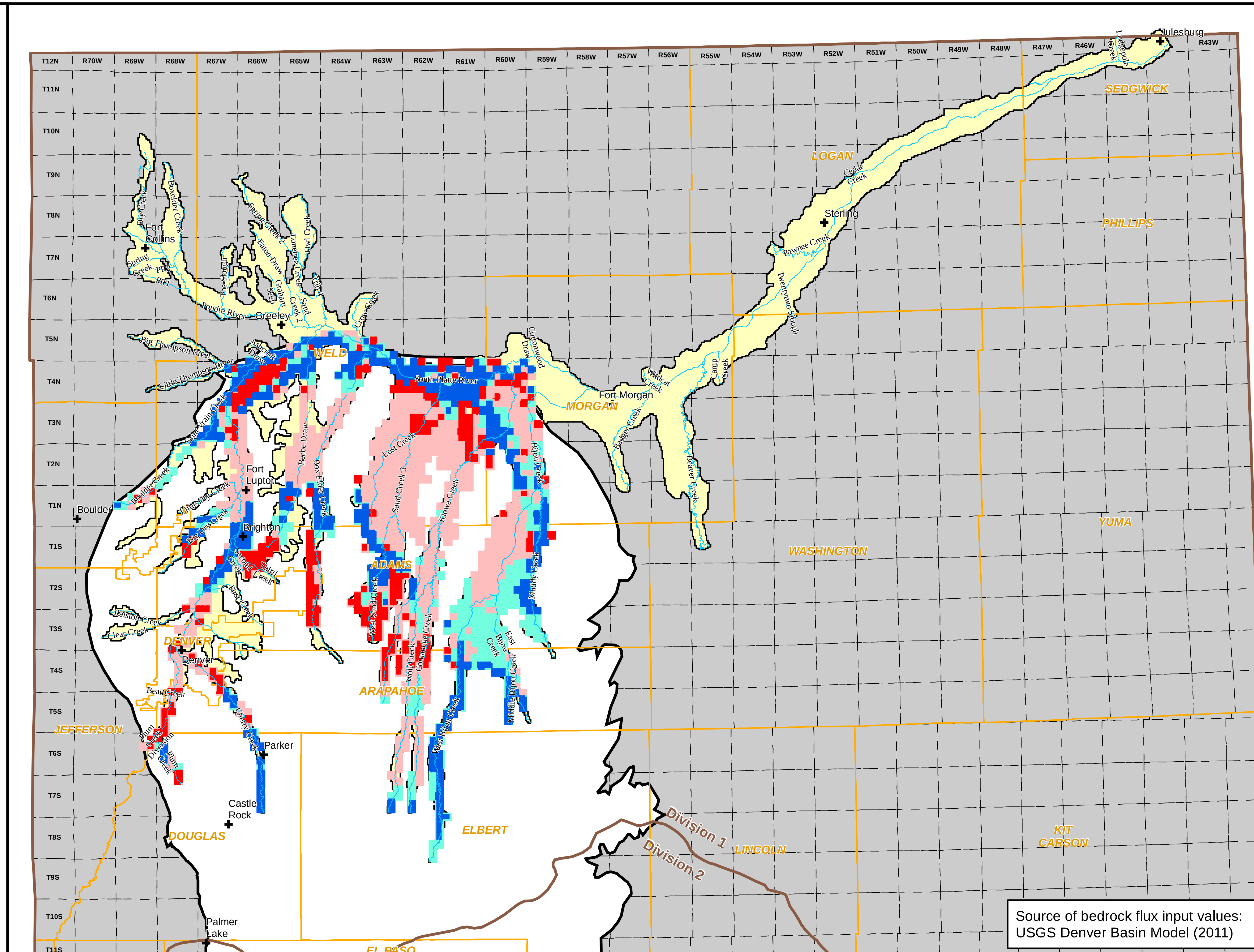
- City
- Stream
- County
- Alluvial Aquifer Extent
- Denver Basin Extent
- Township

Bedrock Aquifer Flux (cfs)

- < -0.00025 (out of alluvium)
- -0.00025 - 0.00000 (out of alluvium)
- 0.00000 - 0.00025 (into alluvium)
- > 0.00025 (into alluvium)

Scale
1:950,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM



SPDSS Alluvial Groundwater Model Report

Figure 3-7: Initial Hydraulic Conductivity (K) Distribution

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

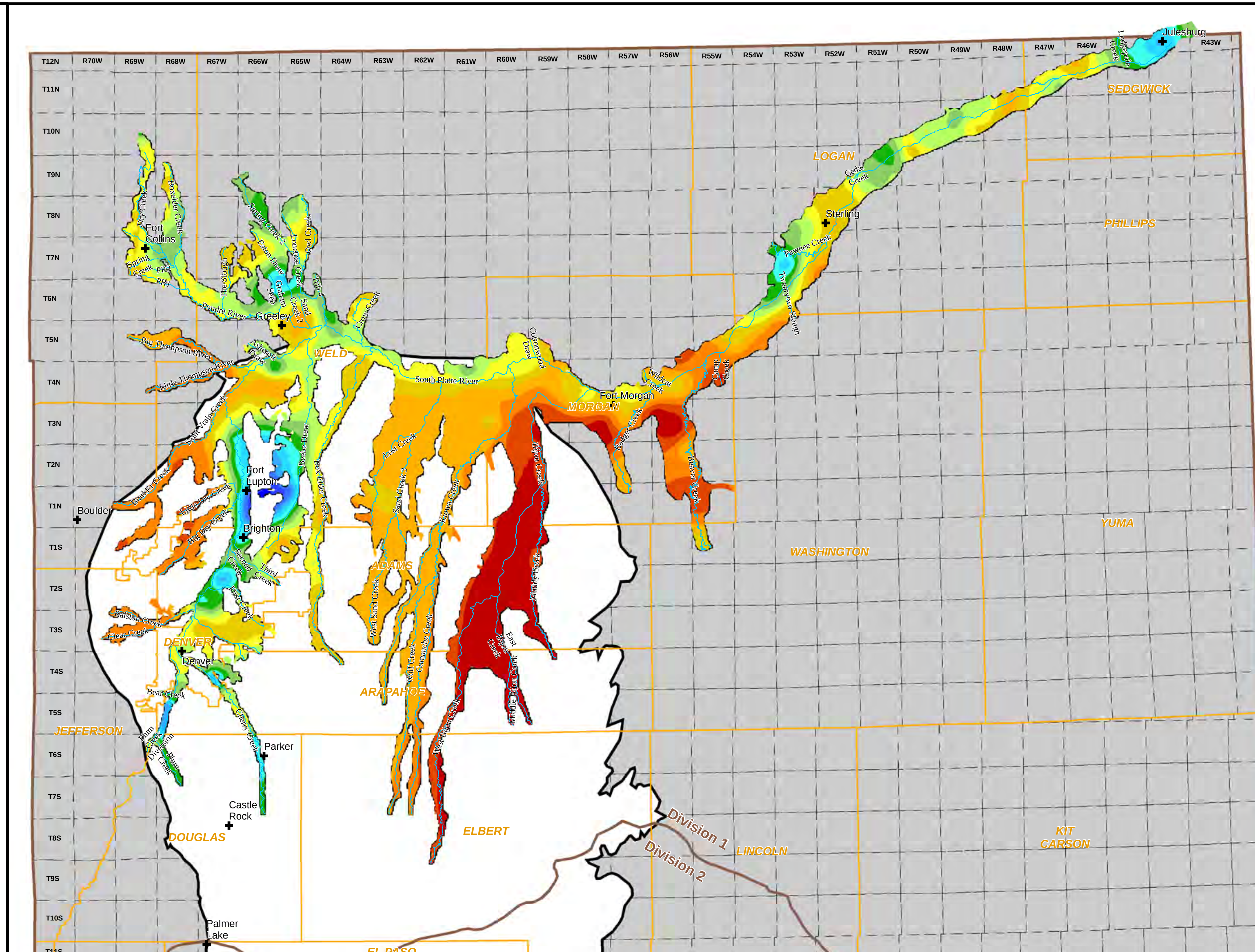
- City
- Stream
- County
- Alluvial Aquifer Extent
- Denver Basin Extent
- Township

Hydraulic Conductivity (ft/day)

- < 150
- 150 - 200
- 200 - 250
- 250 - 300
- 300 - 350
- 350 - 400
- 400 - 450
- 450 - 500
- 500 - 550
- 550 - 600
- 600 - 650
- 650 - 700
- 700 - 750
- 750 - 800
- 800 - 900

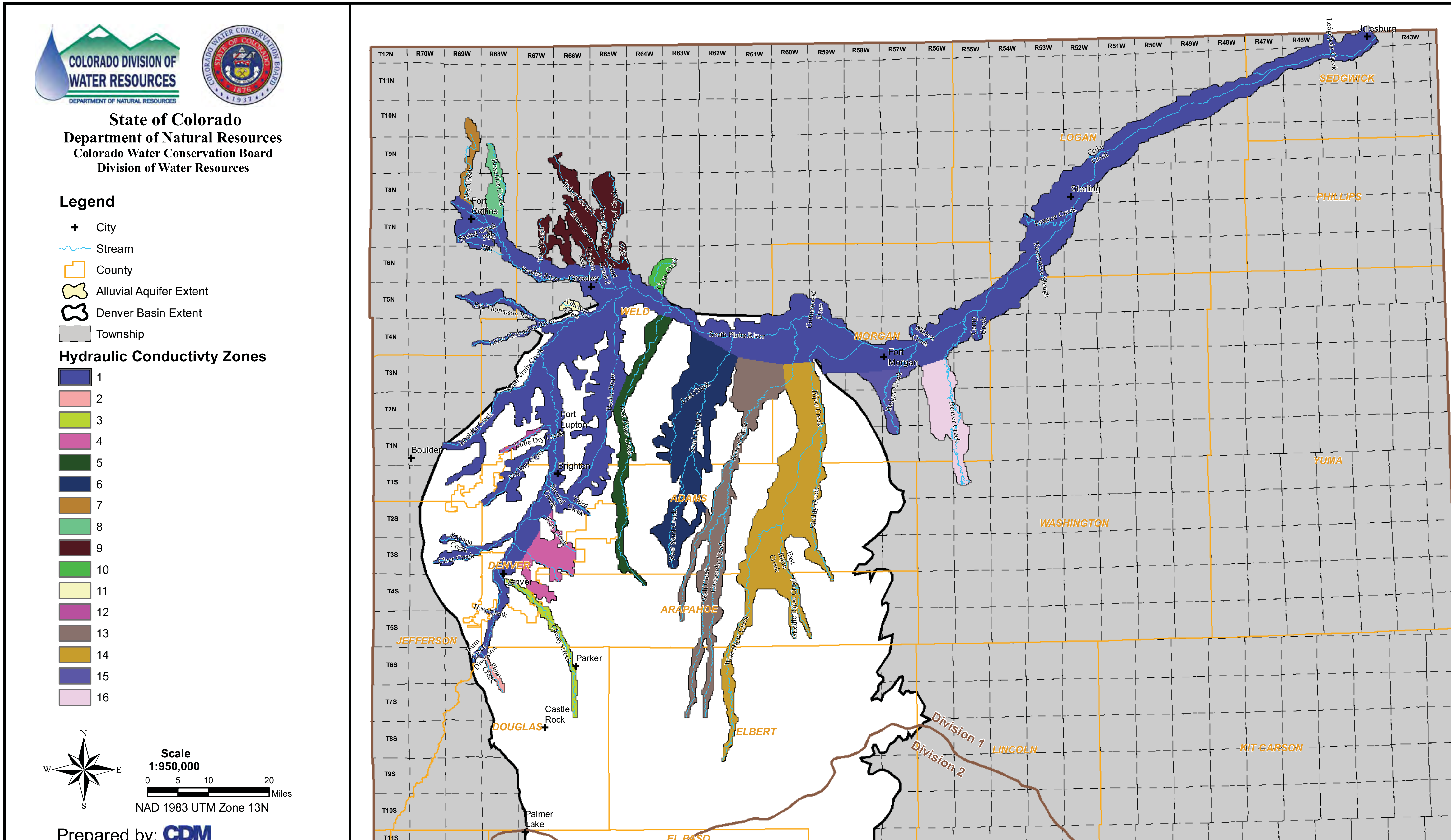
Scale
1:950,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM



SPDSS Alluvial Groundwater Model Report

Figure 3-8: Zones for Hydraulic Conductivity Interpolation



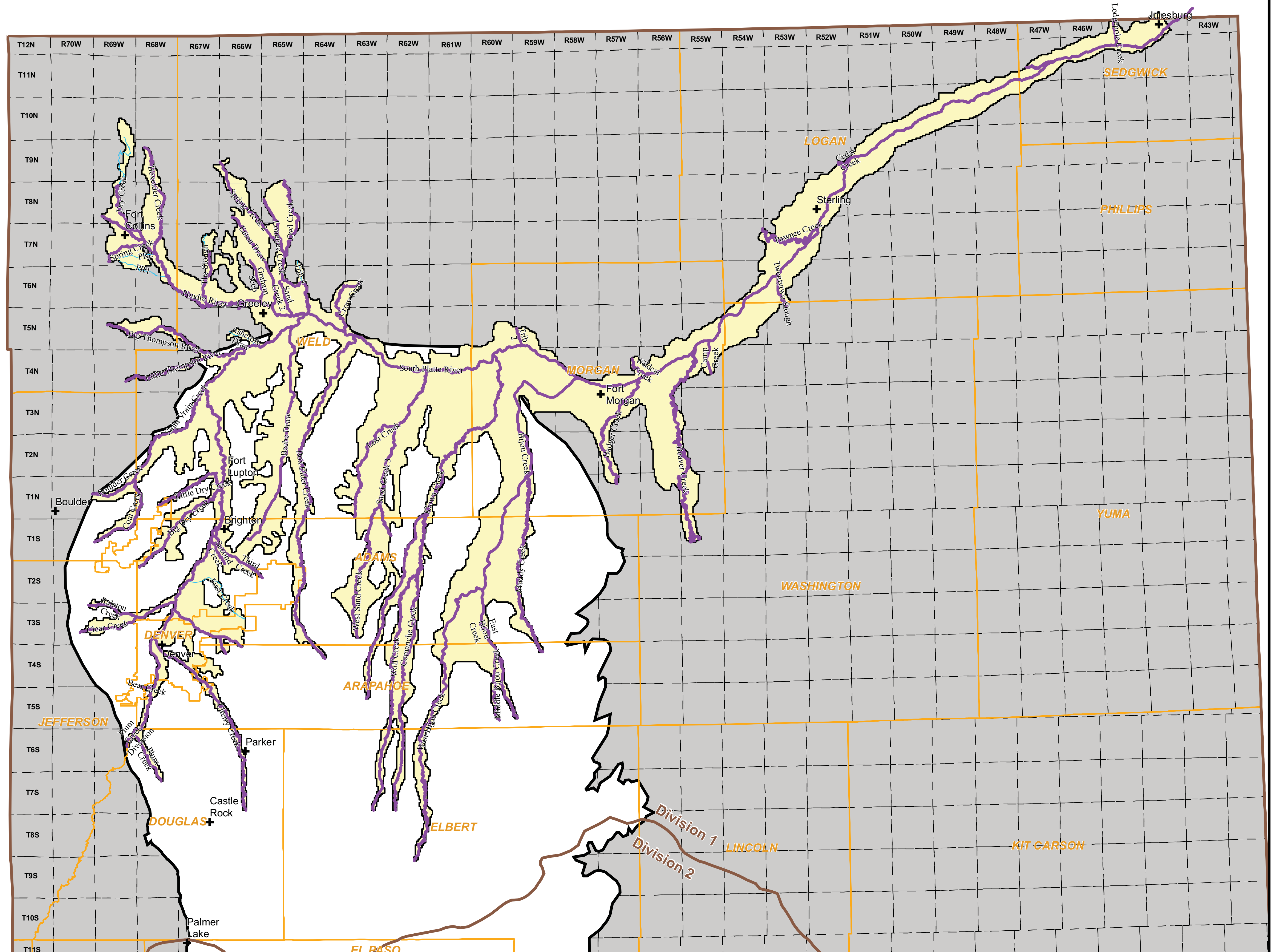
SPDSS Alluvial Groundwater Model Report

Figure 3-9: SFR Stream Network

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

- ✚ City
- SFR Stream
- Stream
- County
- Alluvial Aquifer Extent
- Denver Basin Extent
- Township



Scale
1:950,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM

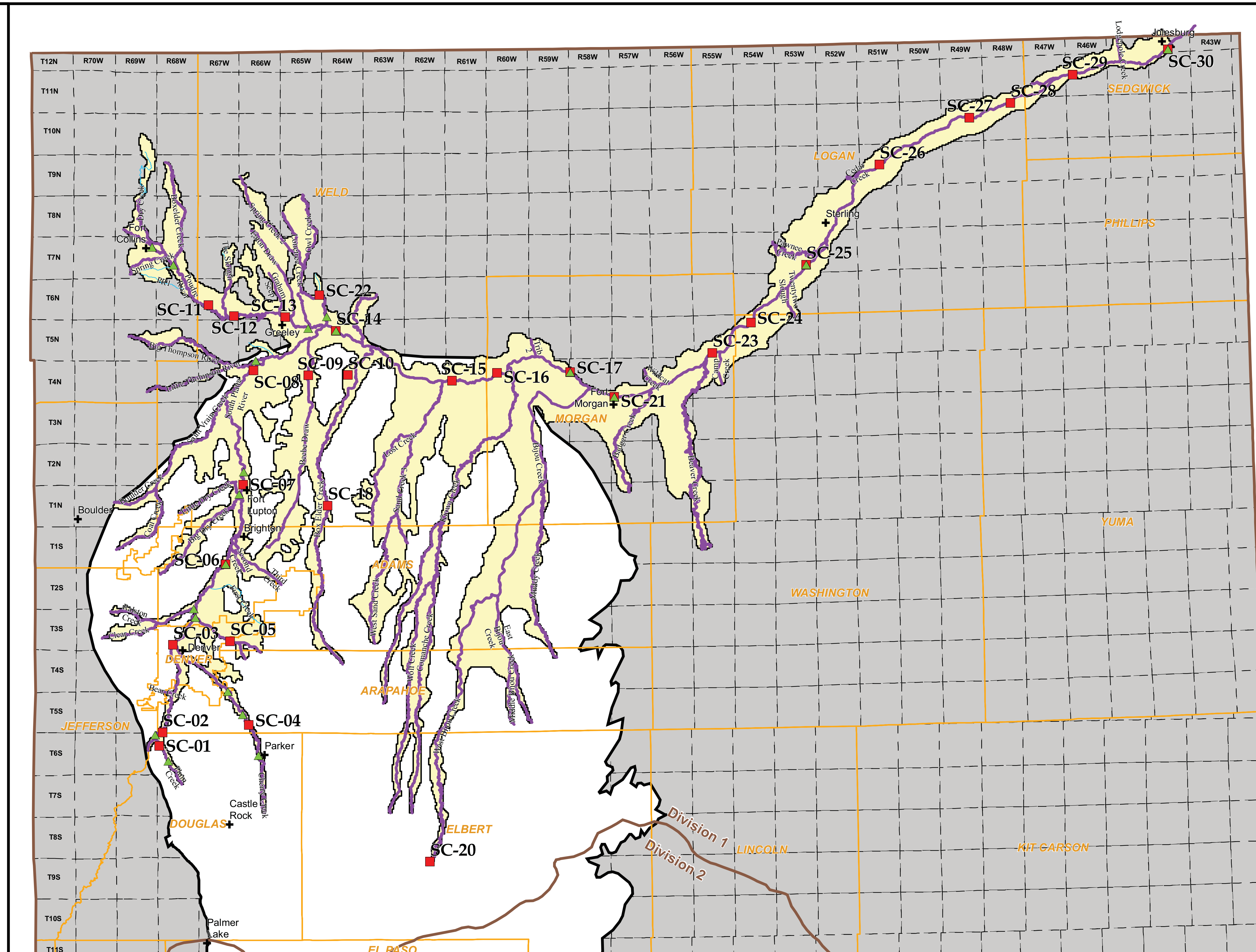
SPDSS Alluvial Groundwater Model Report

Figure 3-10: SFR Stream Network with Task 34 Test and Streamflow Gage Locations

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

- City
- Stream
- County
- Alluvial Aquifer Extent
- Denver Basin Extent
- Township
- Task 34 Test
- Streamflow Gage
- SFR Stream

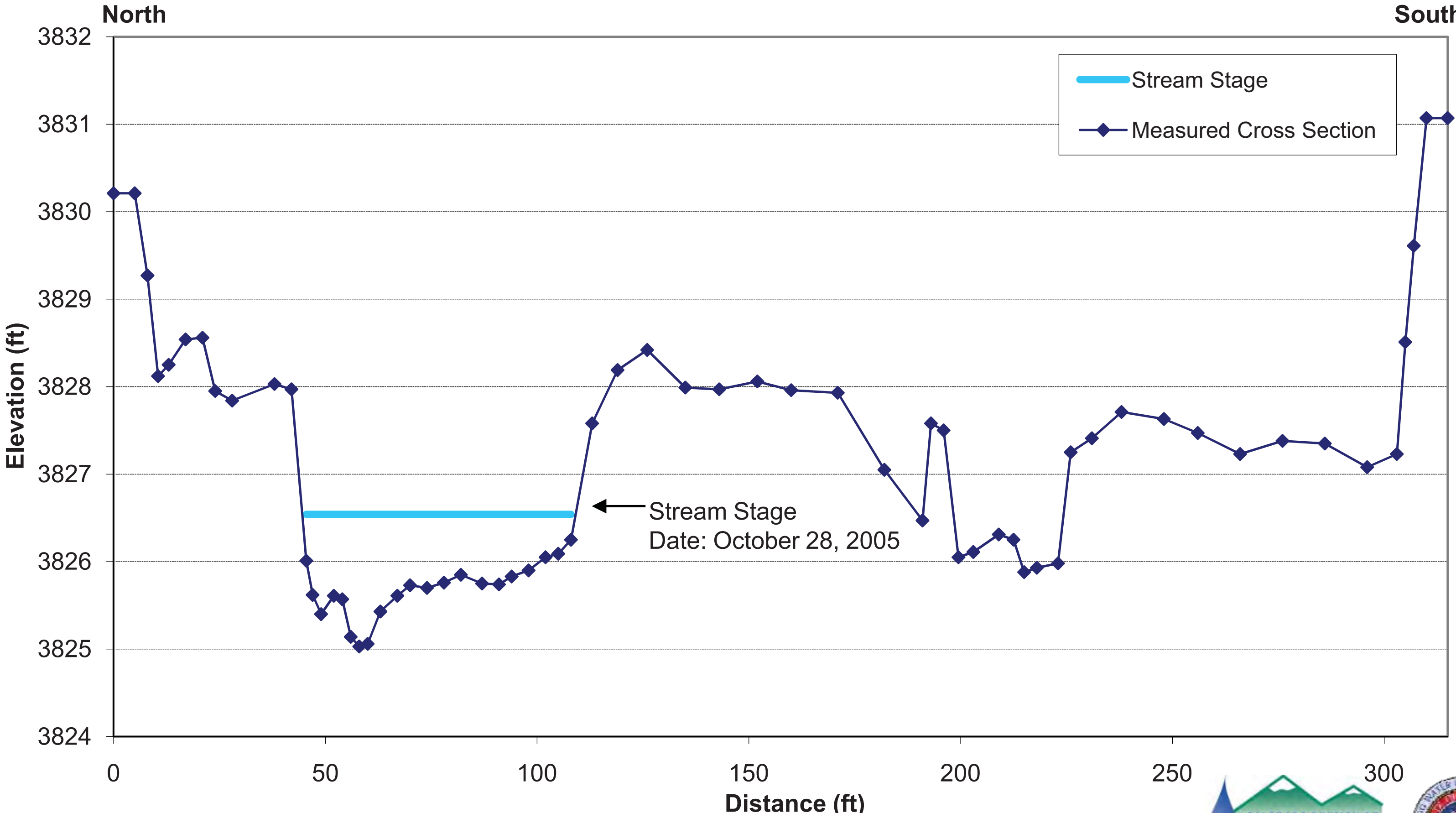


Scale 1:950,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 3-11: Example Mainstem Cross Section – South Platte River (SC-26)
All Cross Sections can be found in Appendix G



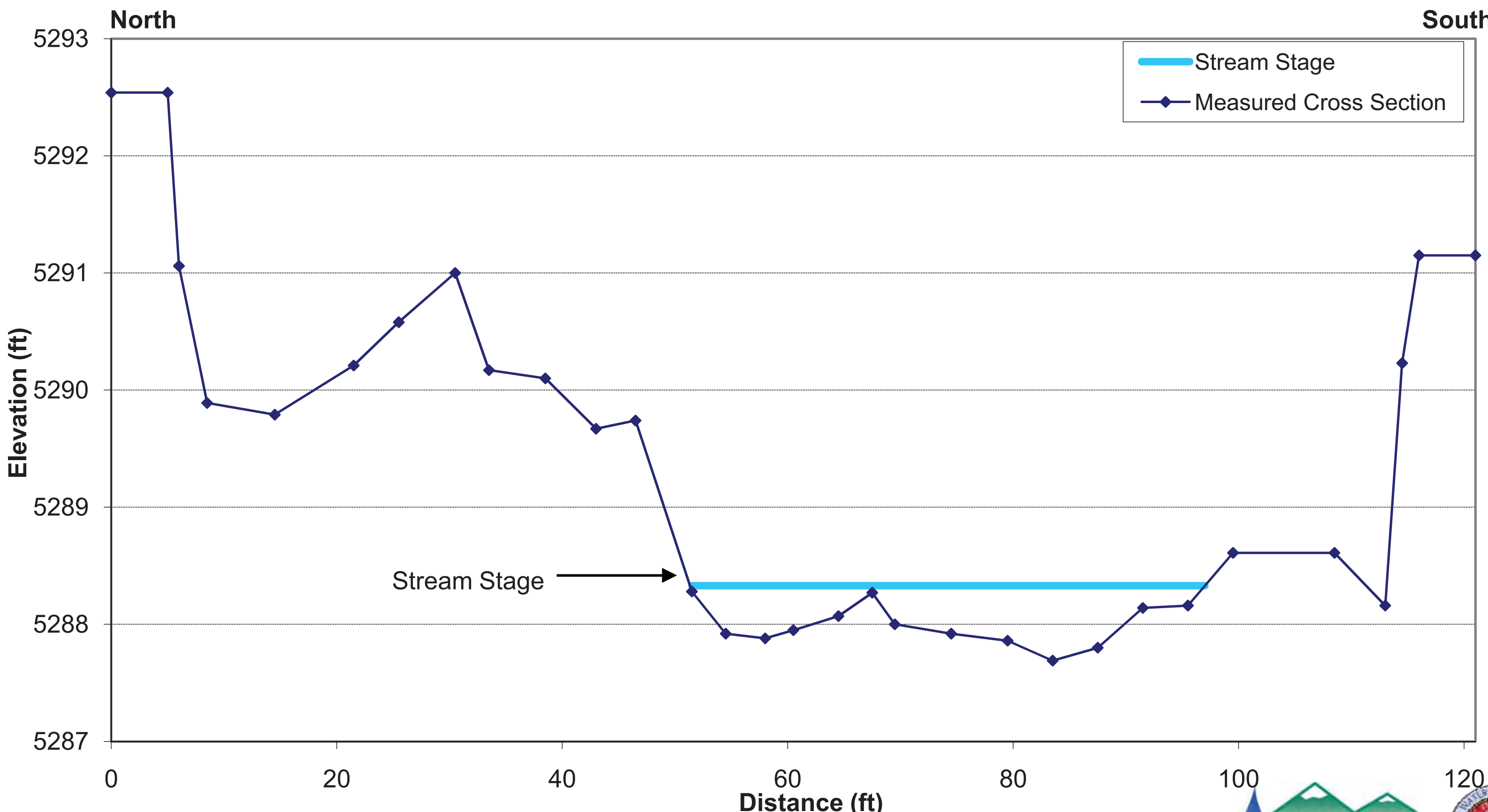
State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 3-12: Example Tributary Cross Section – Sand Creek (SC-05)

