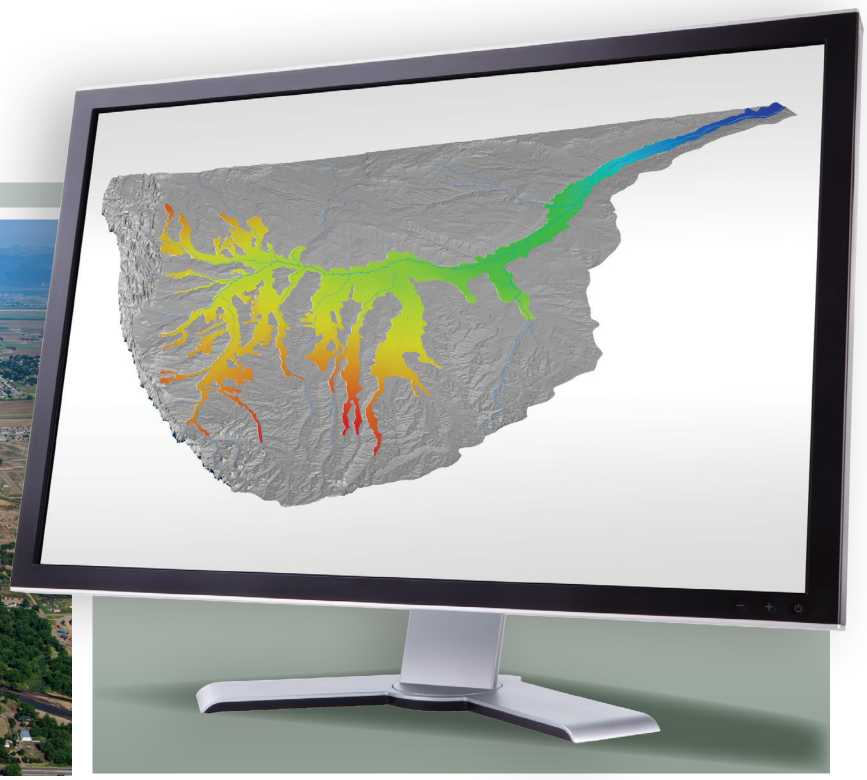
Brown AND Caldwell

FINAL REPORT | Prepared for
The Colorado Water Conservation Board and Division of Water Resources

South Platte Decision Support System Alluvial Groundwater Model Update Documentation

June 2017



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Executive Summary

This report documents the update of a numerical groundwater flow model (model) developed for a major portion of the alluvial groundwater system of the South Platte River Basin (Basin). The model area includes the unconsolidated alluvial deposits of the mainstem South Platte River from Chatfield Reservoir downstream to the Colorado-Nebraska border and the connected, unconsolidated alluvial deposits of significant tributaries to the South Platte River. The model is constructed in MODFLOW, the widely used and accepted U.S. Geological Survey (USGS) groundwater simulation code. The updated model is a part of the continued, ongoing development of the South Platte Decision Support System (SPDSS), which in turn is a component of Colorado's Decision Support Systems (CDSS). CDSS is a joint effort of the Colorado Water Conservation Board (CWCB) and the Colorado Division of Water Resources (DWR) to develop publicly available data sets and analytical tools to assist in water resources management and planning activities within Colorado.

The model was developed to be a planning-level tool for the management of the alluvial aquifer associated with the South Platte River and its tributaries and is designed to simulate groundwater flow and groundwater/surface water interactions at a regional scale in the Basin (Figure ES-1).

The previous version of the model simulated the period from 1950 through 2006 and was completed and documented in 2013 by CDM-Smith for the CWCB and DWR.

The current modeling effort included:

- Extending the simulated period of the model from 1950 through 2012 based on additional hydrologic and water use data;
- Upgrading the model execution code from the MODFLOW-2000 version to the modern and currently supported MODFLOW-NWT version;
- Improving and streamlining the simulated water budget accounting process by incorporating the Partition Stress Boundaries (PSB) capability originally developed by the USGS for CDSS;
- Reducing the overall model input and output file sizes to improve the model's usability; and
- Providing improvements and updates to data processing procedures used in the generation of model input files.