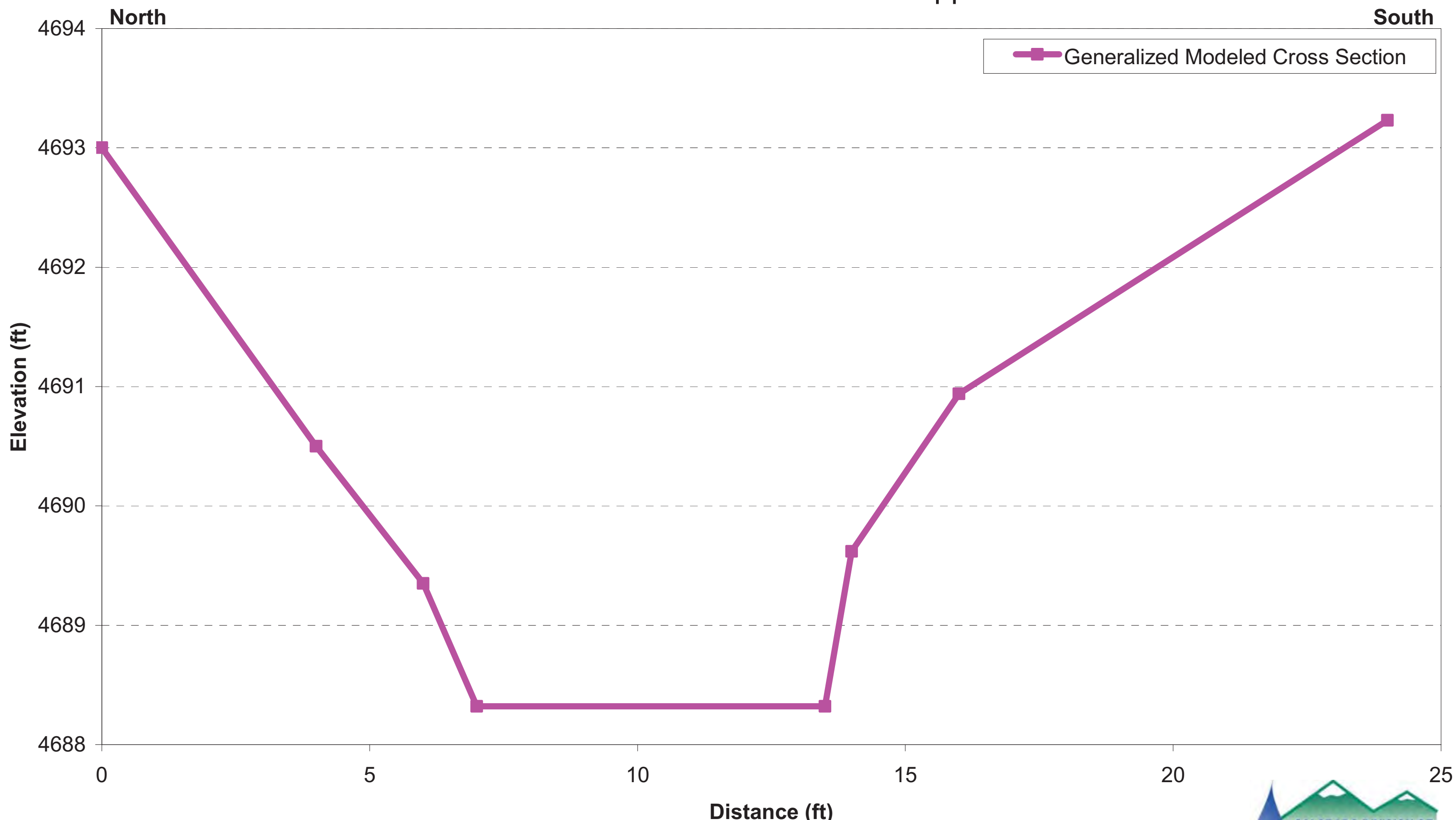
All Cross Sections can be found in Appendix G



State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

Figure 3-13: Generalized Channel Cross Section
Beebe Draw (SC-09), Box Elder Creek (SC-10), Lonetree Creek (SC-22)
All Cross Sections can be found in Appendix G

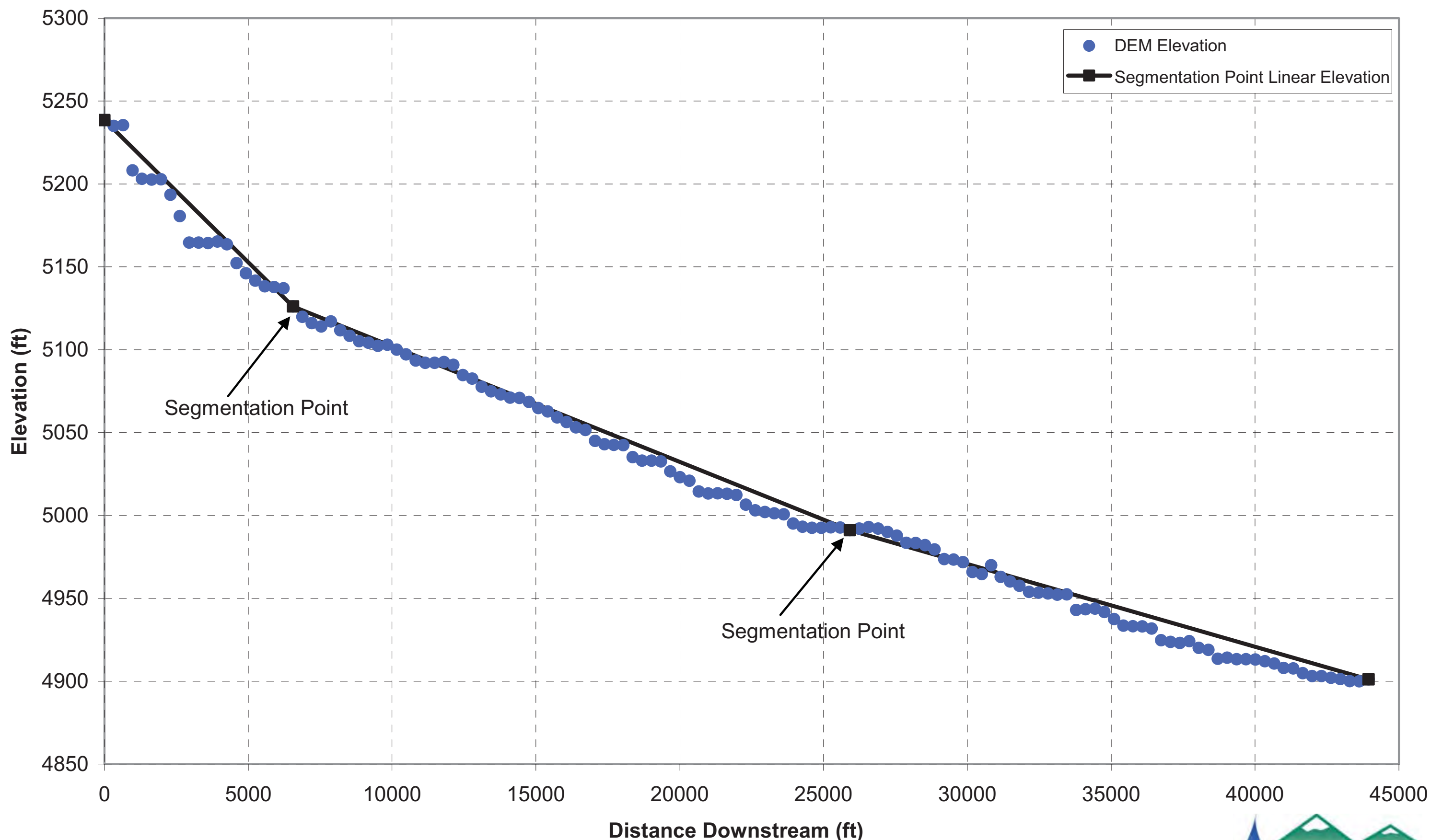


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 3-14: Streambed Elevation Profile using 30-m DEM data
Spring Creek: Spring Creek to Cache la Poudre River

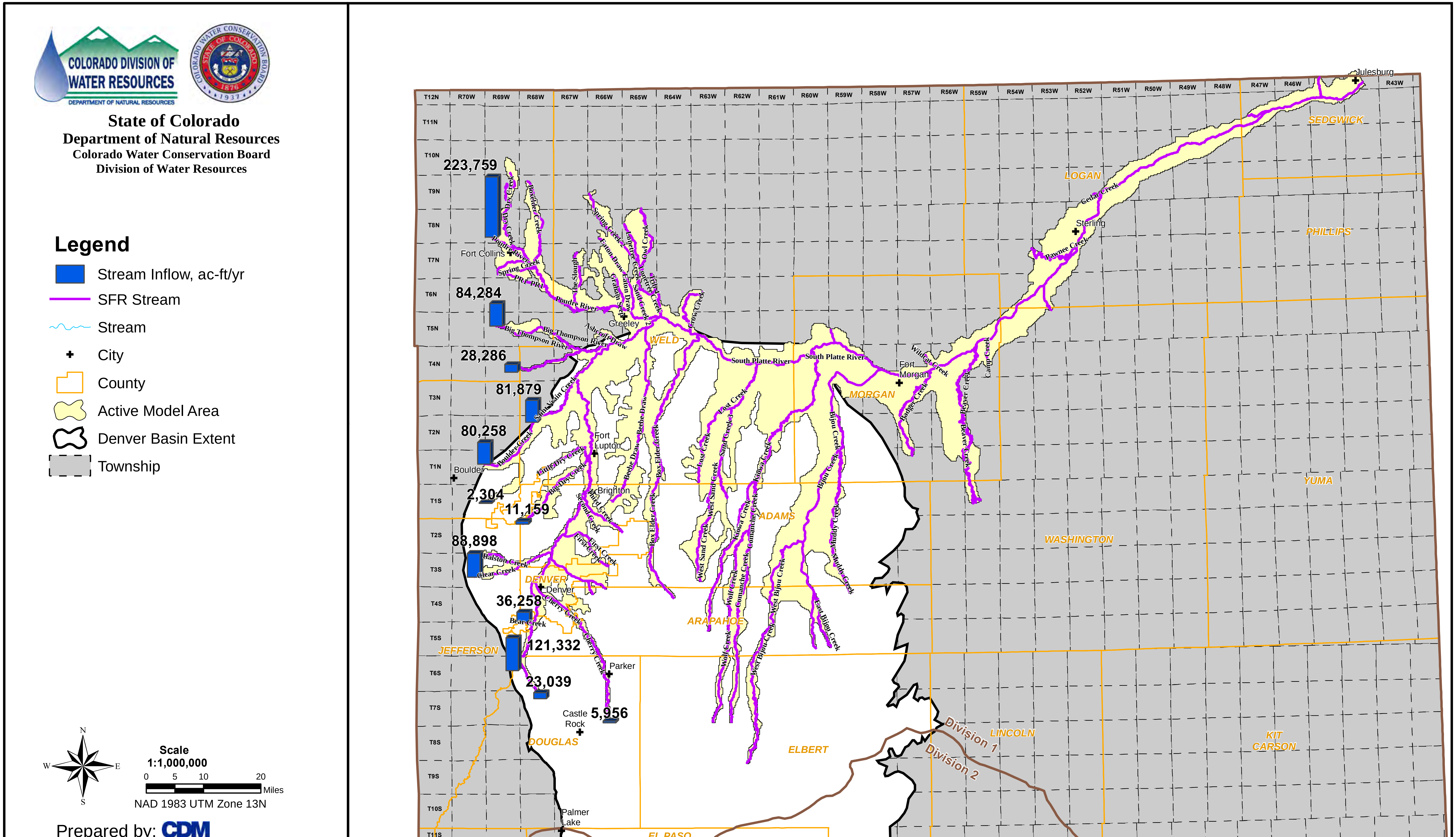


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 3-15: SFR Stream Network with Relative Stream Inflows



SPDSS Alluvial Groundwater Model Report

Figure 3-16: Extent of Phreatophytes

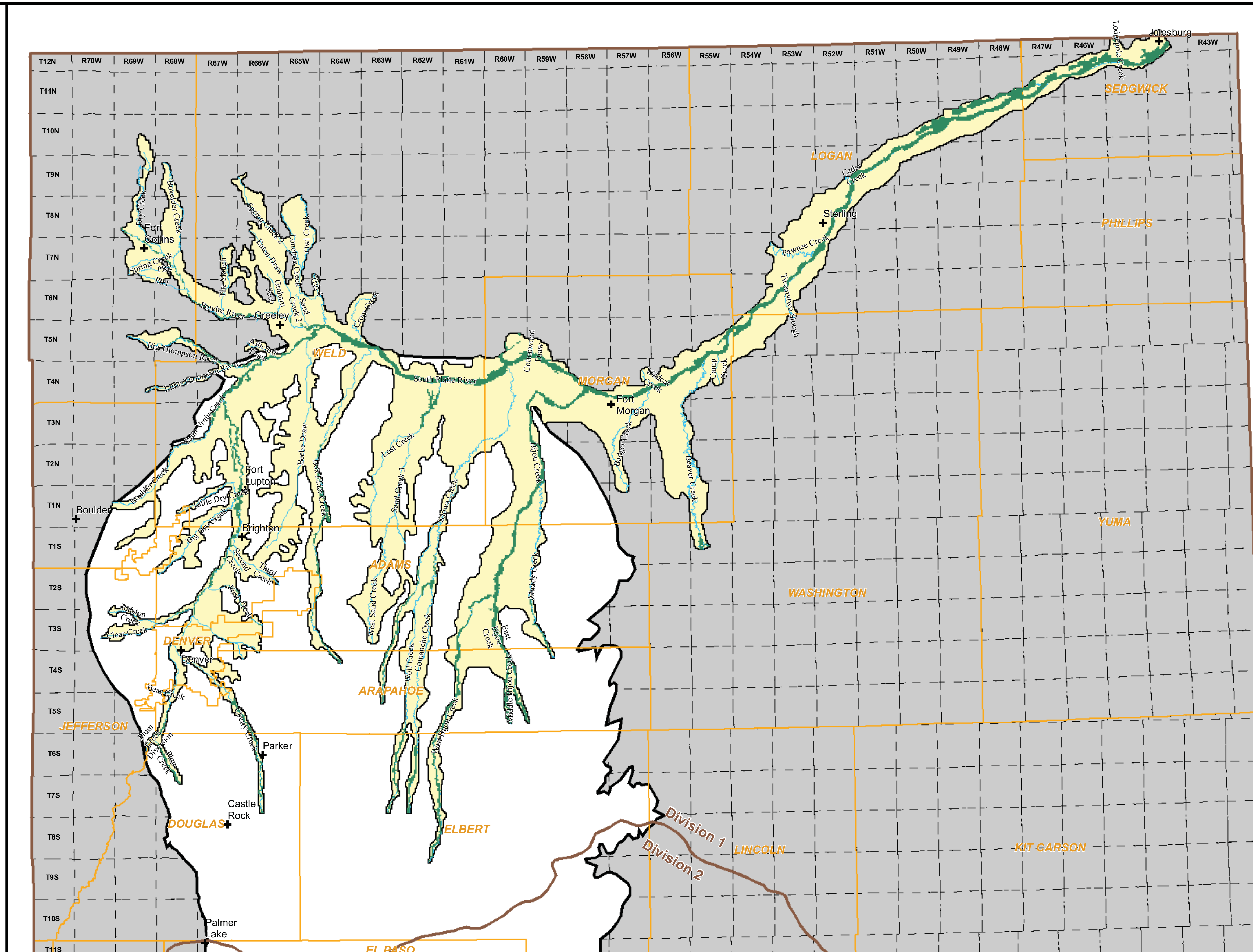
State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

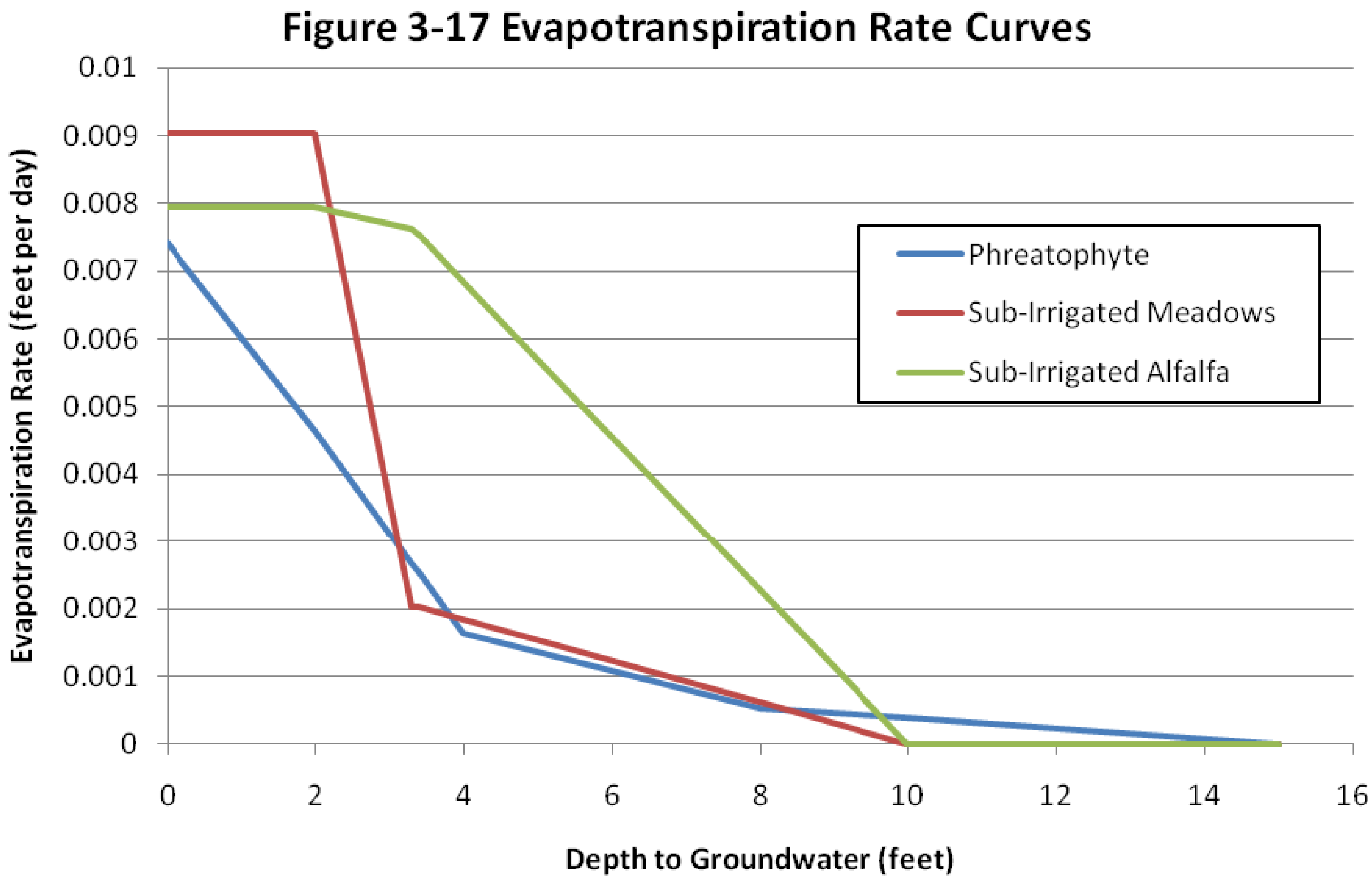
- City
- Stream
- County
- Alluvial Aquifer Extent
- Denver Basin Extent
- Township
- Phreatophyte Vegetation

Scale
1:950,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM



SPDSS Alluvial Groundwater Model Report



State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 3-18: January Recharge

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

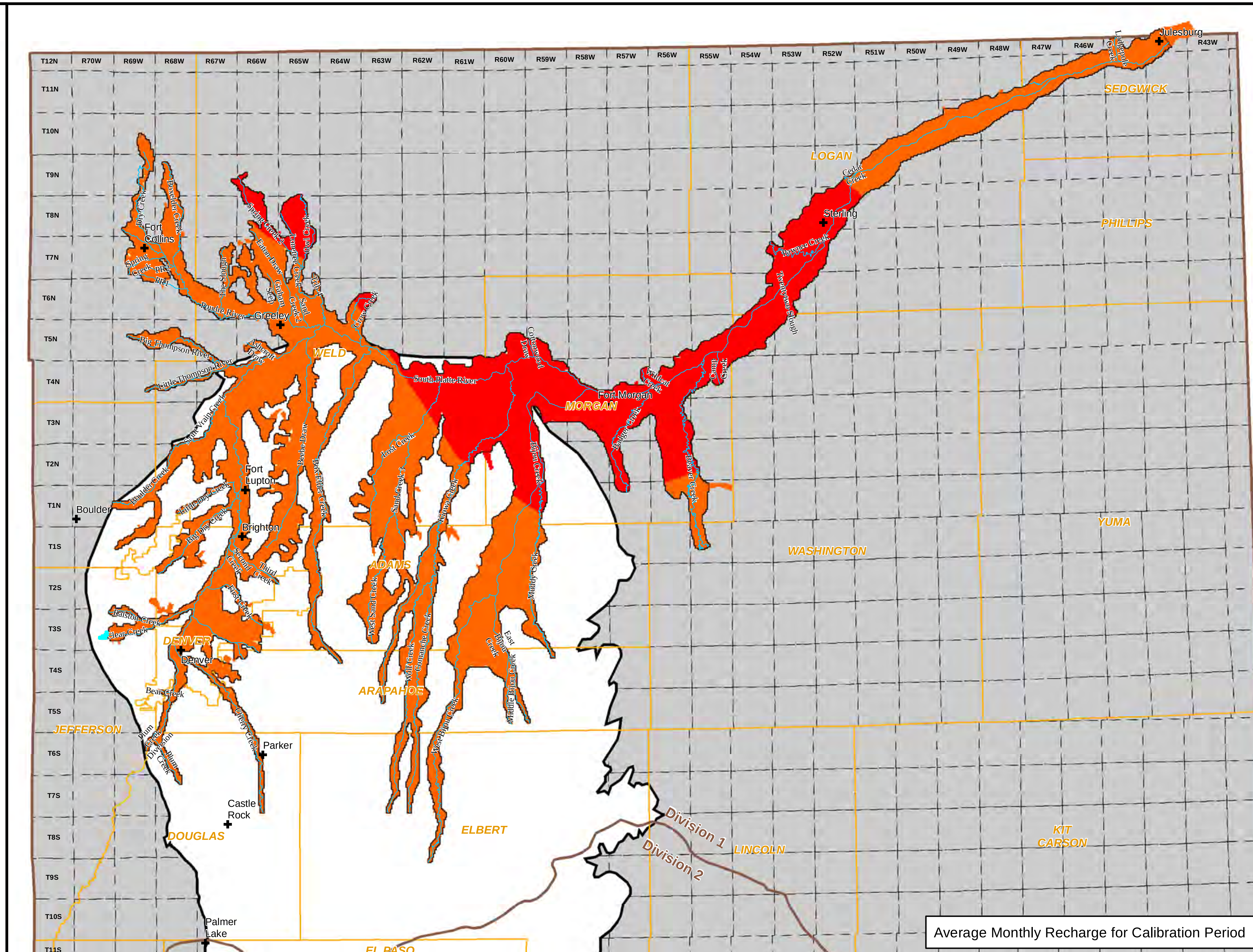
- City
- Stream
- County
- Alluvial Aquifer Extent
- Denver Basin Extent
- Township

Recharge (in/month)

- 0.005 - 0.010
- 0.011 - 0.020
- 0.021 - 0.030
- 0.031 - 0.040
- 0.041 - 0.050
- 0.051 - 0.060
- 0.061 - 0.070
- 0.071 - 0.080
- 0.081 - 0.090
- 0.091 - 0.100
- 0.101 - 0.110

Scale 1:950,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM



SPDSS Alluvial Groundwater Model Report

Figure 3-19: February Recharge

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

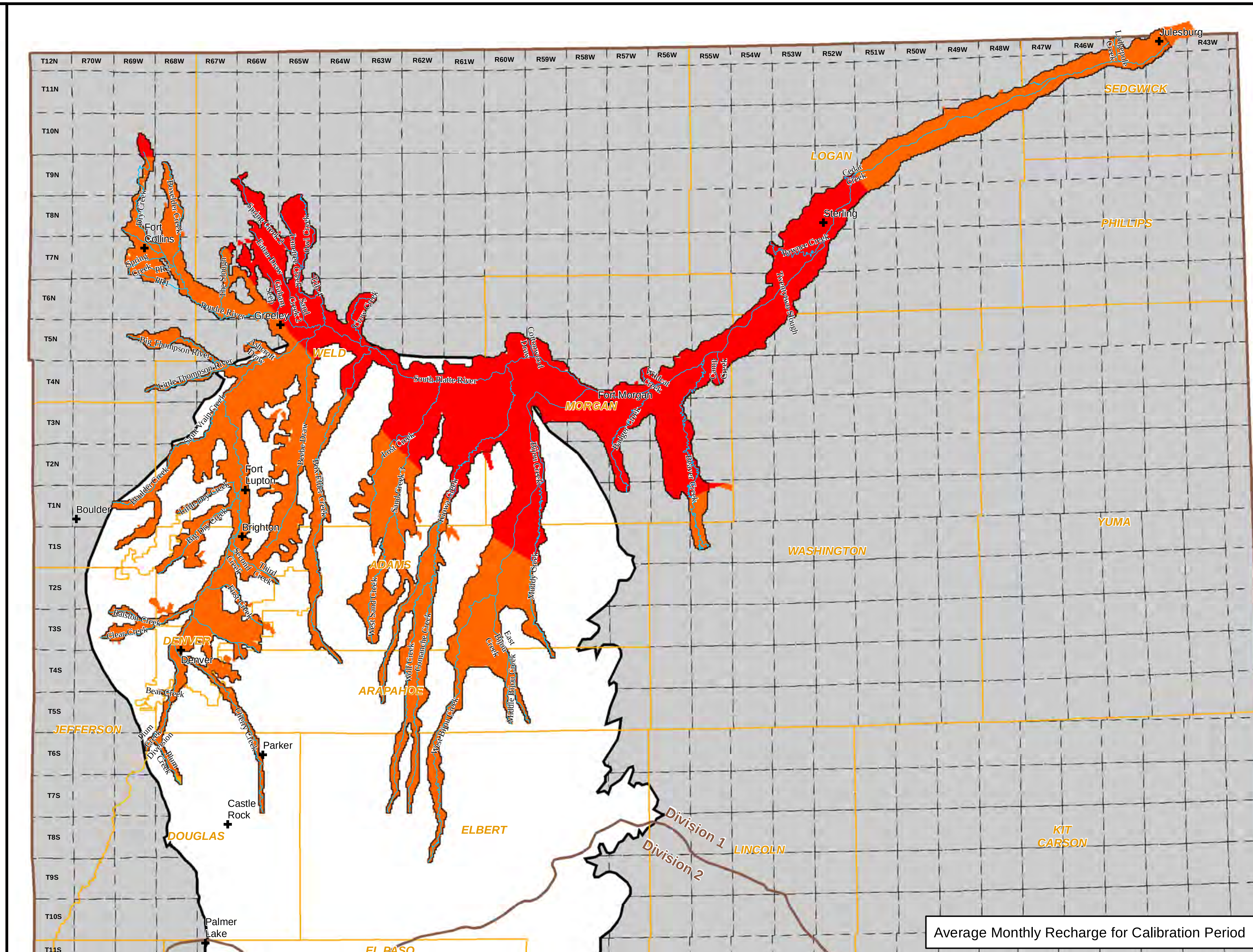
- City
- Stream
- County
- Alluvial Aquifer Extent
- Denver Basin Extent
- Township