This executive summary briefly describes the following: 1) extension of historical time-series data; 2) CDSS Toolbox/StateDGI updates and development of model input files; and 3) model simulation and calibration results.

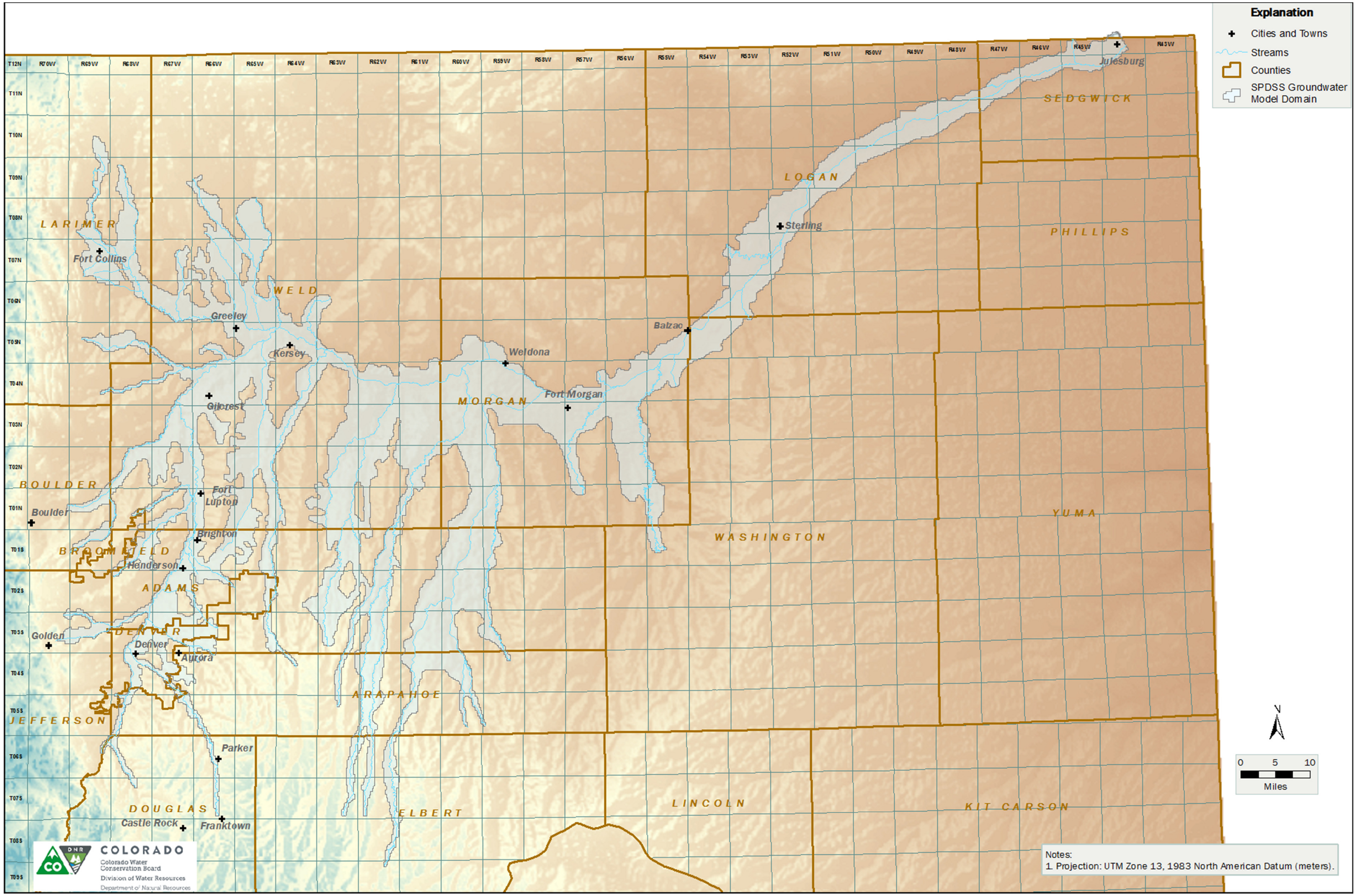

Figure ES-1. Model Study Area

Extension of Historical Time-Series Data

CDSS employs a “data-centered approach” to the development and use of analytical and numerical simulation models. In the data-centered approach, DWR’s water resources database, HydroBase, provides the primary source of data underpinning the models. Table ES-1 lists the time-series data sets that were extended and describes the processes for extending the data sets. The extended data sets were used to develop model input files and reflect the most recent available data.