Recharge (in/month)

- 0.006 - 0.010
- 0.011 - 0.020
- 0.021 - 0.030
- 0.031 - 0.040
- 0.041 - 0.050
- 0.051 - 0.060
- 0.061 - 0.070
- 0.071 - 0.080
- 0.081 - 0.090
- 0.091 - 0.100
- 0.101 - 0.110

Scale 1:950,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM



SPDSS Alluvial Groundwater Model Report

Figure 3-20: March Recharge

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

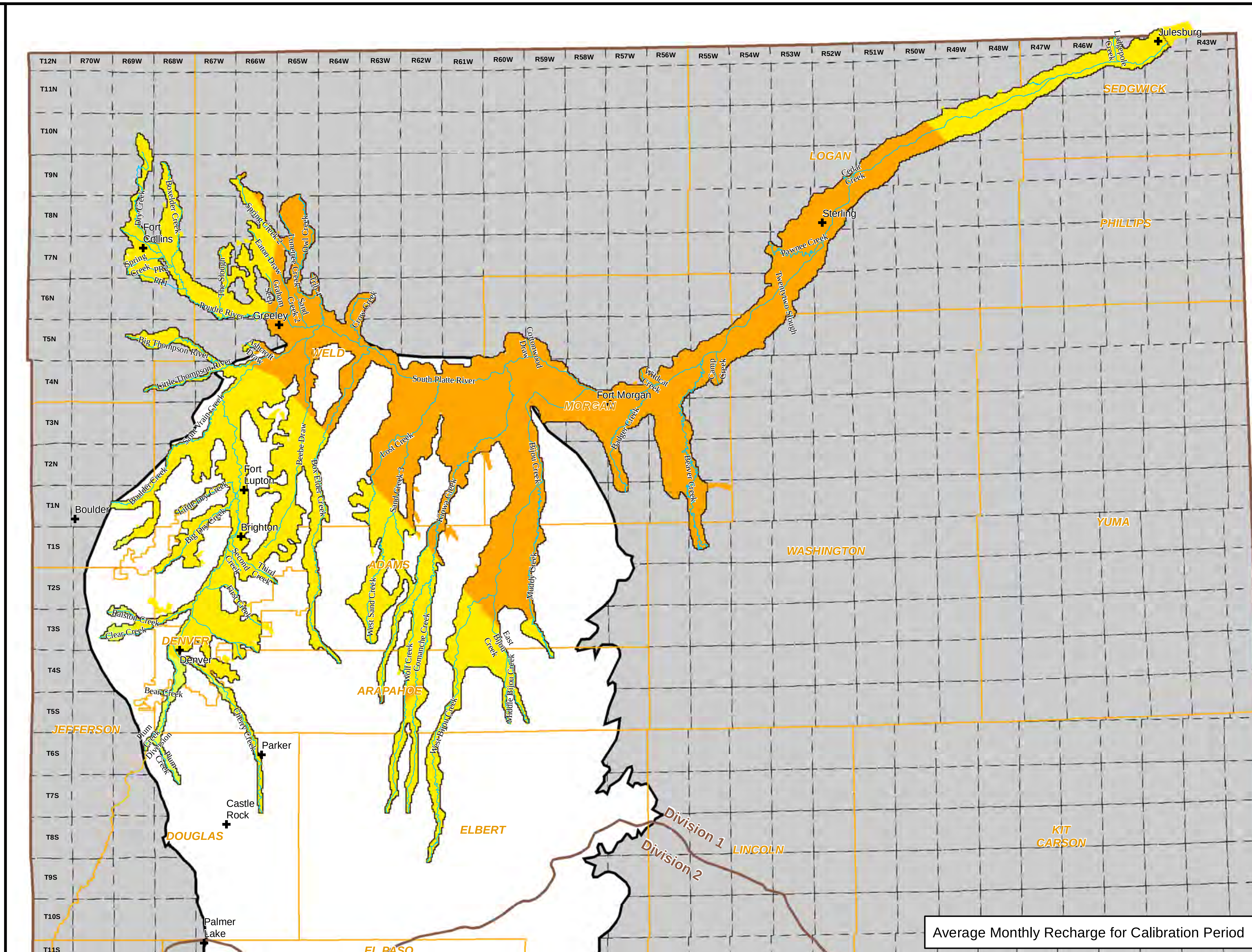
- City
- Stream
- County
- Alluvial Aquifer Extent
- Denver Basin Extent
- Township

Recharge (in/month)

- 0.005 - 0.010
- 0.011 - 0.020
- 0.021 - 0.030
- 0.031 - 0.040
- 0.041 - 0.050
- 0.051 - 0.060
- 0.061 - 0.070
- 0.071 - 0.080
- 0.081 - 0.090
- 0.091 - 0.100
- 0.101 - 0.110

Scale 1:950,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM



SPDSS Alluvial Groundwater Model Report

Figure 3-21: April Recharge

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

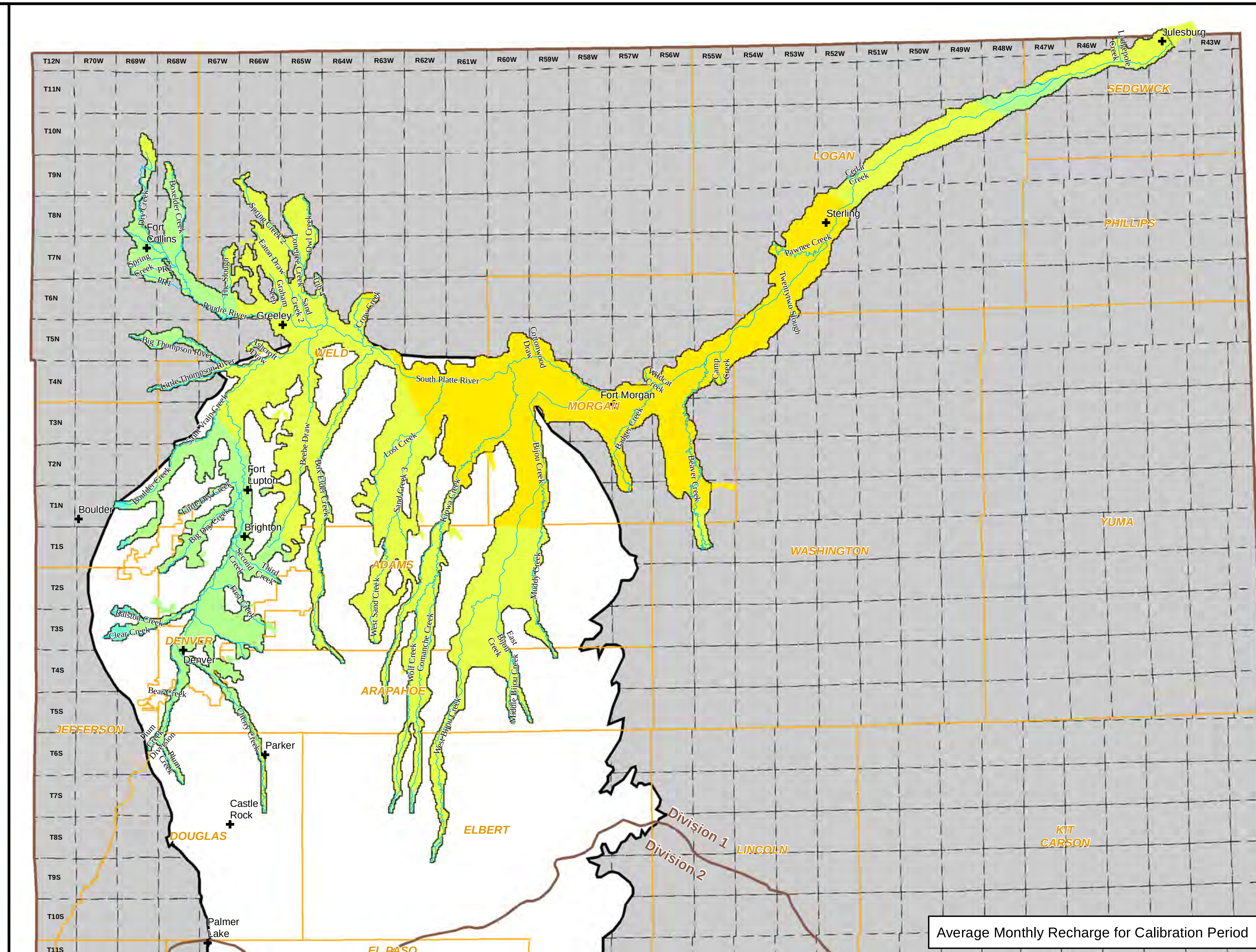
- City
- Stream
- County
- Alluvial Aquifer Extent
- Denver Basin Extent
- Township

Recharge (in/month)

- 0.006 - 0.010
- 0.011 - 0.020
- 0.021 - 0.030
- 0.031 - 0.040
- 0.041 - 0.050
- 0.051 - 0.060
- 0.061 - 0.070
- 0.071 - 0.080
- 0.081 - 0.090
- 0.091 - 0.100
- 0.101 - 0.110

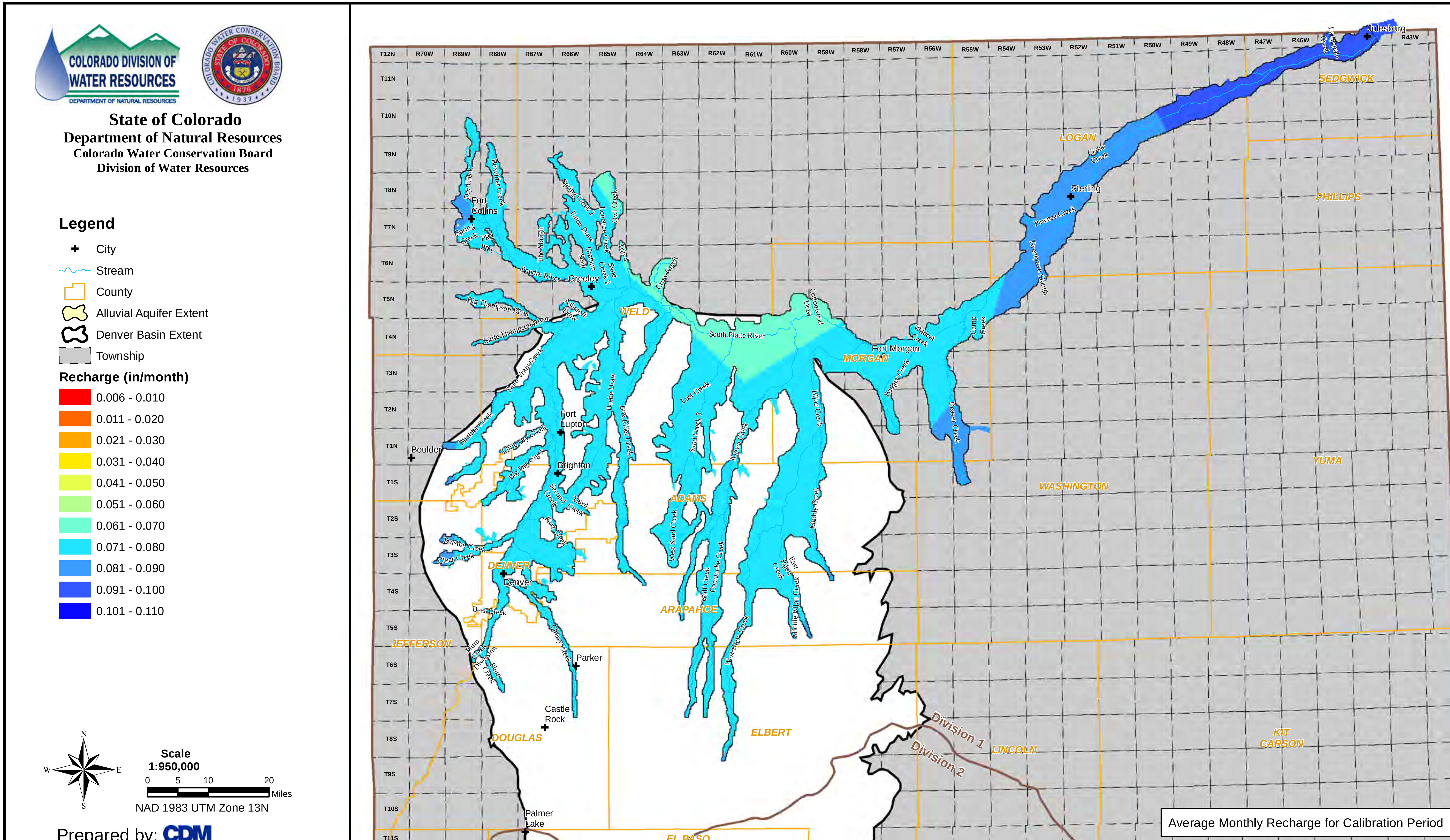
Scale
1:950,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM



SPDSS Alluvial Groundwater Model Report

Figure 3-22: May Recharge



SPDSS Alluvial Groundwater Model Report

Figure 3-23: June Recharge

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

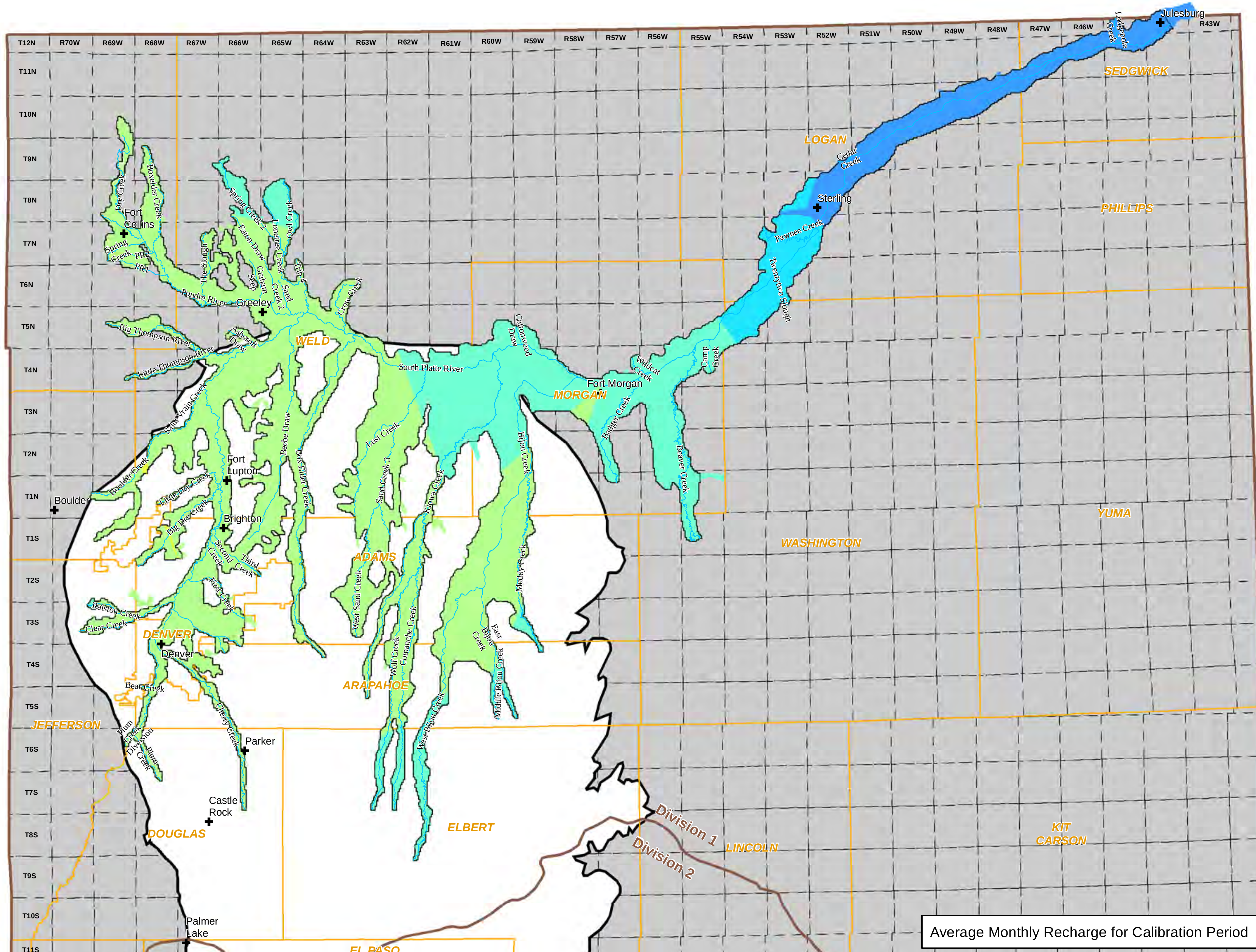
- City
- Stream
- County
- Alluvial Aquifer Extent
- Denver Basin Extent
- Township

Recharge (in/month)

- 0.006 - 0.010
- 0.011 - 0.020
- 0.021 - 0.030
- 0.031 - 0.040
- 0.041 - 0.050
- 0.051 - 0.060
- 0.061 - 0.070
- 0.071 - 0.080
- 0.081 - 0.090
- 0.091 - 0.100
- 0.101 - 0.110

Scale
1:950,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM



SPDSS Alluvial Groundwater Model Report

Figure 3-24: July Recharge

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

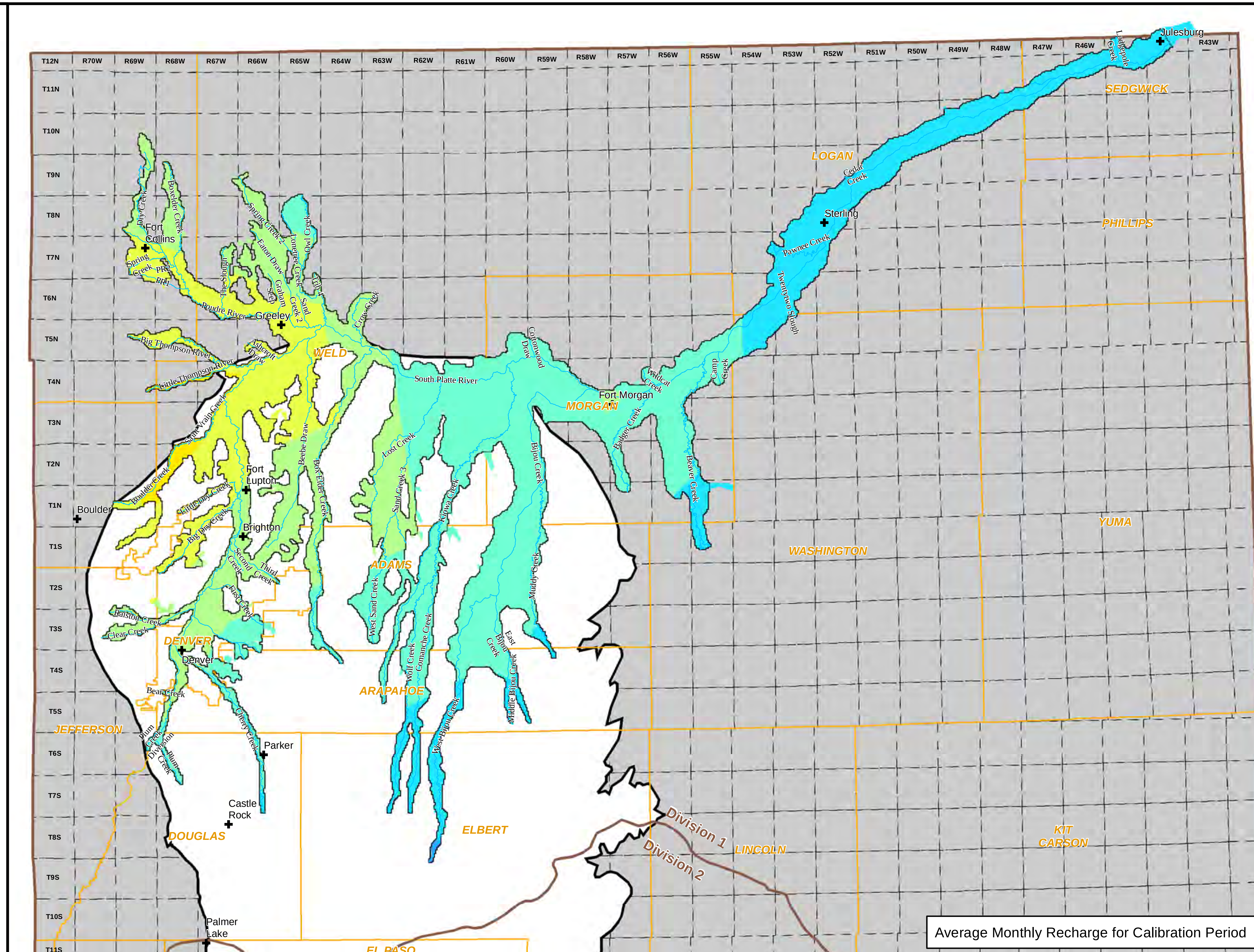
- City
- Stream
- County
- Alluvial Aquifer Extent
- Denver Basin Extent
- Township

Recharge (in/month)

- 0.006 - 0.010
- 0.011 - 0.020
- 0.021 - 0.030
- 0.031 - 0.040
- 0.041 - 0.050
- 0.051 - 0.060
- 0.061 - 0.070
- 0.071 - 0.080
- 0.081 - 0.090
- 0.091 - 0.100
- 0.101 - 0.110

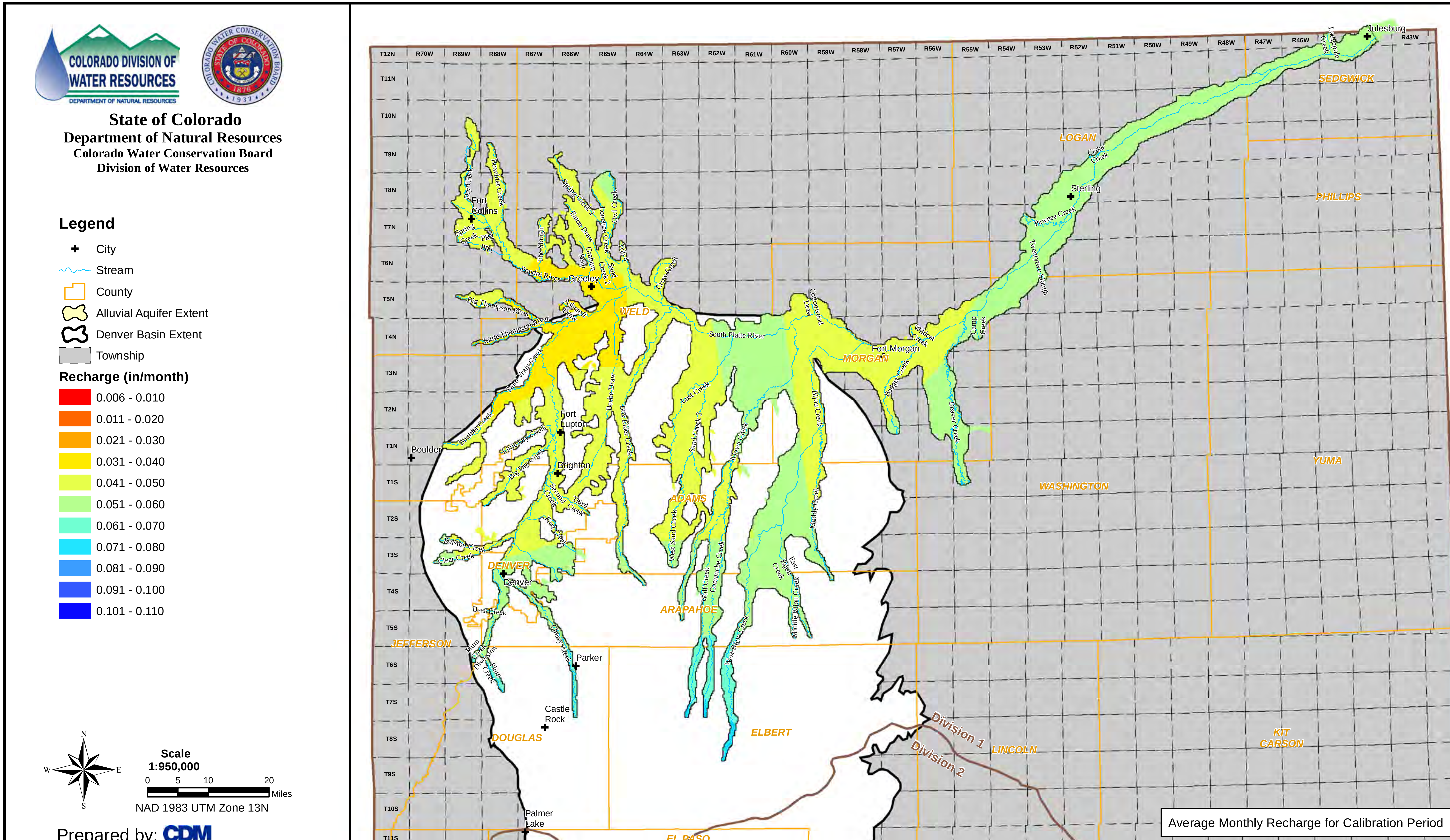
Scale
1:950,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM



SPDSS Alluvial Groundwater Model Report

Figure 3-25: August Recharge



SPDSS Alluvial Groundwater Model Report

Figure 3-26: September Recharge

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

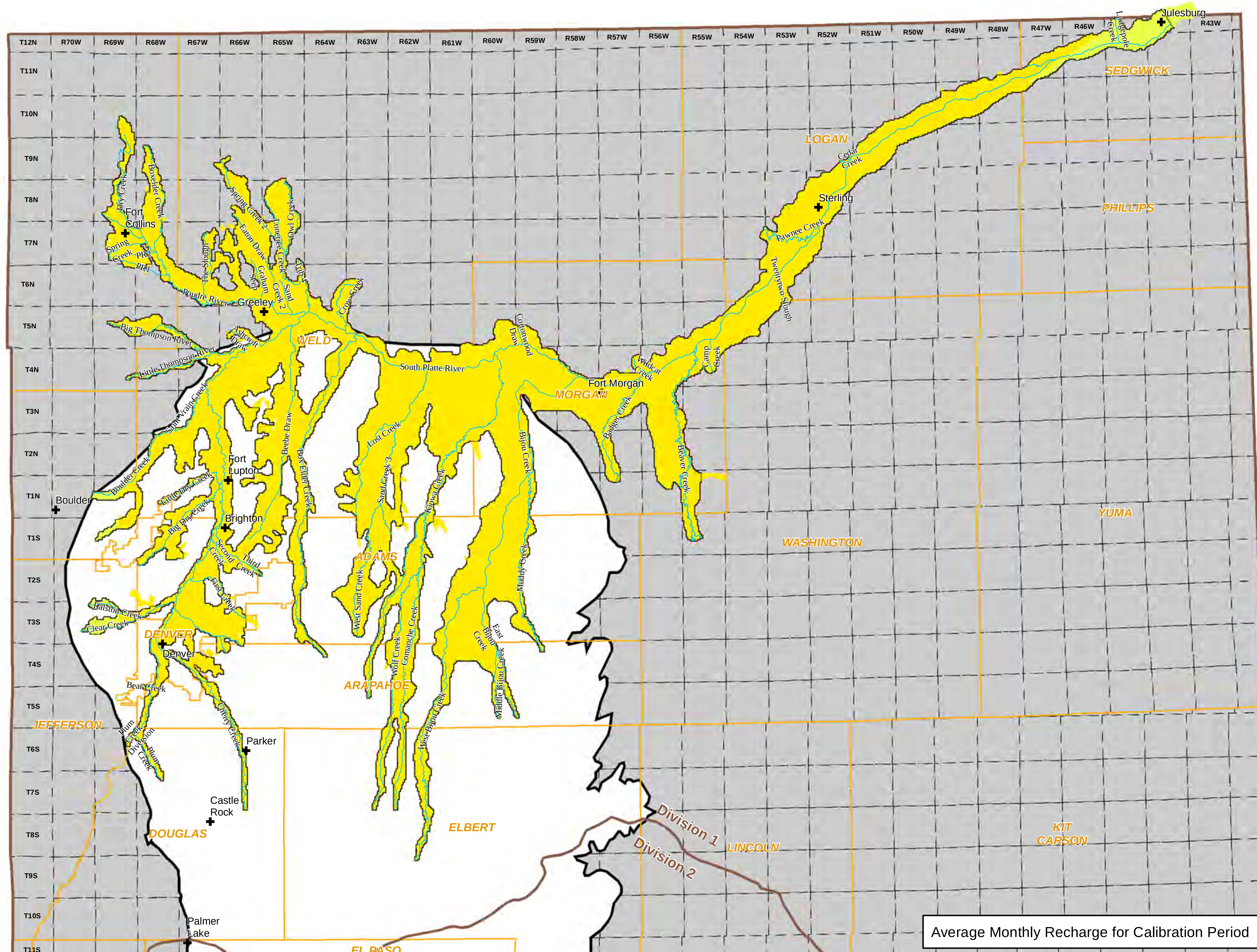
- City
- Stream
- County
- Alluvial Aquifer Extent
- Denver Basin Extent
- Township

Recharge (in/month)

- 0.006 - 0.010
- 0.011 - 0.020
- 0.021 - 0.030
- 0.031 - 0.040
- 0.041 - 0.050
- 0.051 - 0.060
- 0.061 - 0.070
- 0.071 - 0.080
- 0.081 - 0.090
- 0.091 - 0.100
- 0.101 - 0.110

Scale
1:950,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM



SPDSS Alluvial Groundwater Model Report

Figure 3-27: October Recharge

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

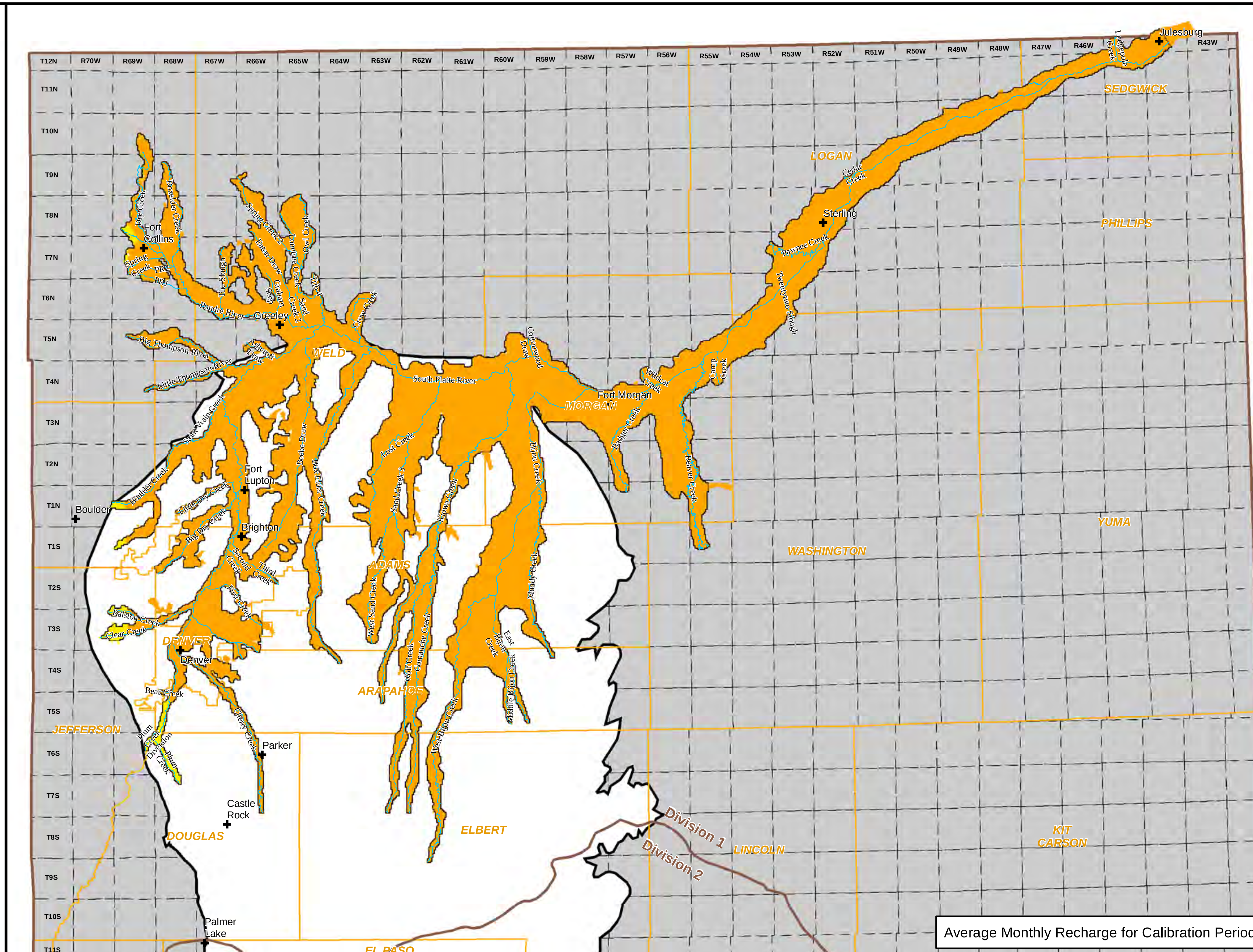
- City
- Stream
- County
- Alluvial Aquifer Extent
- Denver Basin Extent
- Township

Recharge (in/month)

- 0.006 - 0.010
- 0.011 - 0.020
- 0.021 - 0.030
- 0.031 - 0.040
- 0.041 - 0.050
- 0.051 - 0.060
- 0.061 - 0.070
- 0.071 - 0.080
- 0.081 - 0.090
- 0.091 - 0.100
- 0.101 - 0.110

Scale
1:950,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM



SPDSS Alluvial Groundwater Model Report

Figure 3-28: November Recharge

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

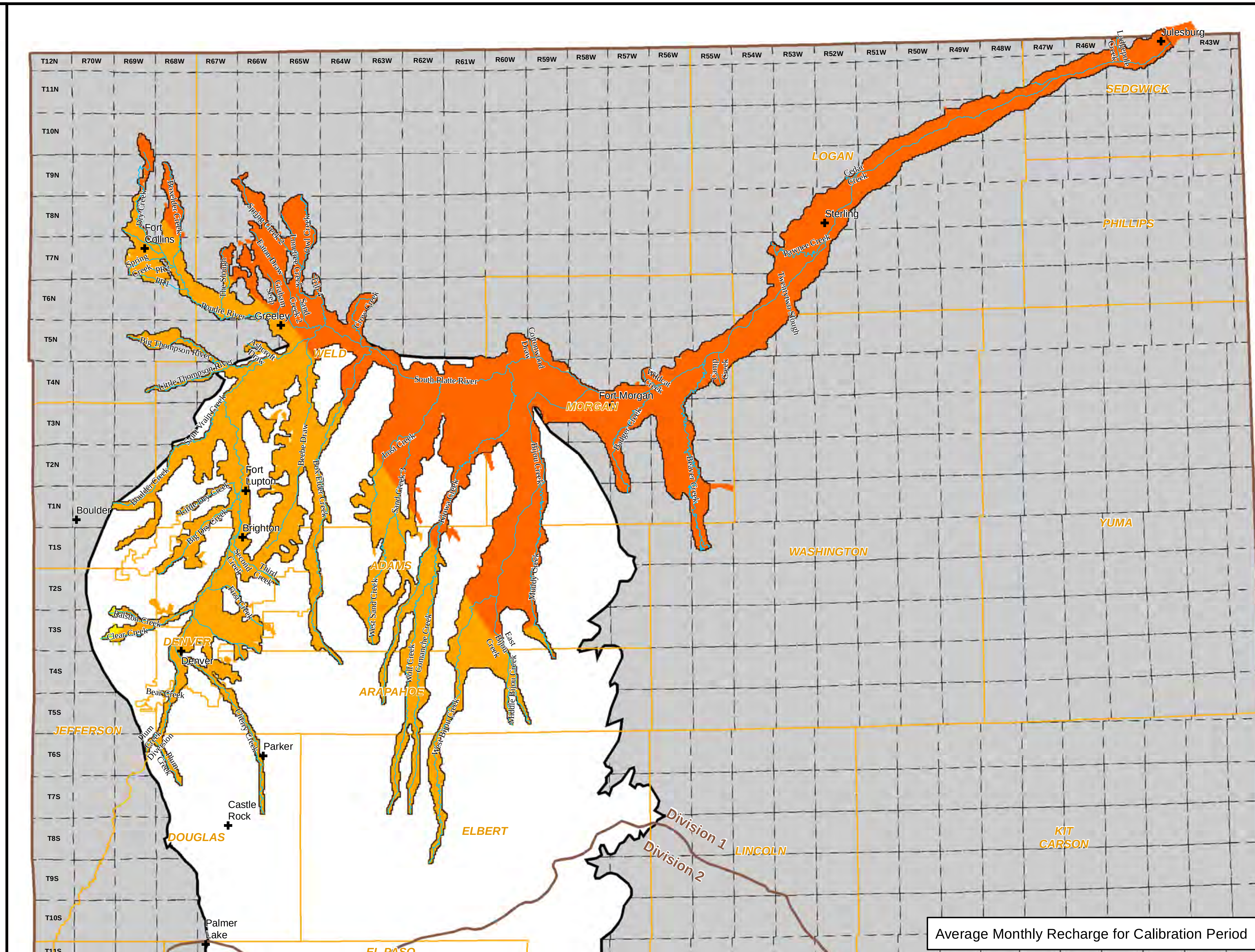
- City
- Stream
- County
- Alluvial Aquifer Extent
- Denver Basin Extent
- Township

Recharge (in/month)

- 0.006 - 0.010
- 0.011 - 0.020
- 0.021 - 0.030
- 0.031 - 0.040
- 0.041 - 0.050
- 0.051 - 0.060
- 0.061 - 0.070
- 0.071 - 0.080
- 0.081 - 0.090
- 0.091 - 0.100
- 0.101 - 0.110

Scale 1:950,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM



SPDSS Alluvial Groundwater Model Report

Figure 3-29: December Recharge

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

- City
- Stream
- County
- Alluvial Aquifer Extent
- Denver Basin Extent
- Township

Recharge (in/month)

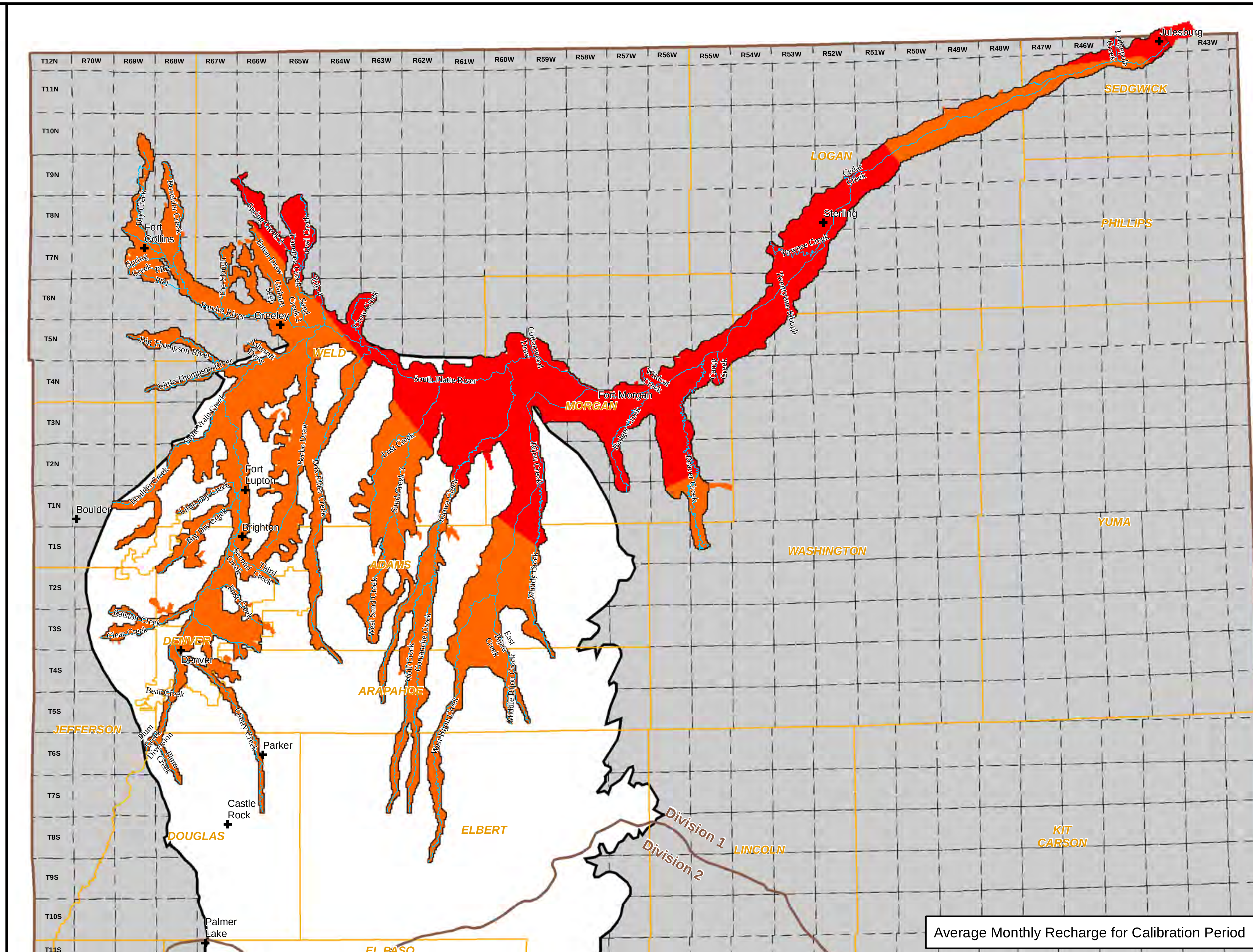
- 0.006 - 0.010
- 0.011 - 0.020
- 0.021 - 0.030
- 0.031 - 0.040
- 0.041 - 0.050
- 0.051 - 0.060
- 0.061 - 0.070
- 0.071 - 0.080
- 0.081 - 0.090
- 0.091 - 0.100
- 0.101 - 0.110

Scale 1:950,000

0 5 10 20 Miles

NAD 1983 UTM Zone 13N

Prepared by: CDM



SPDSS Alluvial Groundwater Model Report

Figure 4-1: Hydraulic Conductivity Zones and Pilot Point Locations

COLORADO DIVISION OF WATER RESOURCES
DEPARTMENT OF NATURAL RESOURCES

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

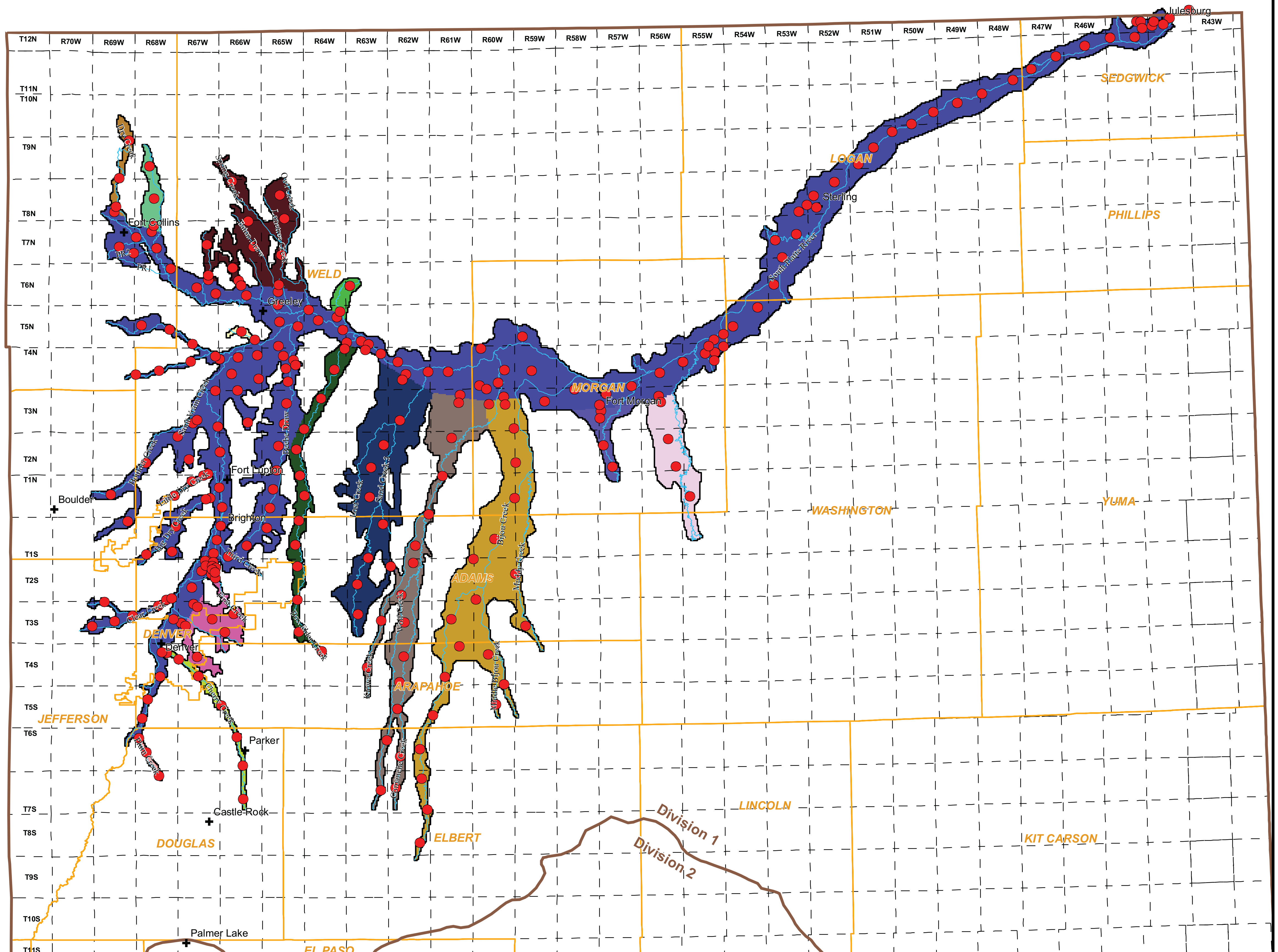
- City
- Stream
- County
- Pilot Point Locations

Pilot Point Zones

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

Scale
1:950,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM



SPDSS Alluvial Groundwater Model Report

Figure 4-2: Distribution of Hydraulic Conductivity in Calibrated Model

COLORADO DIVISION OF WATER RESOURCES
DEPARTMENT OF NATURAL RESOURCES

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

- City
- Stream
- County

Hydraulic Conductivity (ft/day)

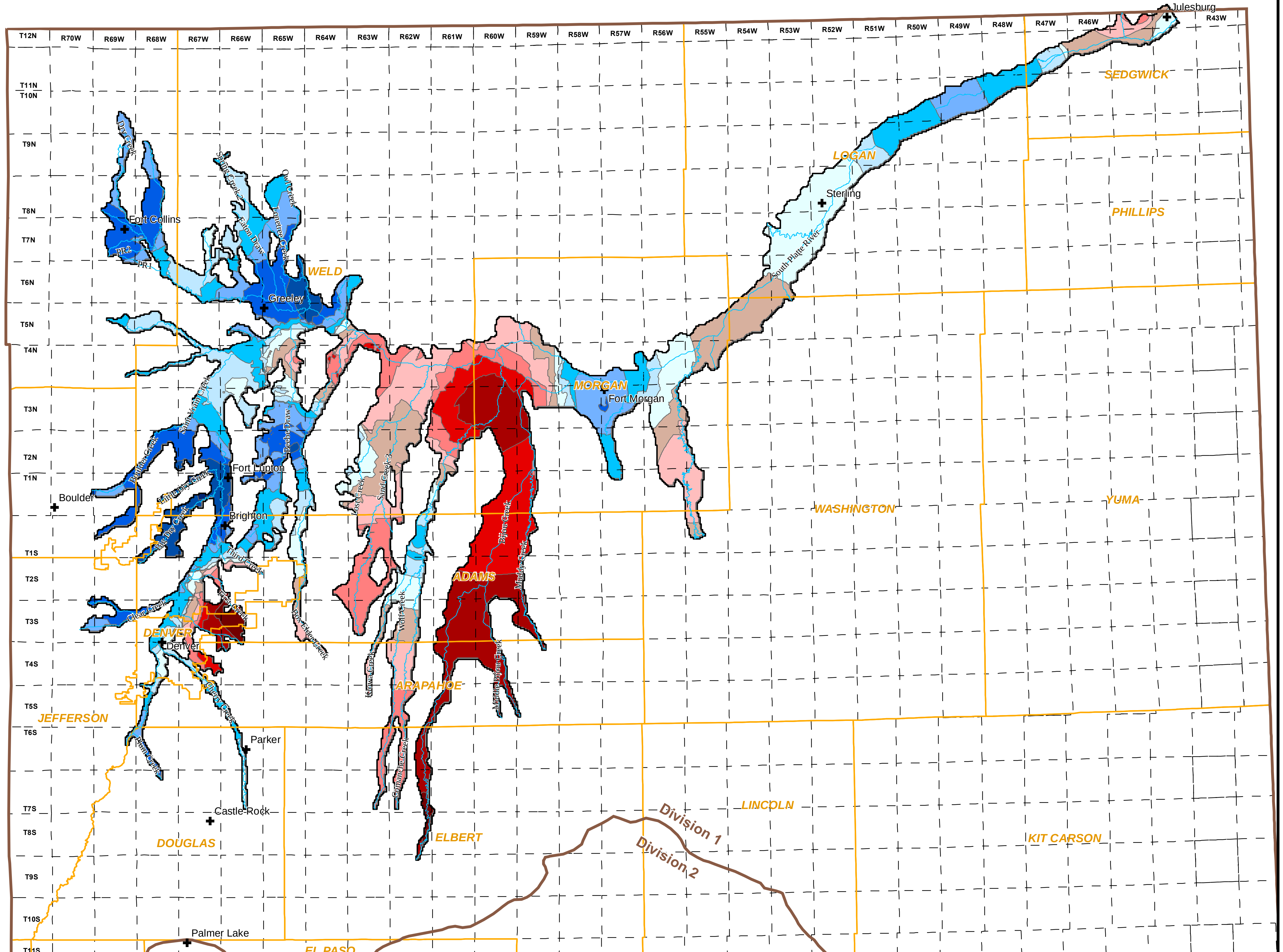
- 700-750
- 650-700
- 600-650
- 550-600
- 500-600
- 450-500
- 400-450
- 350-400
- 300-350
- 250-300
- 200-250
- 150-200
- 100-150

Scale 1:950,000

0 5 10 20 Miles

NAD 1983 UTM Zone 13N

Prepared by: CDM



SPDSS Alluvial Groundwater Model Report

Figure 4-3: Simulated Water Table Surface August 2004

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

- City
- Stream
- County

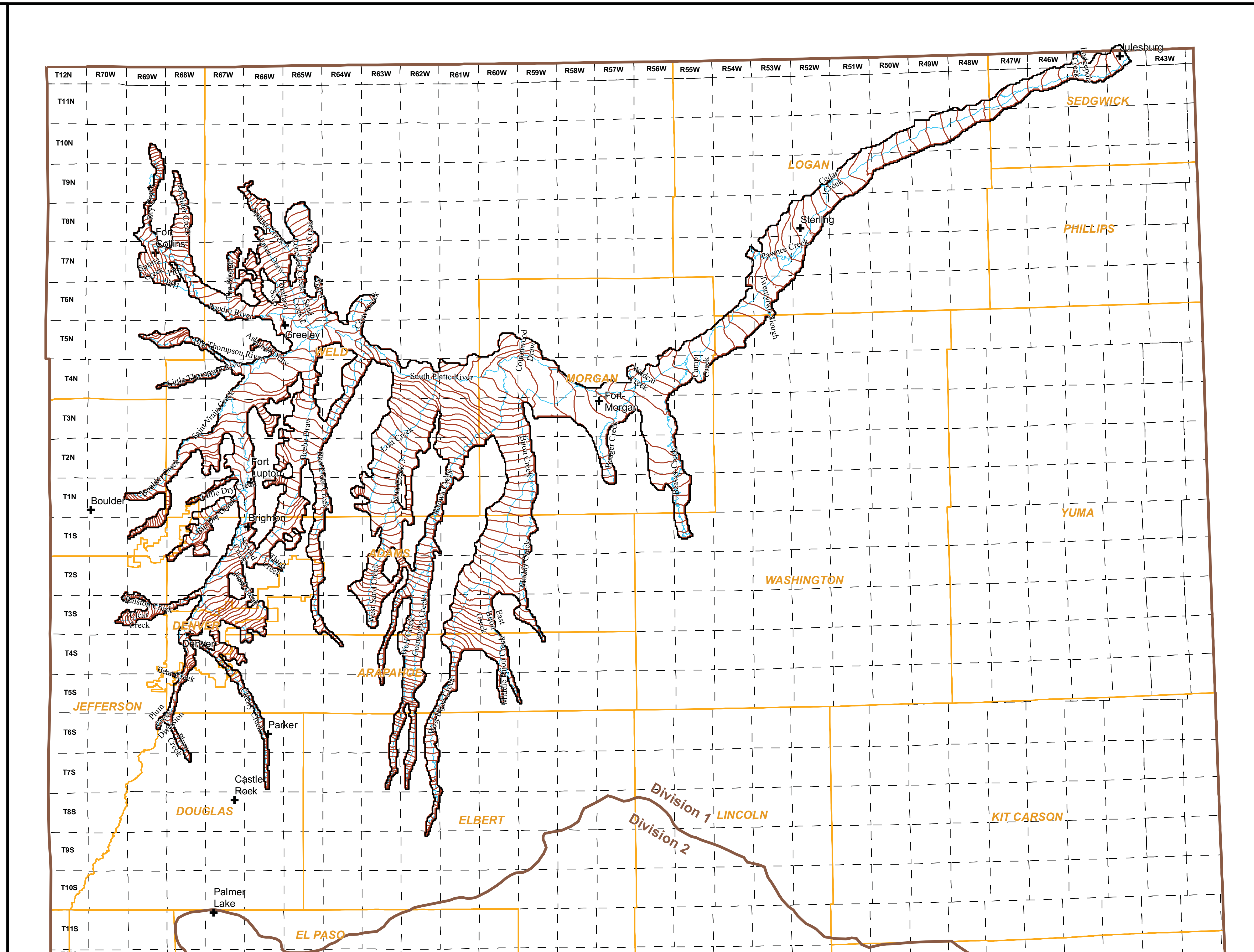
Water Table Surface - August 2004

- 20 ft Contours

Scale 1:1,000,000

0 5 10 20 Miles

NAD 1983 UTM Zone 13N



Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-4: Simulated Water Table Surface February 2005