Table ES-1. Time-Series Data Set Extension Approach

Time-Series Data Set	Extension Approach
Alluvial underflow into model	The rates of monthly alluvial groundwater inflow entering the model domain at modeled tributary branches were calculated during the initial modeling effort and are constant year-to-year. The same values were used for the extended modeling period.
Bedrock fluxes	Bedrock fluxes were calculated using the USGS Denver Basin model. The USGS model simulation period of record ended in 2003. The 2003 fluxes were repeated for subsequent years of the model, including the extended modeling period.
Reservoir seepage	Reservoir seepage rates were assumed to be constant for a given soil type underlying the reservoirs. The seepage rates already in the initial model were used for the extended modeling period.
Streamflow routing components: streamflow, M&I discharges, and diversions	Historical streamflows and diversion records for the extended modeling period were collected from HydroBase by Wilson Water Group (SPDSS consumptive use analysis contractor) and were provided. Incomplete records were filled using regression or other suitable methods as described in the SPDSS Task 2 technical memorandum (Leonard Rice Engineers 2007). Tributary inflows at the edge of the model domain were estimated using the nearest downstream gage and then adding diversions occurring between the gage and the model boundary. See Appendix A of the main report for details on the data collection efforts. M&I discharge data were collected from the EPA database.
Precipitation	Historical monthly precipitation data from the key climate stations identified in the initial modeling effort were retrieved from HydroBase by Wilson Water Group and were provided. Missing data were filled using linear regression. The climate station weights used to distribute precipitation across the model domain and the percentages used to determine the amount of precipitation that becomes recharge (based on land use and soil types) were not changed from the initial modeling effort.
Consumptive-use model output: agricultural pumping, canal seepage, and irrigation recharge	Agricultural pumping, canal seepage, and irrigation recharge time-series data were estimated using StateCU model output. The consumptive-use modeling was completed by Wilson Water Group and results were provided. The model output contained monthly values for each parameter. See Appendix A of the main report for details on the data-collection efforts.
M&I pumping	The historical M&I pumping data were extended using a combination of data retrieved from HydroBase and data provided by the well users. HydroBase data were preferred to user-supplied data. Missing or incomplete records were filled using similar methods from the initial modeling effort. The availability of HydroBase data was limited during the initial modeling effort. Estimated values prior to 2006 were replaced with newly available HydroBase records when possible. See Appendix A of the main report for details on the data-collection efforts and filling procedures.

Table ES-1. Time-Series Data Set Extension Approach	
Time-Series Data Set	**Extension Approach**
Augmentation and recharge	Recharge areas: Augmentation recharge was estimated using recharge pond delivery records. Delivery records were retrieved from HydroBase and provided by Wilson Water Group. New recharge facilities that came on line during the extended modeling period were added to the model as part of the model update. Recharge and augmentation pumping: Historical recharge pumping records were compiled by Wilson Water Group and provided. Appropriate wells were identified with the help of the Division 1 Engineer's office. Pumping records were retrieved from HydroBase. Historical augmentation pumping records were also collected from HydroBase by Wilson Water Group and provided. The Division 1 Engineer's office assisted in identifying the appropriate wells. See Appendix A of the main report for details on the data-collection efforts.
Lateral boundary inflow fluxes	Lateral boundary inflow fluxes represent a combination of precipitation recharge, irrigation recharge, canal seepage, and pumping that occur outside the active model domain and that generate groundwater flux across the active model domain boundary. Existing tools were updated and used to combine the component fluxes and generate lagged boundary inflow values.

CDSS Toolbox/StateDGI Updates and Development of Model Input Files

During the model update effort, several CDSS tools and data management interfaces (DMIs) were updated and improved in a number of ways, including: modernizing code, removing redundant code, improving code performance and consistency, ensuring compatibility where possible with open source software by replacing code specific to proprietary compilers, and adding functionality. The updates and improvements to these tools are described in Table ES-2.