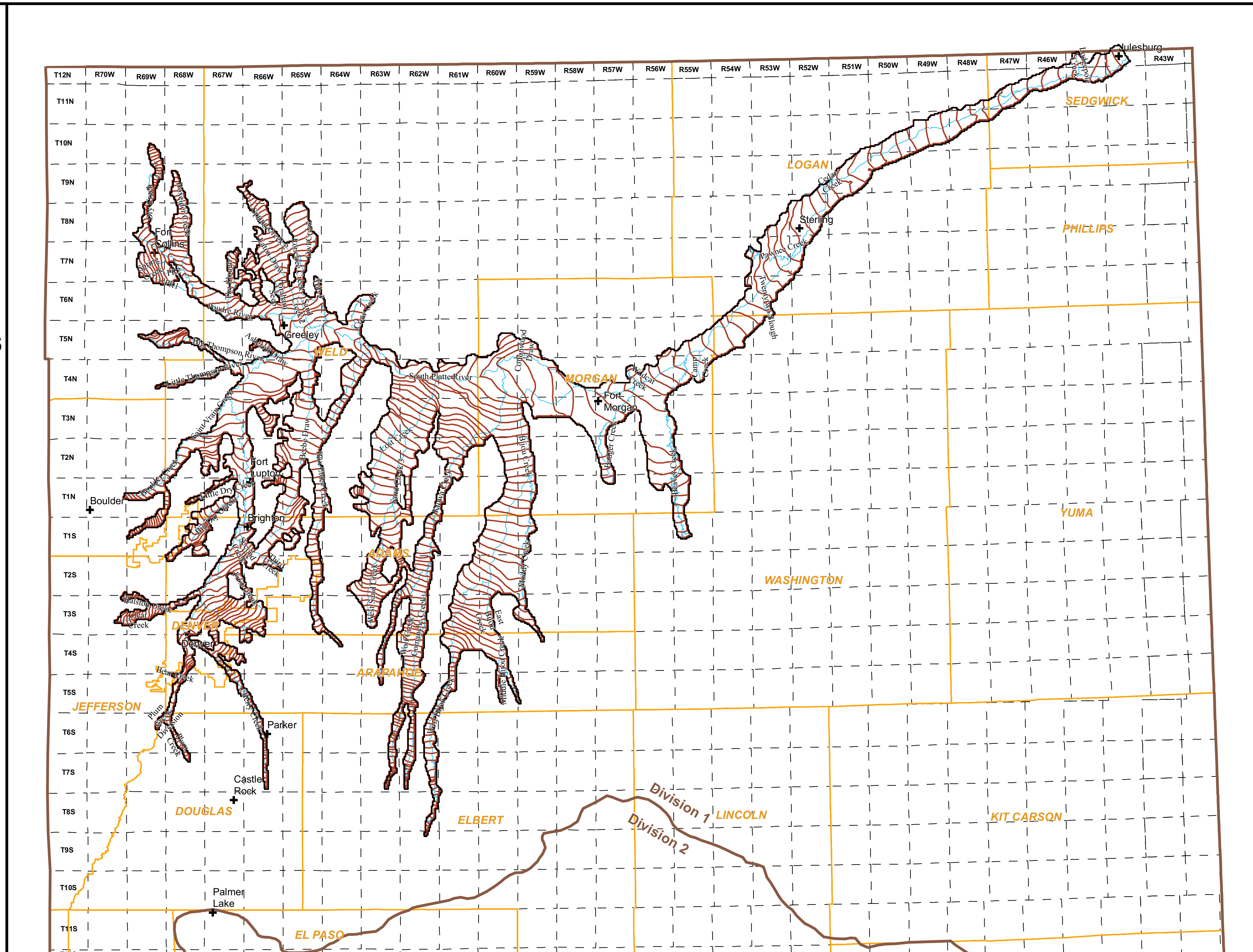
State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

- City
- Stream
- County

Water Table Surface -February 2005

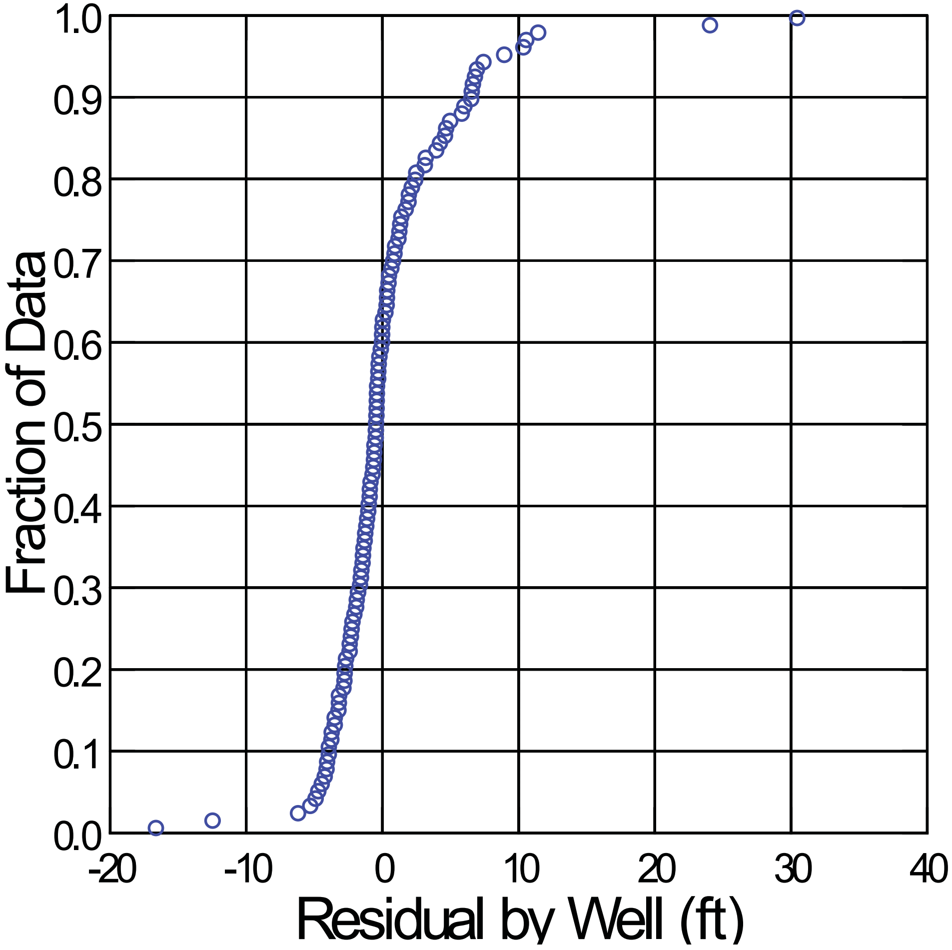
- 20 ft Contours



Scale 1:1,000,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM

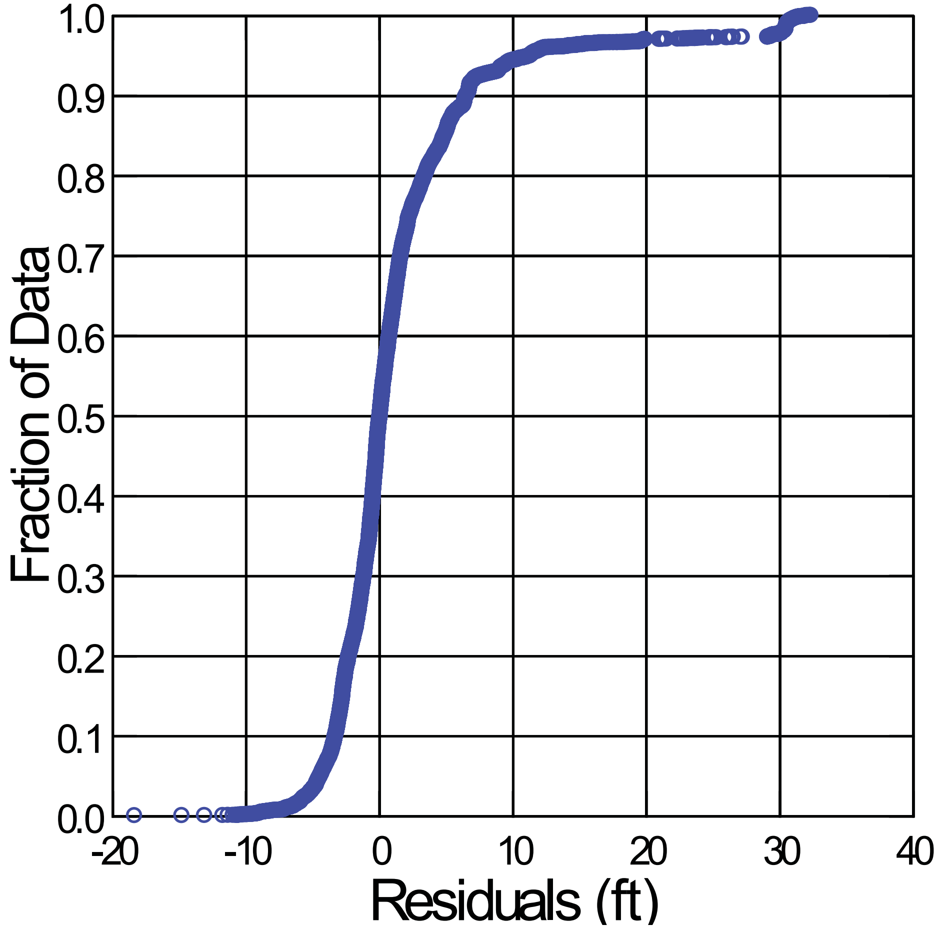
Figure 4-5: Mean Residuals at Surveyed Wells



State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

Figure 4-6: Residuals at Surveyed Wells - All Observations



State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-7: Mean Residuals at All Wells

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

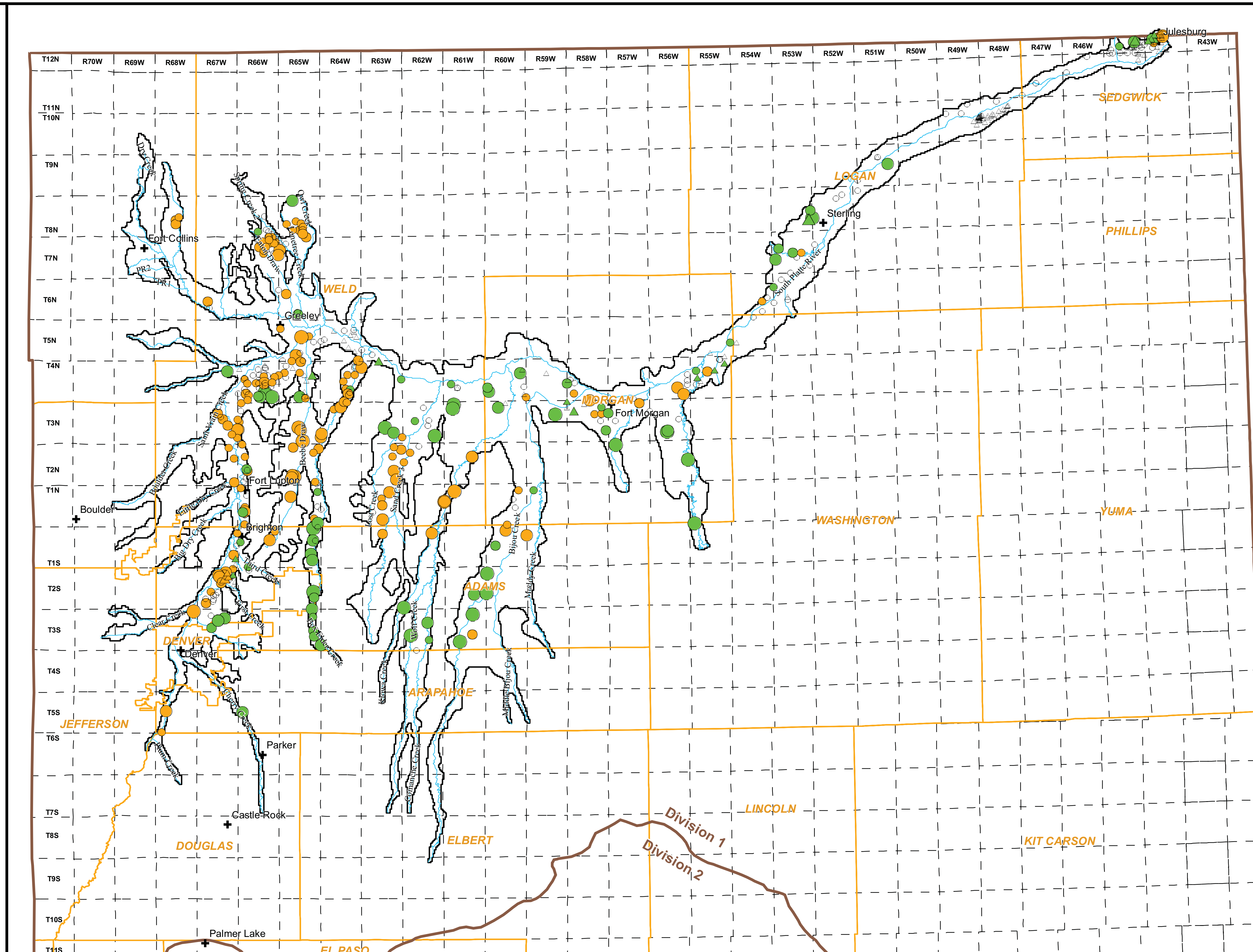
Legend

- Surveyed Wells
- Non-Surveyed Wells

Mean Residuals

- Residuals great than 25 ft
- Residuals between 15 ft to 25 ft
- Residuals between 10 ft and 15 ft
- Residuals between 5 ft and 10 ft
- Residuals between -5 ft and 5 ft
- Residuals between -10 ft and -5 ft
- Residuals between -15 ft and -10 ft
- Residuals between -25 ft and -15 ft
- Residuals less than -25 ft
- City
- Stream
- County

Scale 1:950,000
0 5 10 20 Miles
NAD 1983 UTM Zone 13N



Prepared by: CDM

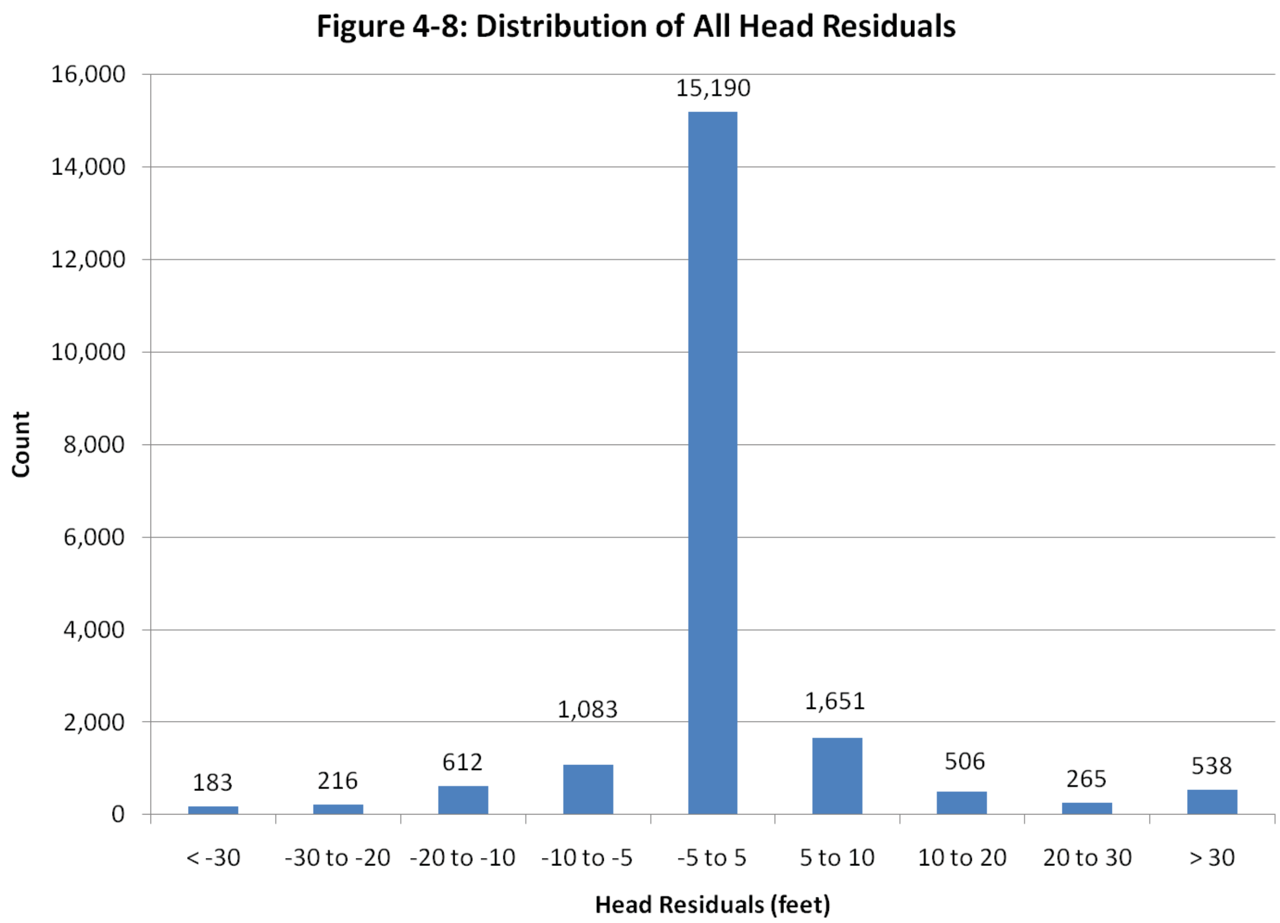
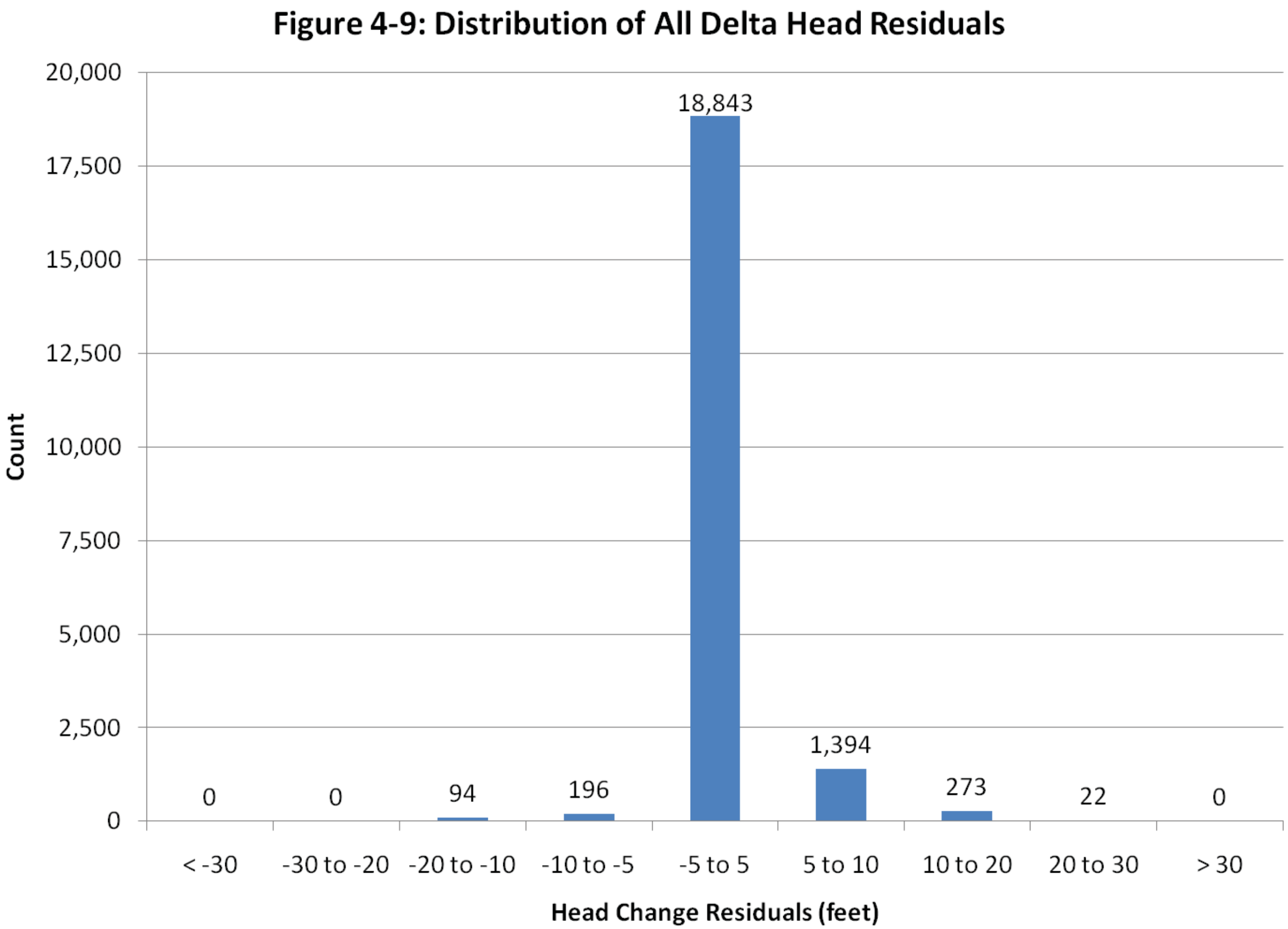


Figure 4-8: Distribution of All Head Residuals
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Count
15,190
1,083
1,651
183
216
612
506
265
538
< -30
-30 to -20
-20 to -10
-10 to -5
-5 to 5
5 to 10
10 to 20
20 to 30
> 30
Head Residuals (feet)

SPDSS Alluvial Groundwater Model Report

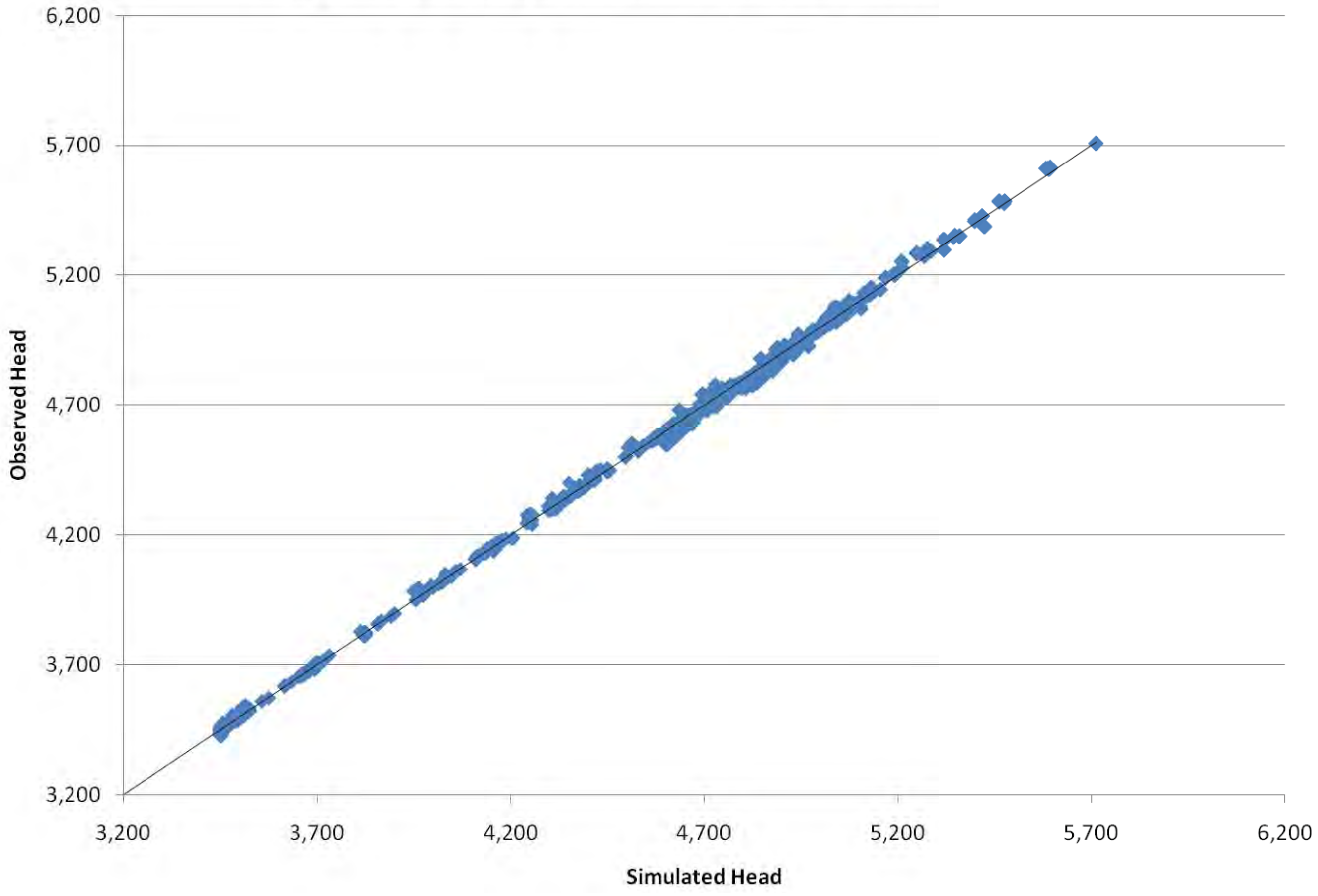


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-10: Plot of Simulated and Observed Heads



State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-11: Selected Modeled and Observed Hydrographs

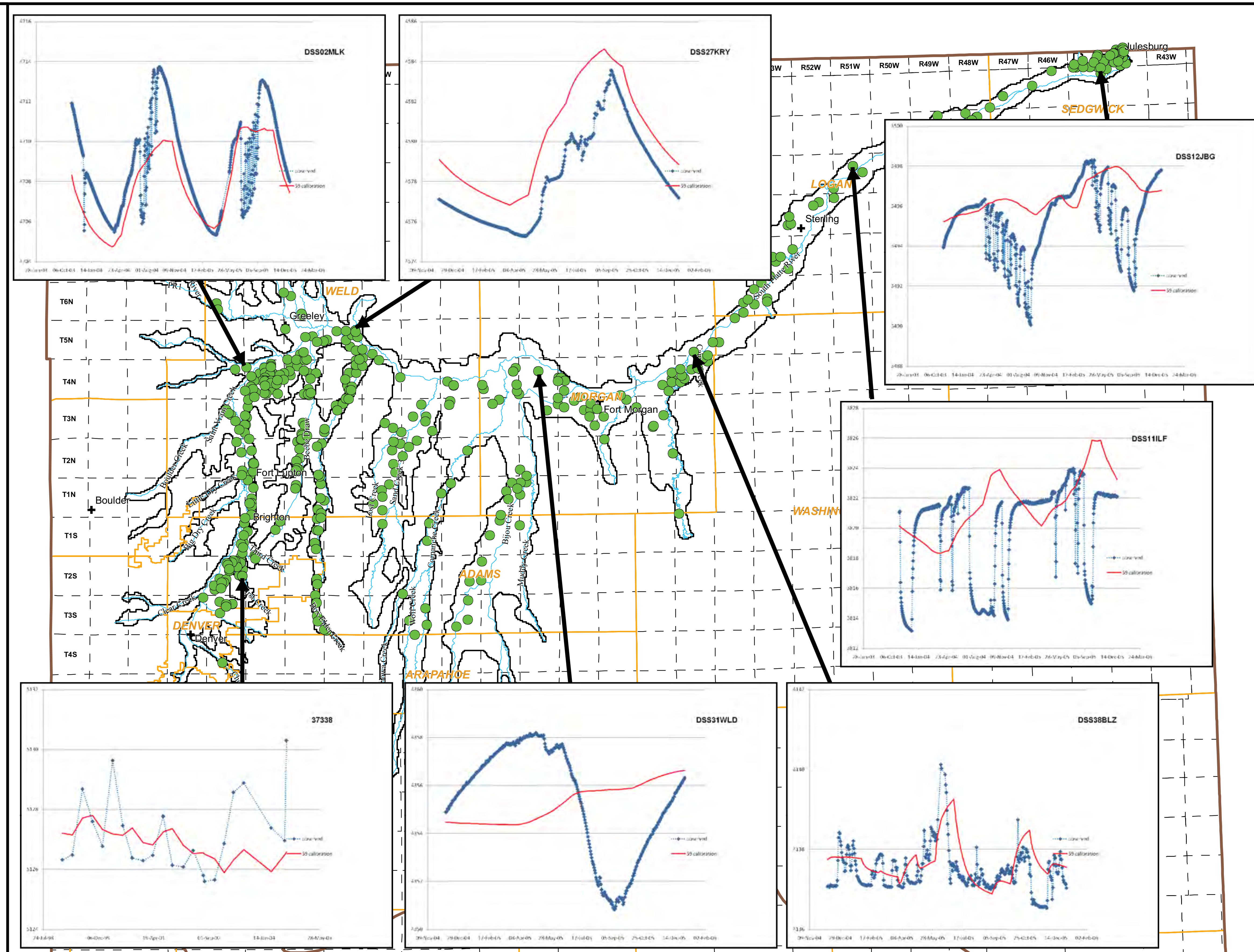
COLORADO DIVISION OF WATER RESOURCES
DEPARTMENT OF NATURAL RESOURCES

COLORADO WATER CONSERVATION BOARD
STATE OF COLORADO
1876
1937

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

- Modeled Well
- City
- Stream
- County



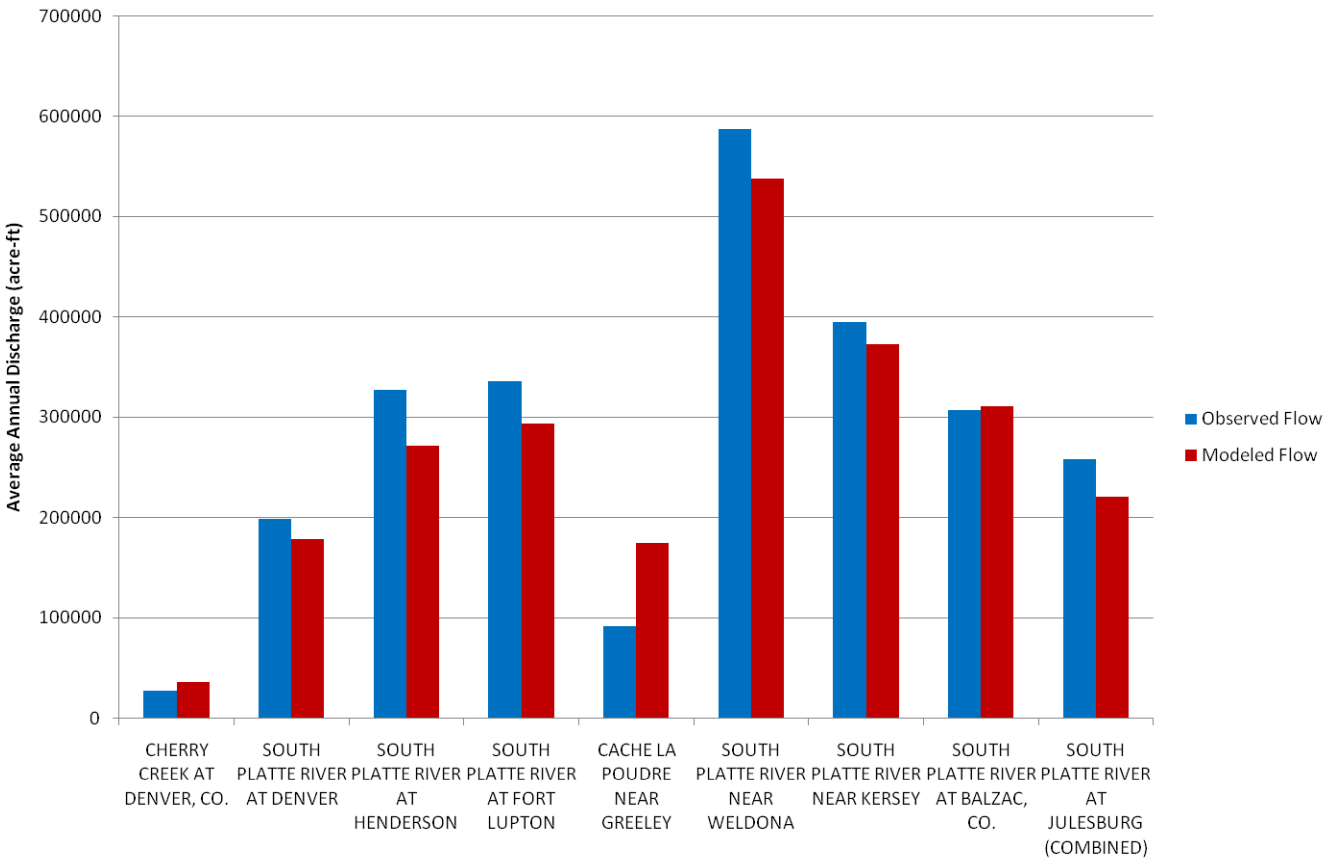
N
W E
S

Scale
1:1,000,000
0 5 10 20
Miles
NAD 1983 UTM Zone 13N

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-12: Comparison of Simulated and Observed Average Annual Stream Discharge

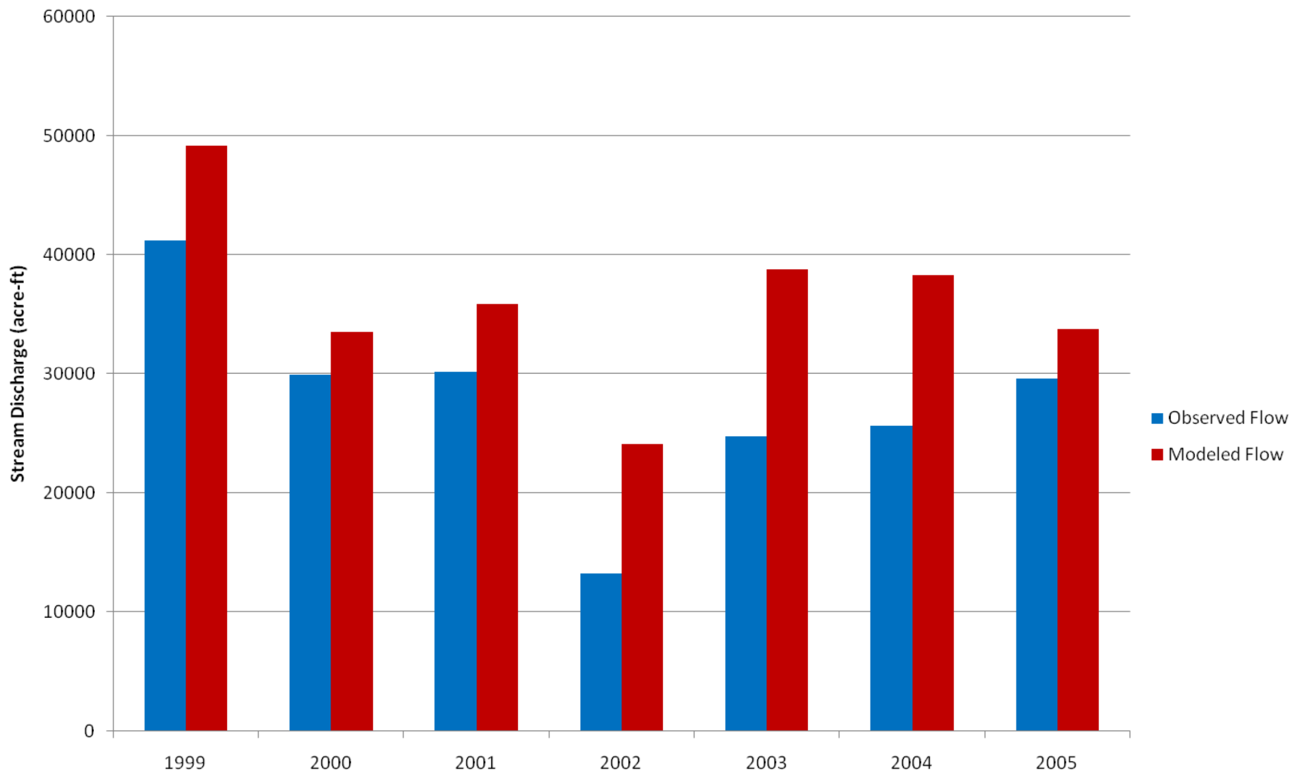


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-13: Comparison of Simulated and Observed Stream Discharge at Cherry Creek at Denver

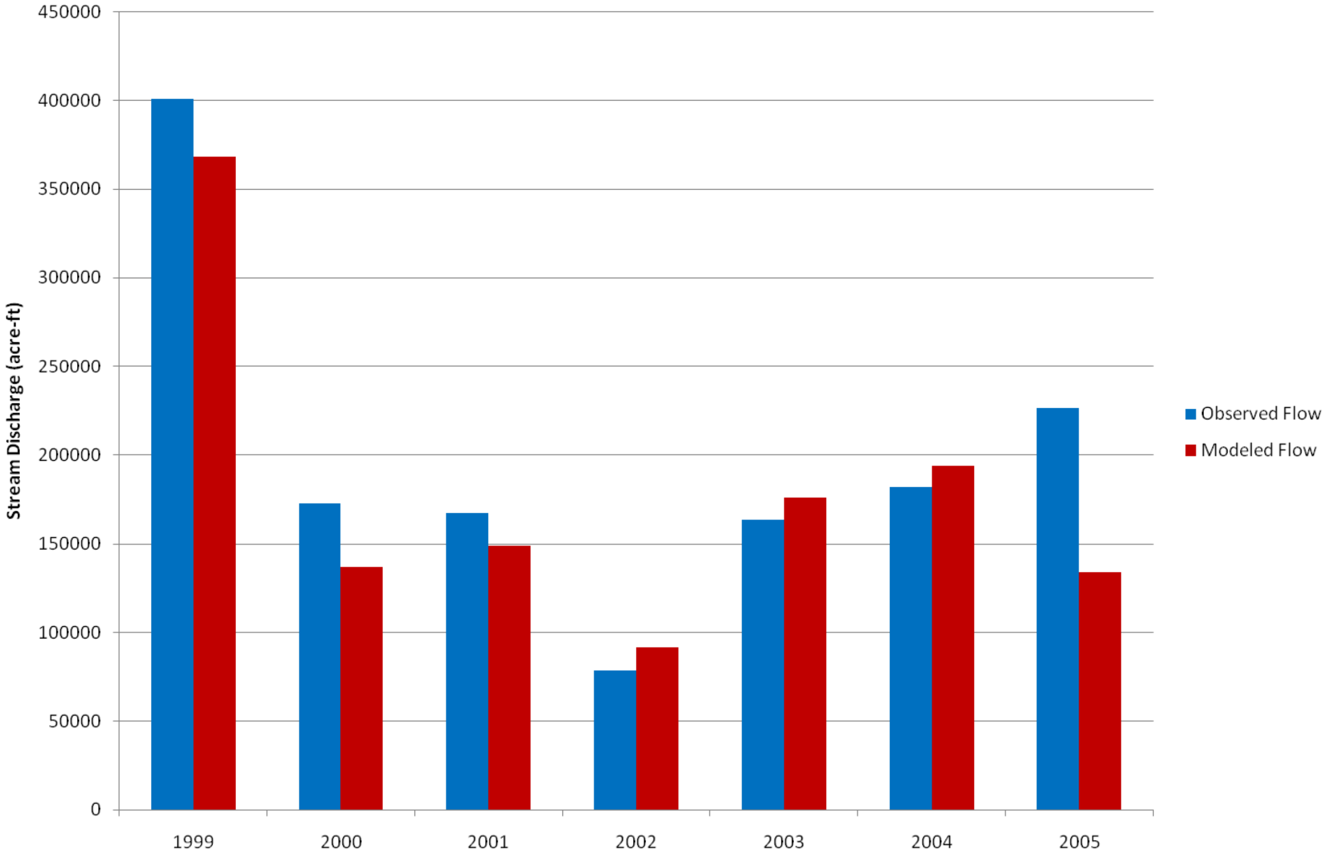


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-14: Comparison of Simulated and Observed Stream Discharge at South Platte River at Denver

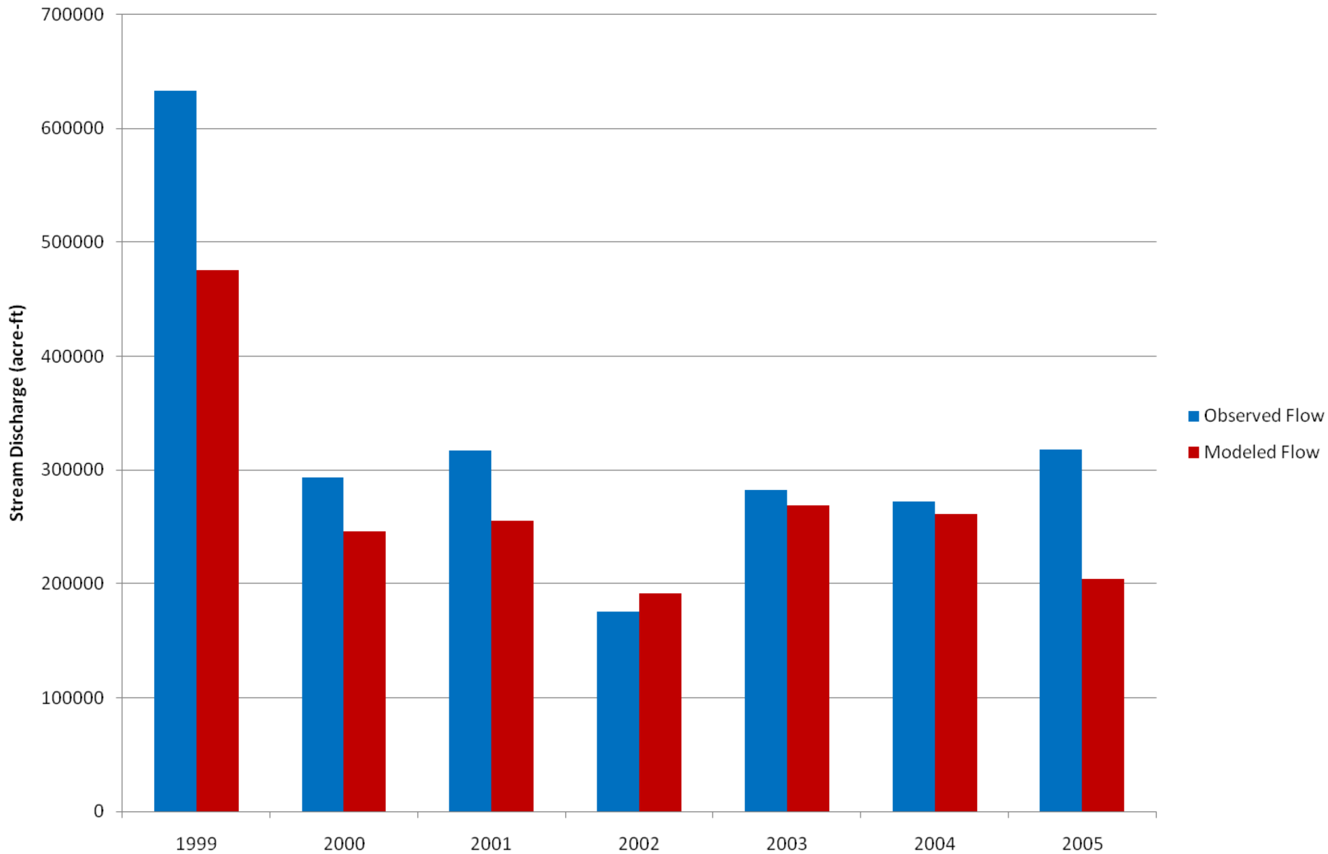


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-15: Comparison of Simulated and Observed Stream Discharge at South Platte River at Henderson

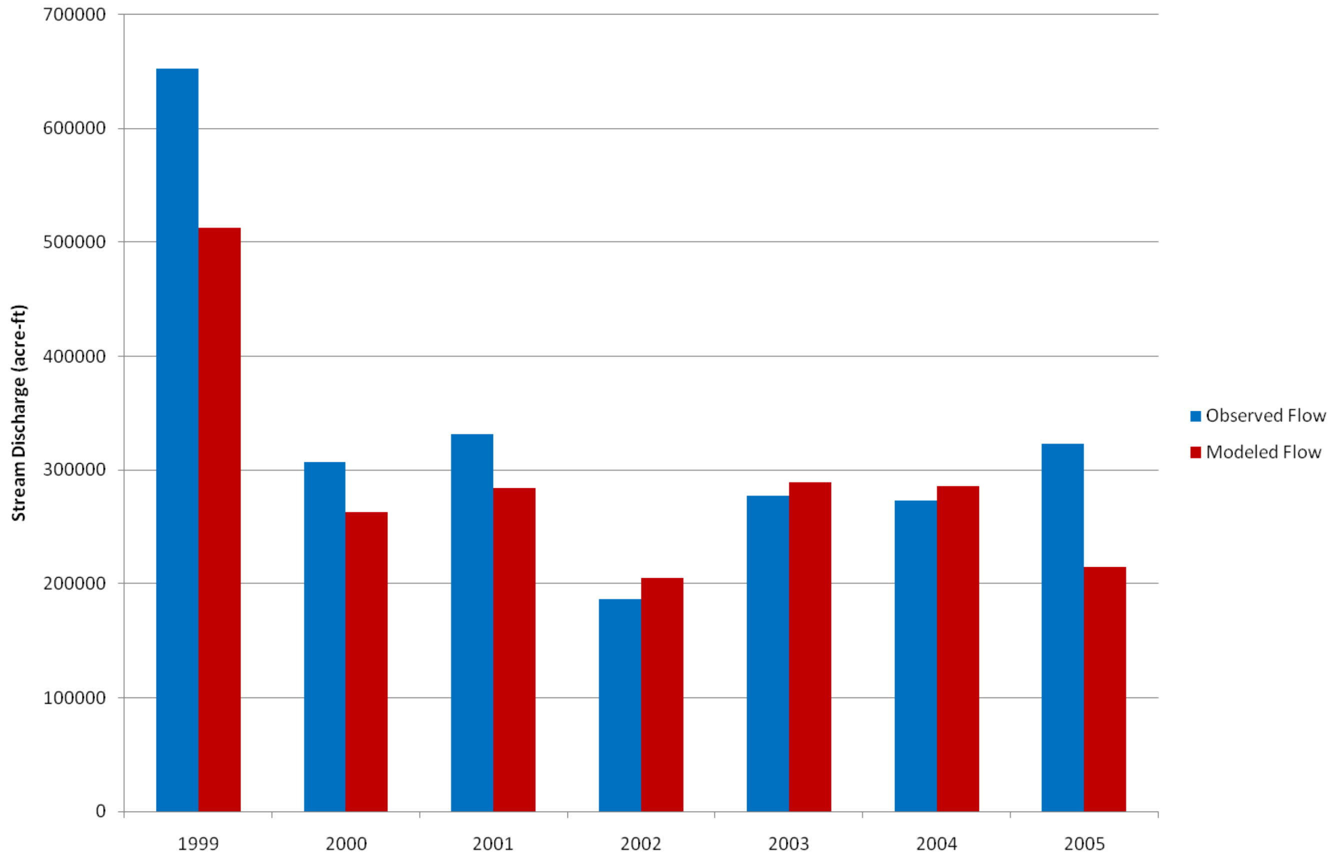


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-16: Comparison of Simulated and Observed Stream Discharge at South Platte River at Fort Lupton

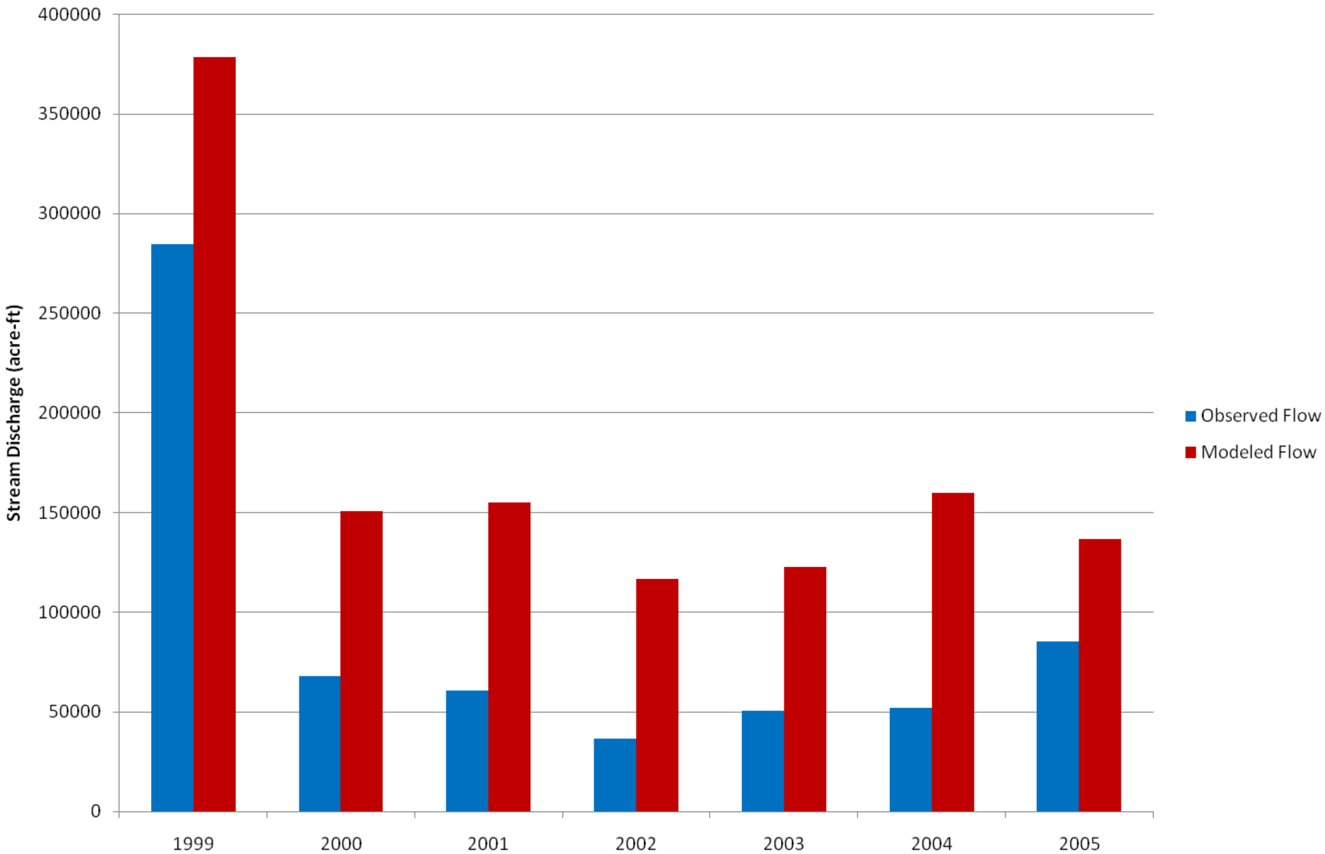


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-17: Comparison of Simulated and Observed Stream Discharge at Cache La Poudre at Greeley

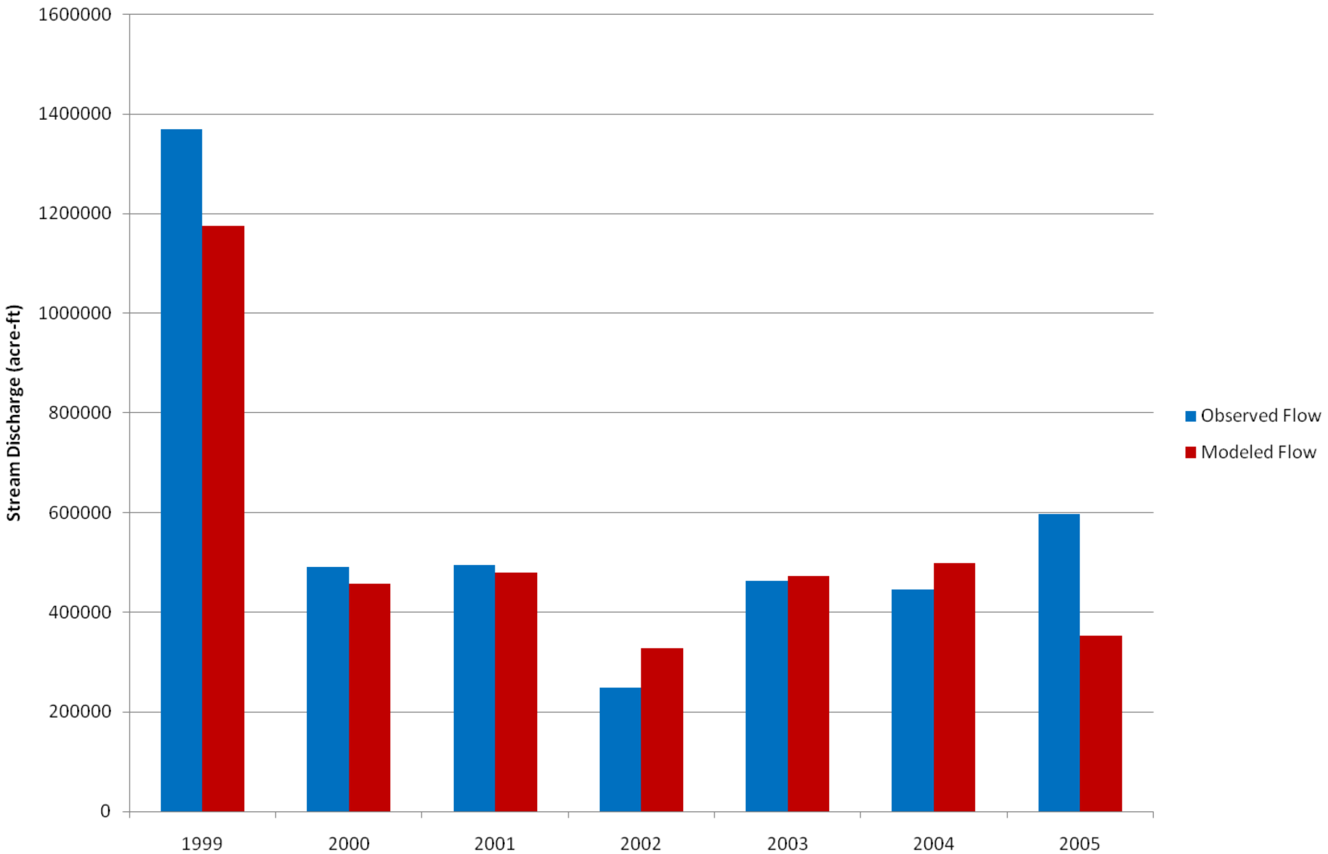


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-18: Comparison of Simulated and Observed Stream Discharge at South Platte River near Weldona

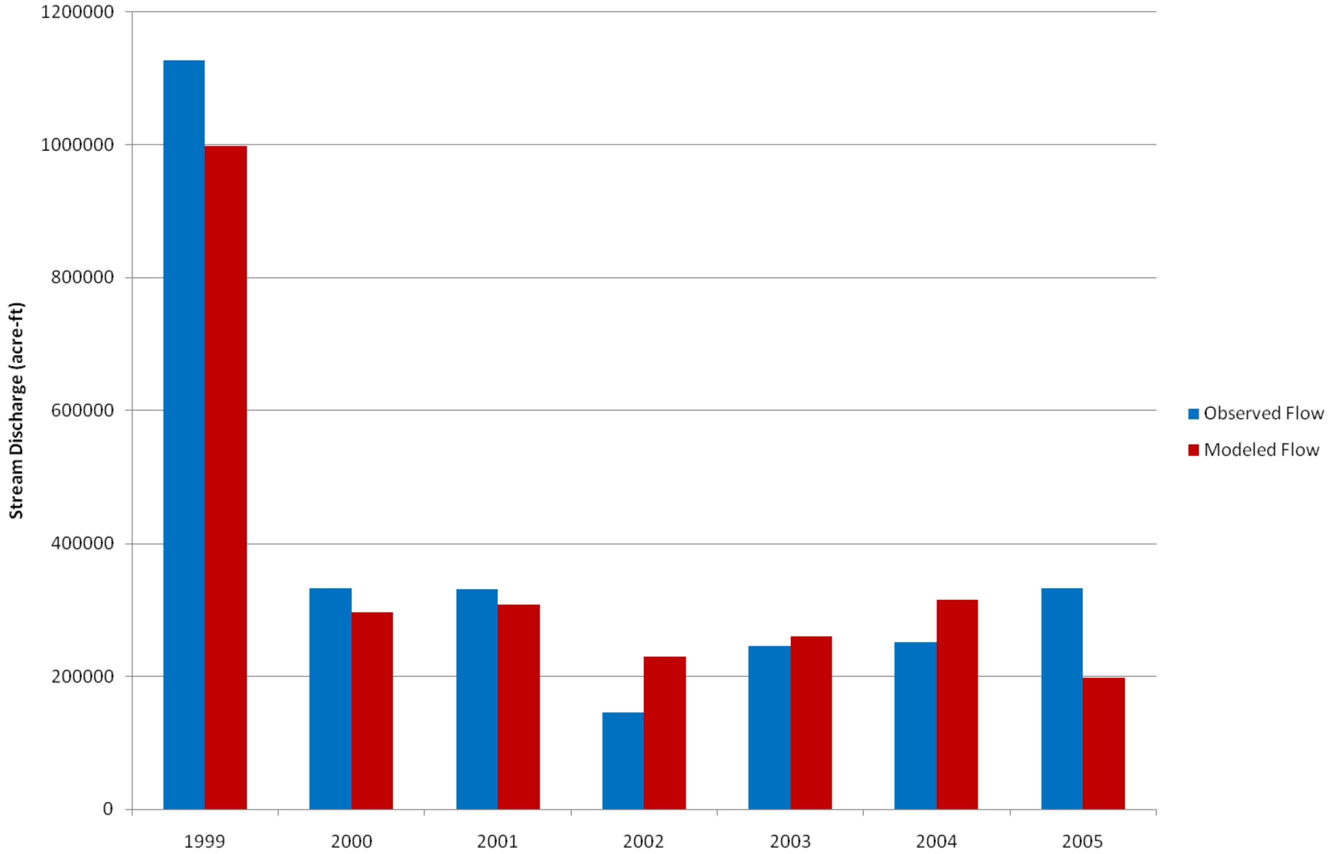


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-19: Comparison of Simulated and Observed Stream Discharge at South Platte River near Kersey

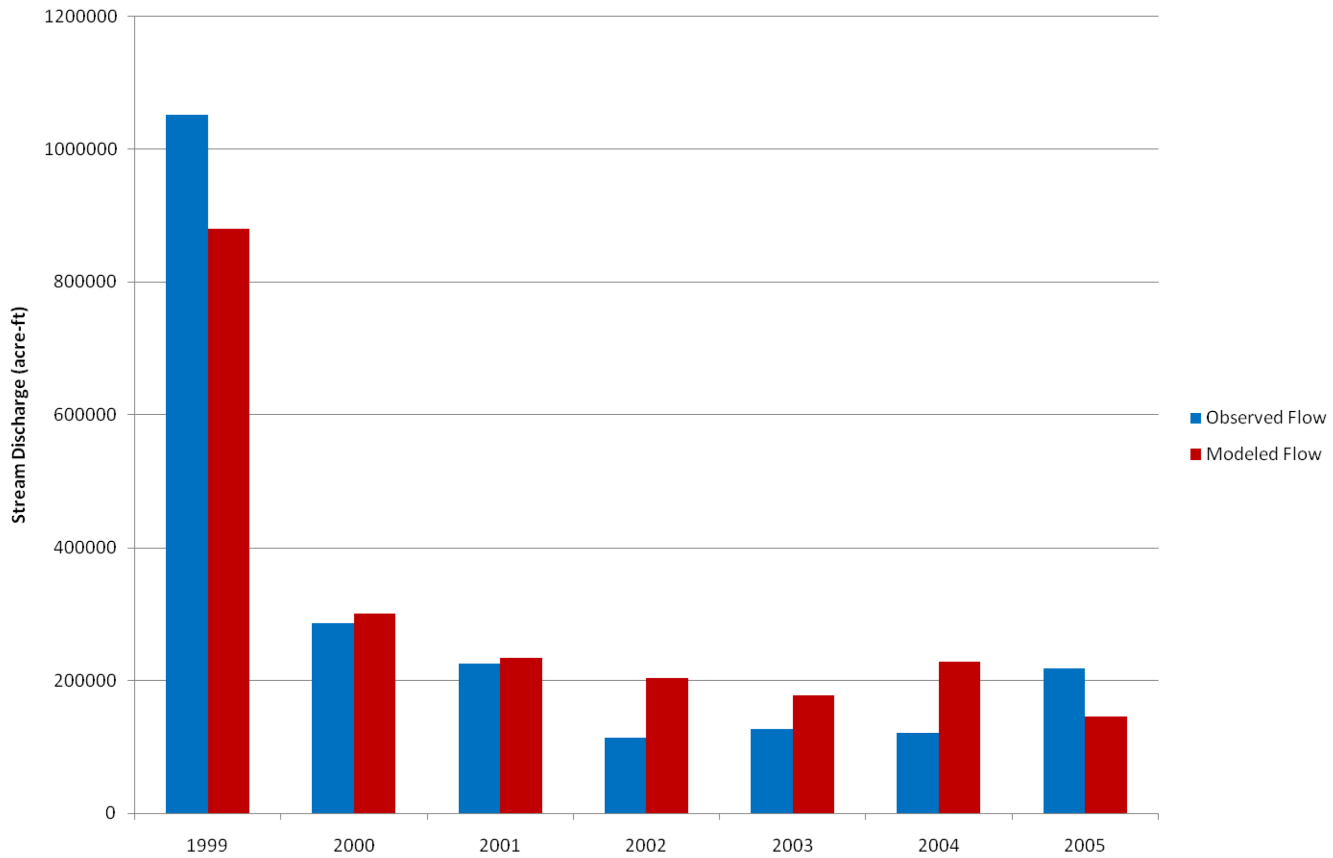


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-20: Comparison of Simulated and Observed Stream Discharge at South Platte River at Balzac

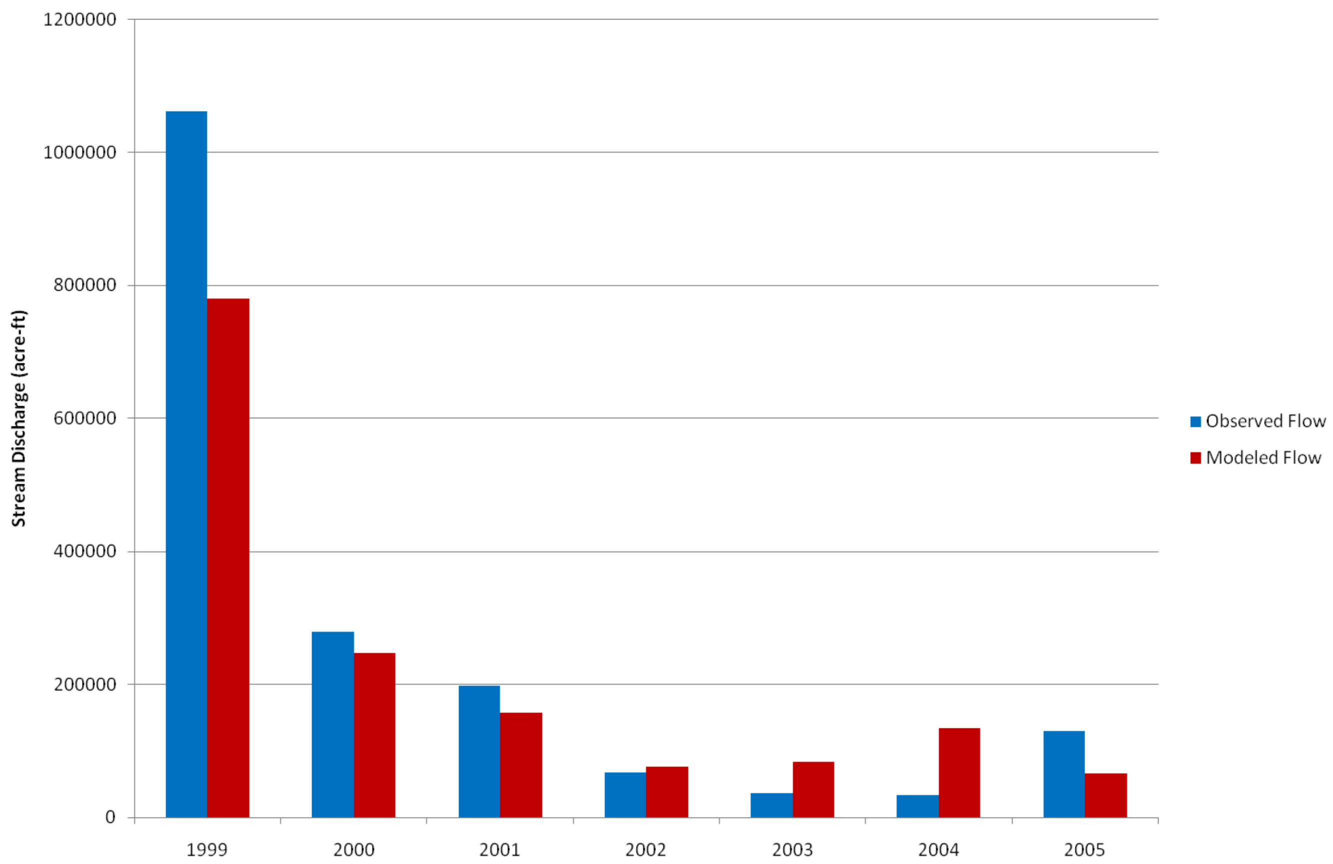


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-21: Comparison of Simulated and Observed Stream Discharge at South Platte River at Julesburg (Combined)

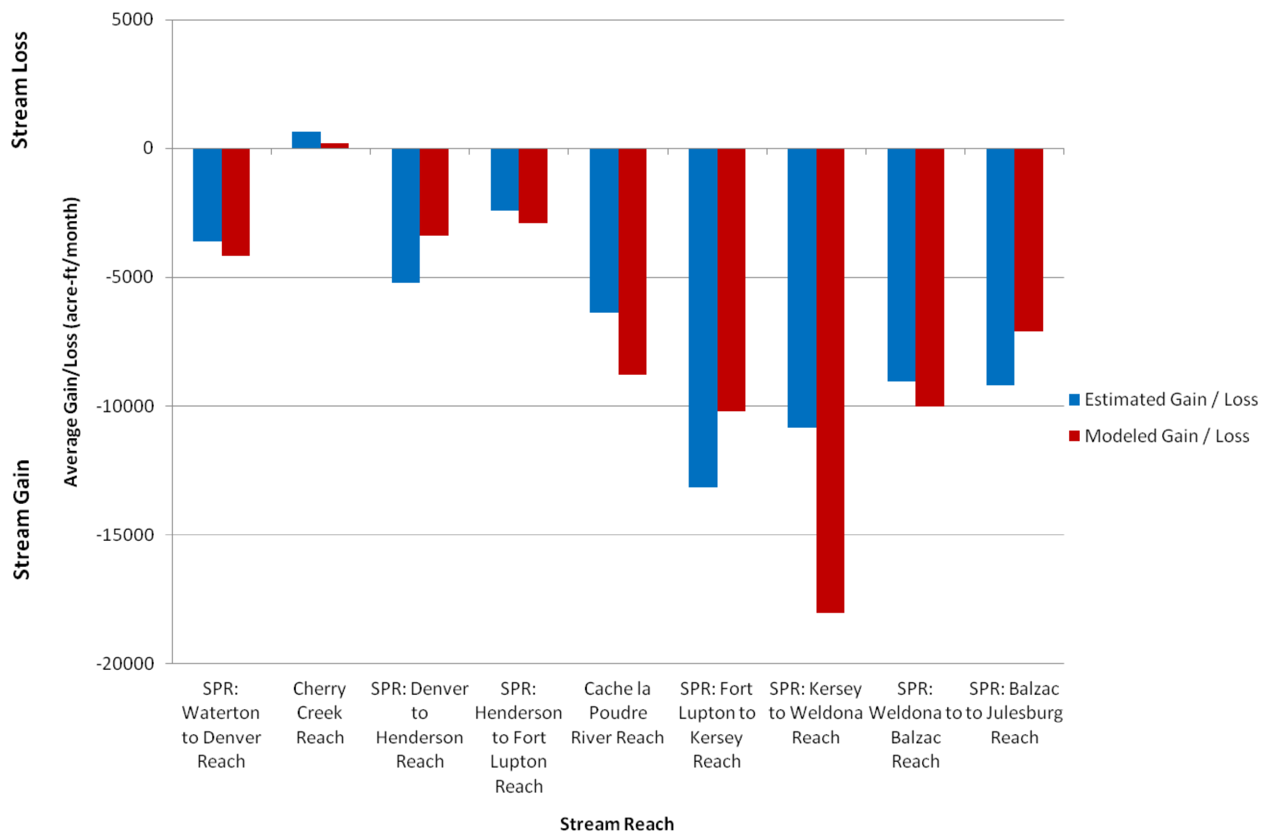


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-22: Comparison of Simulated and Estimated Average Stream Gain/Loss during the Calibration Period

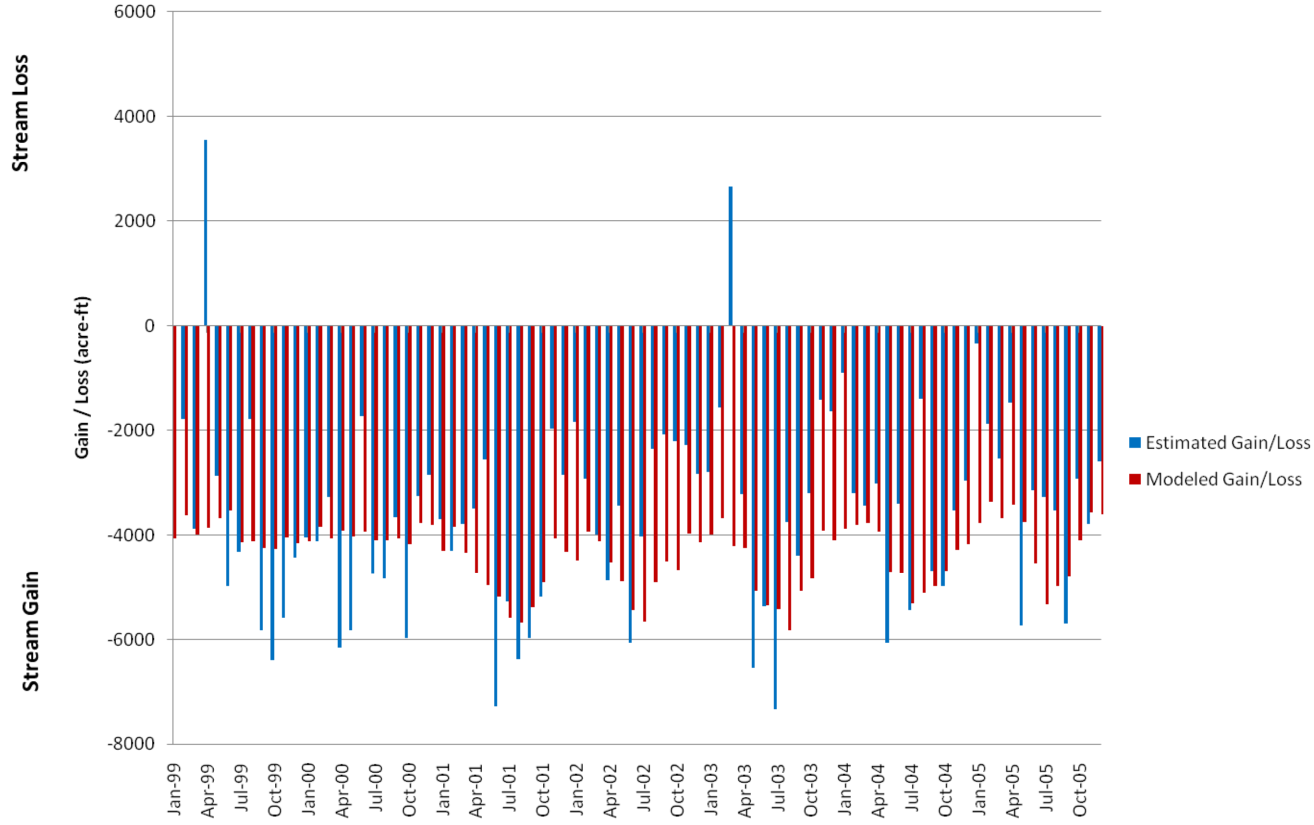


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-23: Comparison of Simulated and Estimated Monthly Stream Gain/Loss for Waterton to Denver Reach on the South Platte River

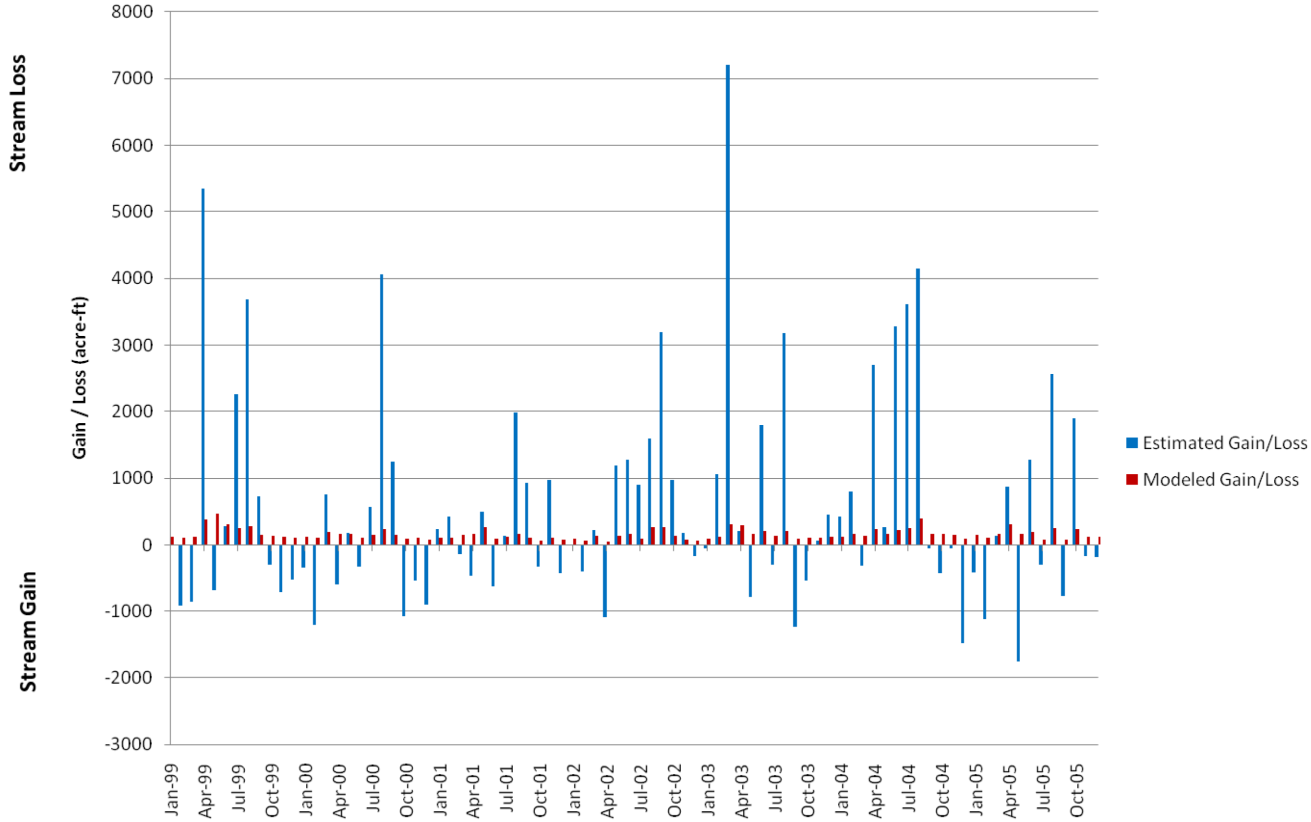


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-24: Comparison of Simulated and Estimated Monthly Stream Gain/Loss for Cherry Creek

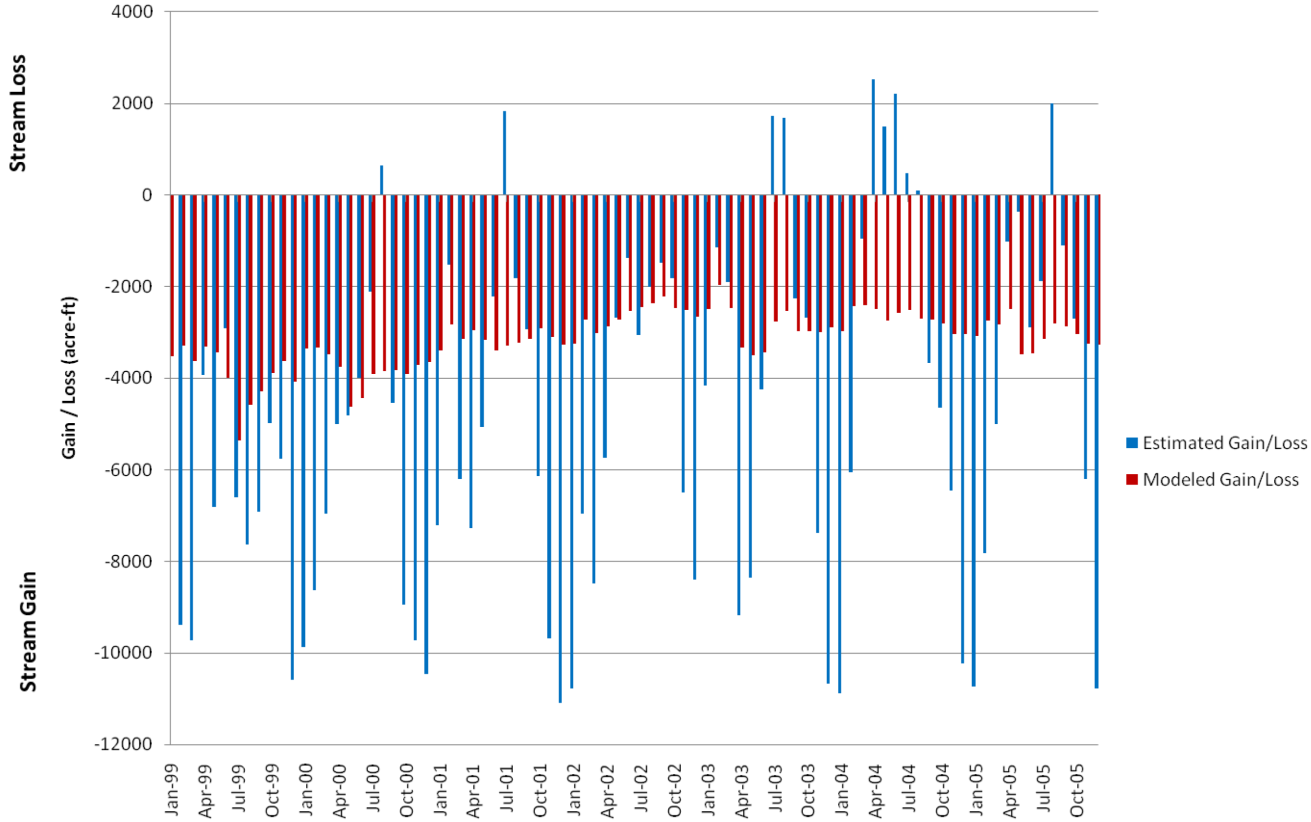


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-25: Comparison of Simulated and Estimated Monthly Stream Gain/Loss for Denver to Henderson Reach on the South Platte River

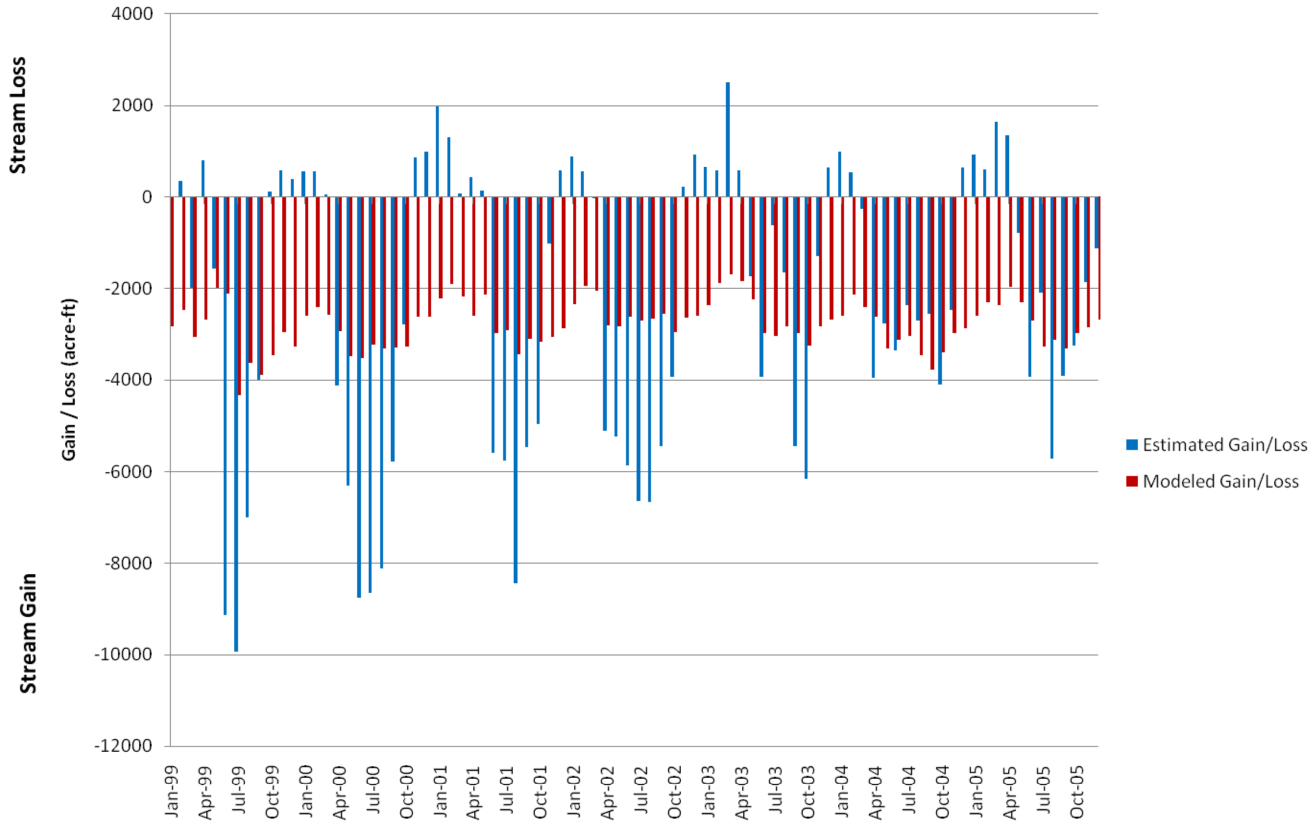


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

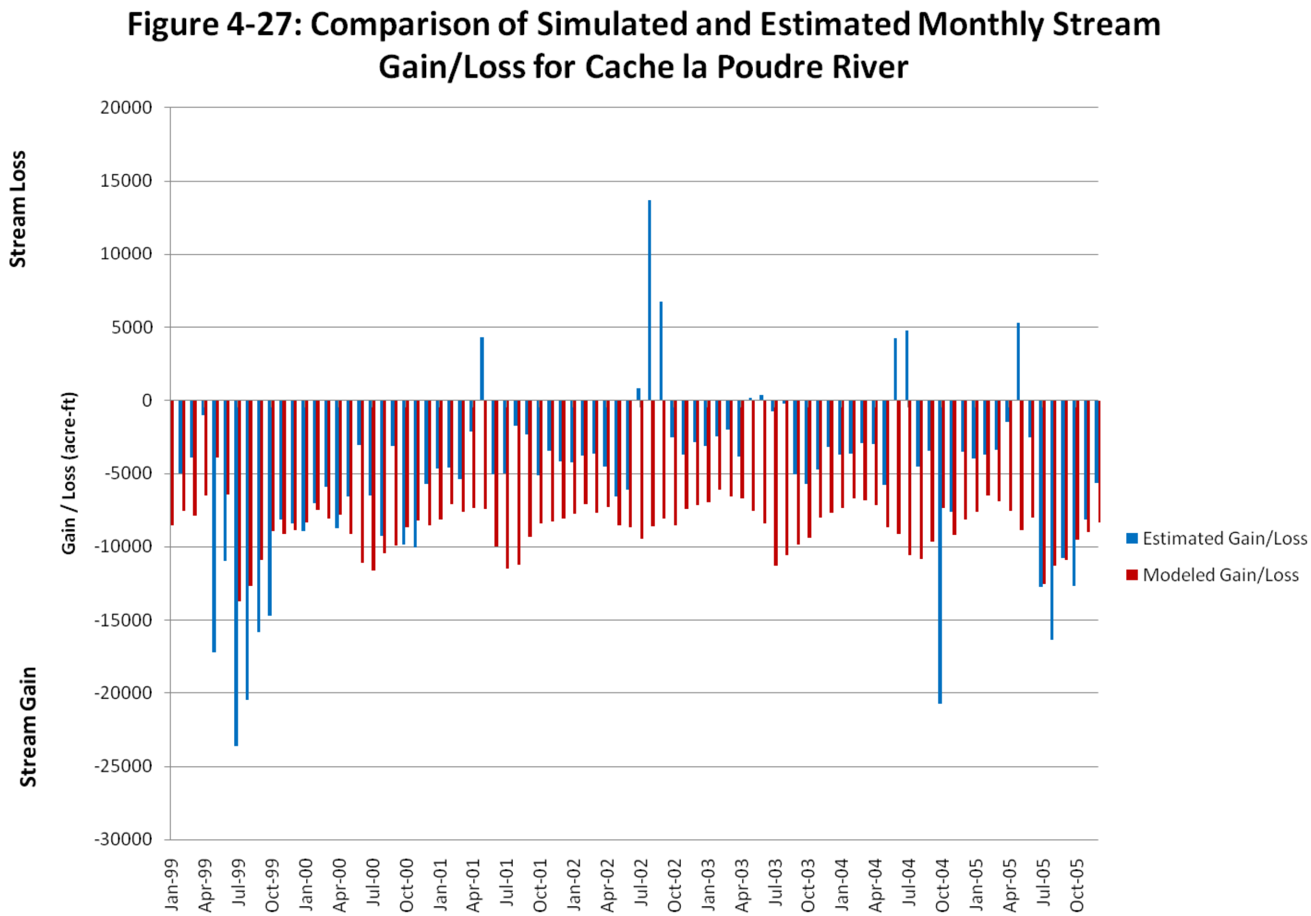
Figure 4-26: Comparison of Simulated and Estimated Monthly Stream Gain/Loss for Henderson to Fort Lupton Reach on the South Platte River



State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

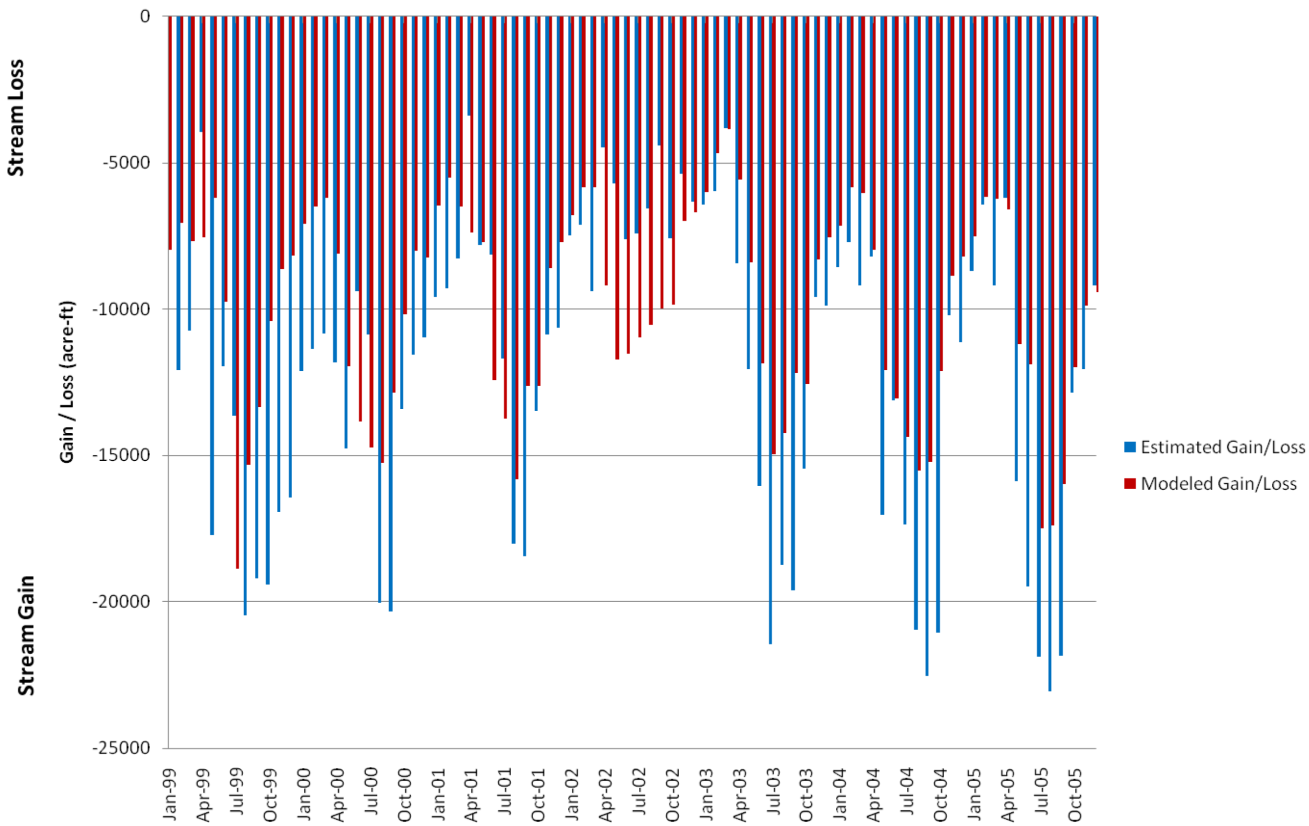


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

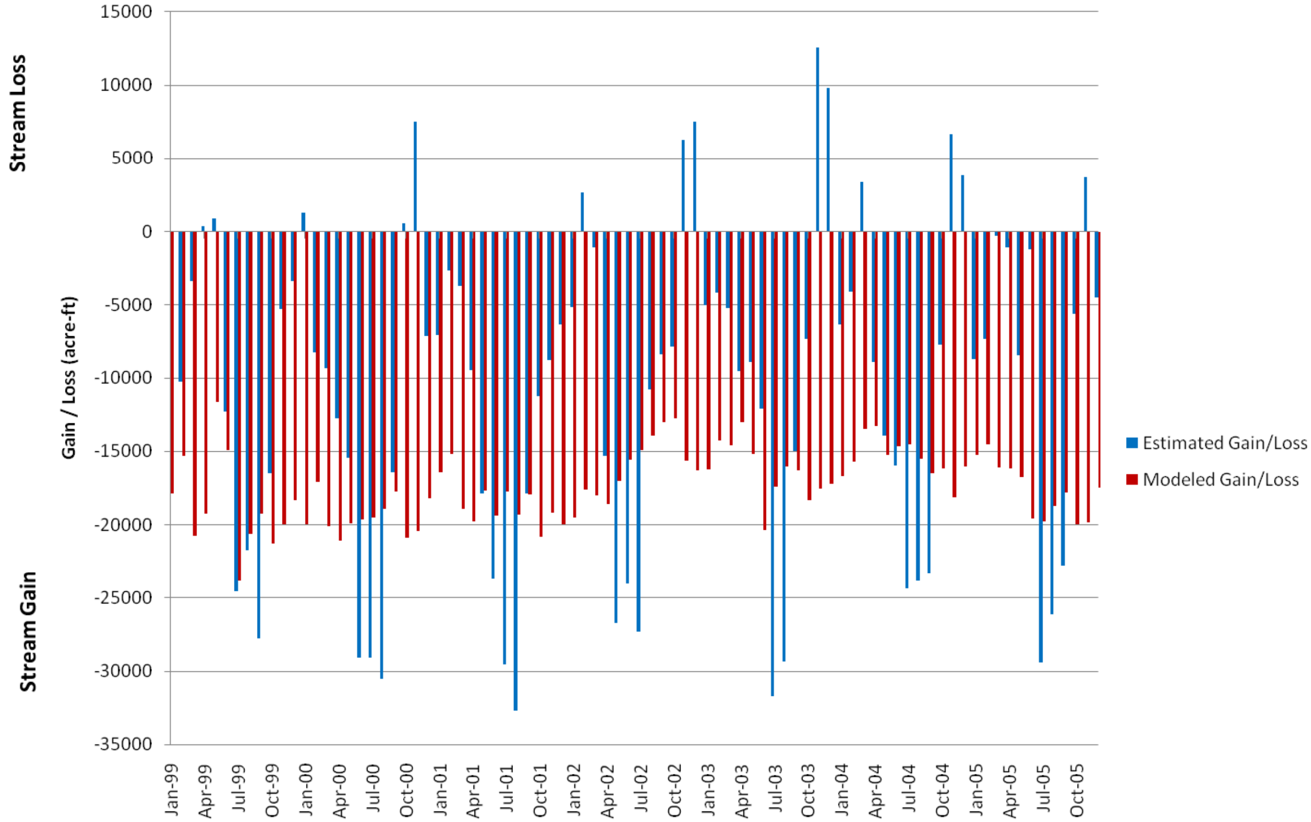
Figure 4-28: Comparison of Simulated and Estimated Monthly Stream Gain/Loss for the Fort Lupton to Kersey Reach on the South Platte River



State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

Figure 4-29: Comparison of Simulated and Estimated Monthly Stream Gain/Loss for the Kersey to Weldona Reach on the South Platte River

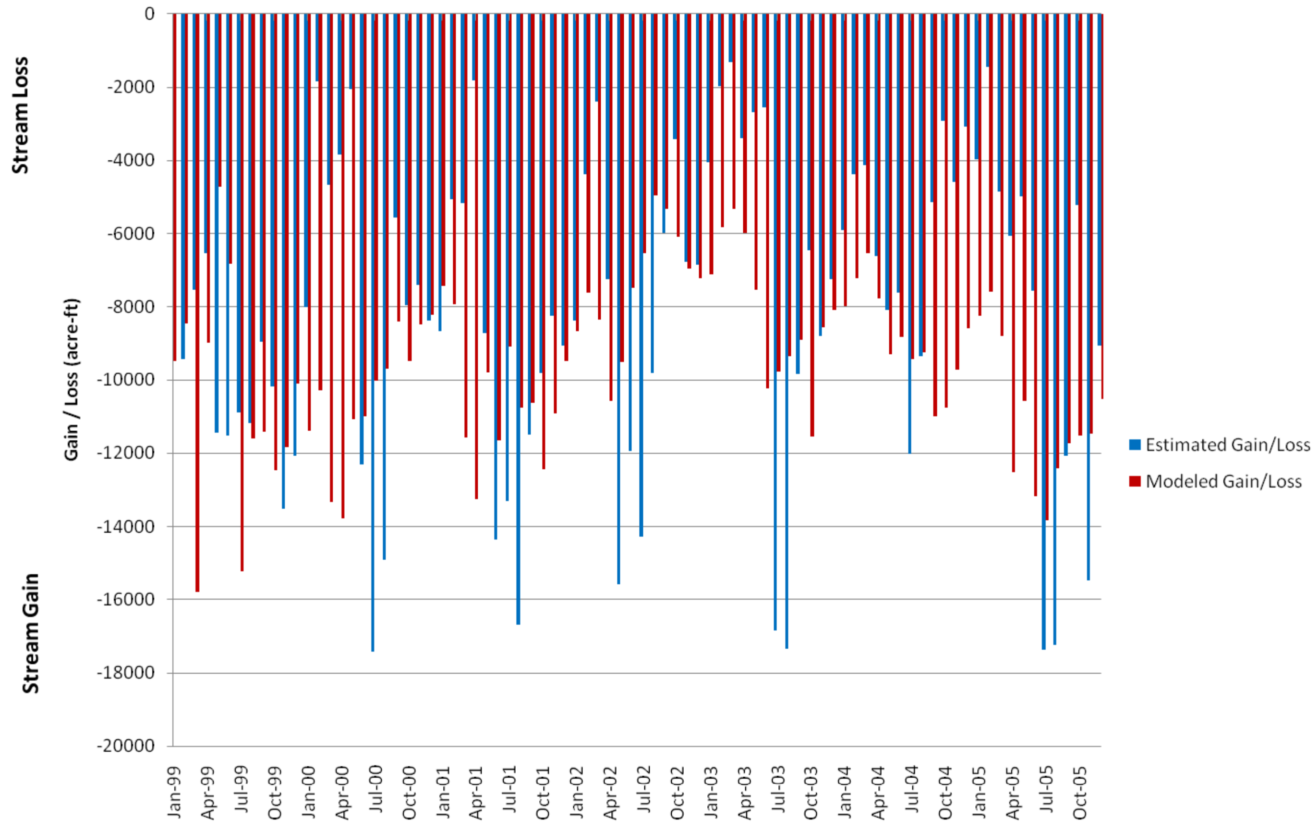


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-30: Comparison of Simulated and Estimated Monthly Stream Gain/Loss for the Weldona to Balzac Reach on the South Platte River

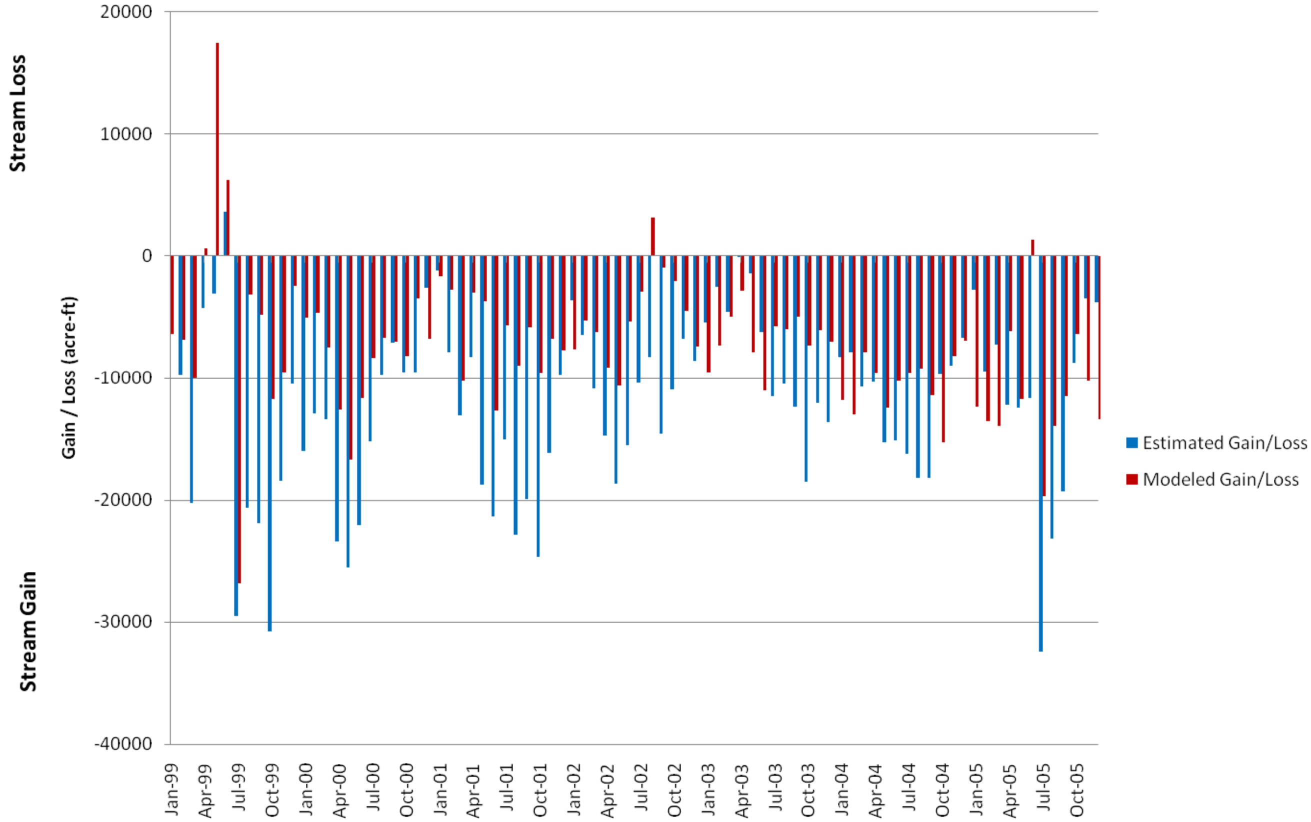


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-31: Comparison of Simulated and Estimated Monthly Stream Gain/Loss for the Balzac to Julesburg Reach on the South Platte River

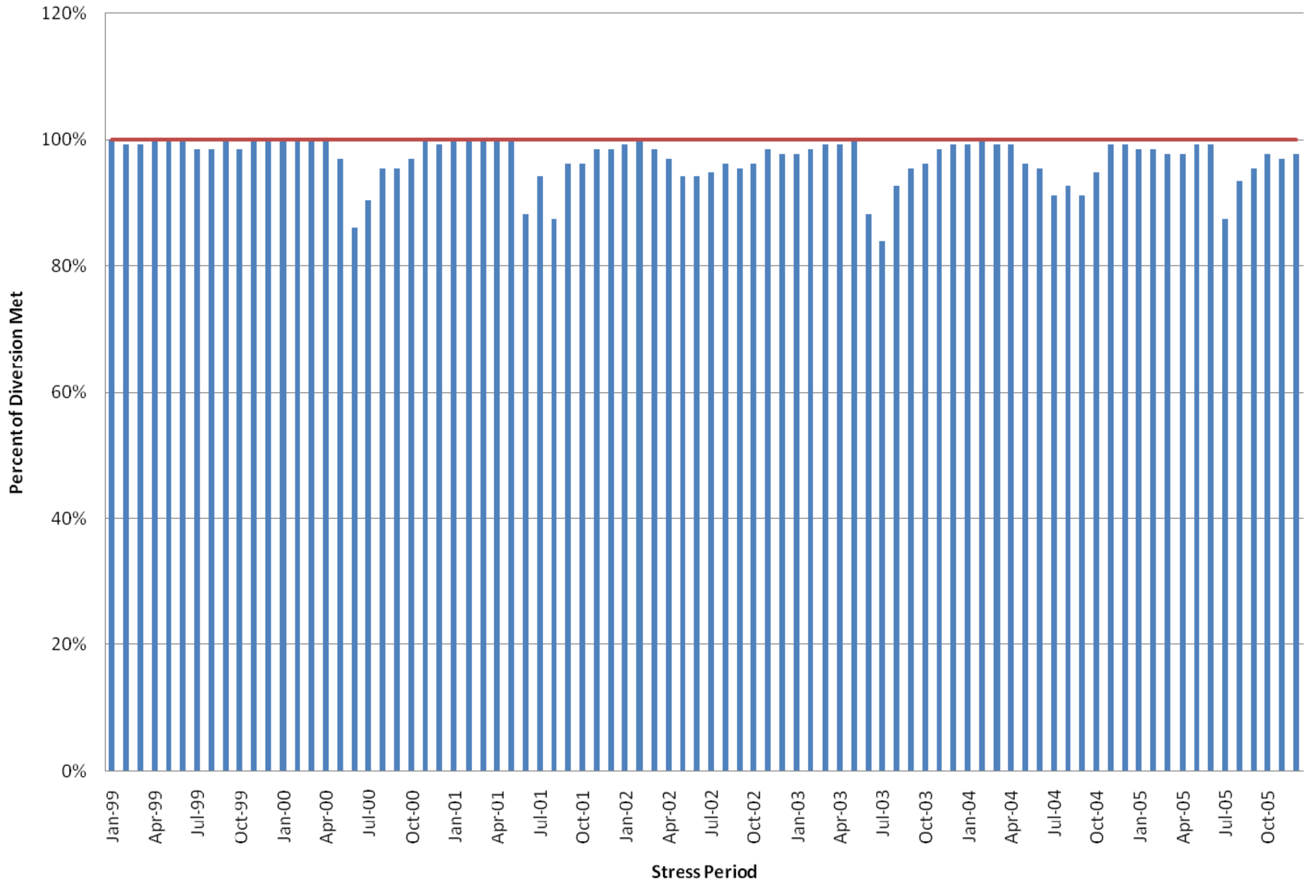


State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-32: Summary of Diversions Met During Calibration Period



State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Prepared by: CDM

SPDSS Alluvial Groundwater Model Report

Figure 4-33: Location of Dry and Flooded Cells in February, 2000

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

Legend

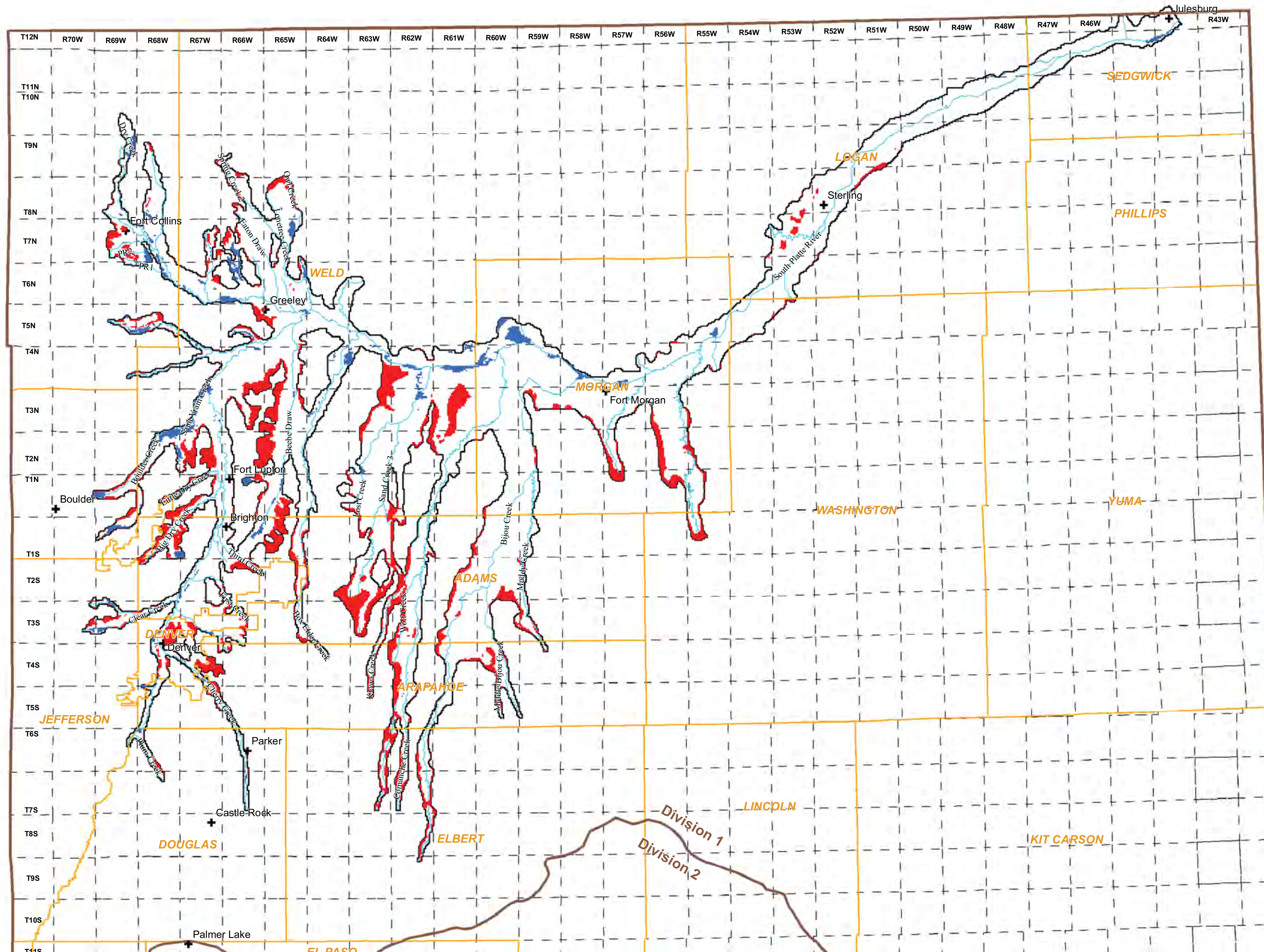
- Flooded Cells
- Dry Cells
- City
- Stream
- County

Scale 1:950,000

0 5 10 20 Miles

NAD 1983 UTM Zone 13N

Prepared by: CDM



SPDSS Alluvial Groundwater Model Report

Figure 4-34: Location of Dry and Flooded Cells in August, 2000