Table ES-2. CDSS Tools and DMIs Updated	
CDSS Tool/DMI	**Description of Updates**
CDSS Toolbox	The Python scripts were converted to use the modern ArcPy GIS environment, redundant code was removed, the logic of geoprocessing operations was checked to ensure that the scripts process data correctly. An updated CDSS Toolbox user manual is included as Appendix B of the main report.
State Data-Centered Ground Water Interface (StateDGI)	An issue was identified and resolved for the series of linked queries that locate groundwater model cells under irrigation canals and label each of those model cells with an identifier for the irrigation canal such that canal seepage recharge estimates from StateCU can be applied to those model cells. A second issue was identified and resolved for the series of linked queries that apportion partial irrigated acreage and pumping capacity between irrigation wells that serve multiple irrigated parcels.
State Pre-Processor (StatePP)	Support was added to produce MODFLOW input files that can be used with PSB to separate and individually track different water budget components. Updates were made to generate MODFLOW electronic input files that are of smaller and more manageable sizes. Additional code comments were added to better document the flow of the code in some places, and minor changes were made to the flow of the code to improve efficiency and speed of execution.
SFR2 Generator	Code was converted from older Visual Basic .NET source code to an ArcPy-based Python script that can be executed in ArcGIS. An ArcToolbox (.tbx) file was created that provides a graphical user interface to execute the script with the appropriate input parameters chosen by the user.
Lateral Boundary Processor	Several coding inefficiencies were found and improved, reducing the time to execute from over 10 hours to approximately 1 hour.

Table ES-2. CDSS Tools and DMIs Updated	
CDSS Tool/DMI	Description of Updates
g2gflow	Instructions specific to the proprietary Intel Fortran compiler were replaced with equivalent standard Fortran to make the code open-source compatible and compliant with all compilers that adhere to Fortran standards.
proc_rainfall	Instructions specific to the proprietary Intel Fortran compiler were replaced with equivalent standard Fortran to make the code open-source compatible and compliant with all compilers that adhere to Fortran standards.
proc_runoff	Code was updated to write estimated runoff values to a specific "RUNOFF" variable for each stream segment rather than adding them to the "FLOW" variable to simplify and improve reporting and analysis of the simulated water budget for streams represented by the model. Instructions specific to the proprietary Intel Fortran compiler were replaced with equivalent standard Fortran to make the code open-source compatible and compliant with all compilers that adhere to Fortran standards.

These tools along with other existing CDSS DMIs were used to generate the MODFLOW electronic input files for the updated model.

The updated model now uses the USGS code MODFLOW-NWT, a version of MODFLOW that uses more powerful numerical methods to solve the equations governing unconfined groundwater flow both more rigorously and quickly (Niswonger et al. 2011). An additional modification was made to the MODFLOW-NWT executable used for the updated model through the incorporation of PSB to simplify and improve the input, tracking, and reporting of each water budget component throughout the simulation.

Model Simulation and Calibration Results

The simulated water budget for the updated model was tabulated and evaluated for the 1950 to 2012 extended simulation period for both groundwater and surface water components. Tables ES-3 and ES-4 present the simulated average annual groundwater and surface water budgets. The following are some key observations on the simulated water budget:

- While groundwater volumes moving in and out of storage throughout the model domain are more than 400,000 acre-feet per year (ac-ft/yr) on average, the average annual net change in groundwater storage is approximately 53,000 ac-ft/yr of groundwater flow into groundwater sinks (e.g., wells, evapotranspiration) from storage.
- The largest average annual simulated inflow to the alluvial aquifer system is from the lateral boundary inflows (approximately 500,000 ac-ft/yr), followed by recharge from both irrigation return flows (more than 400,000 ac-ft/yr for irrigation from surface water sources and 140,000 ac-ft/yr for irrigation from groundwater) and canal seepage (approximately 360,000 ac-ft/yr).
- The largest average annual simulated groundwater outflow is to the surface water system as stream gain (more than 1.3 million ac-ft/yr), followed by agricultural irrigation pumping (approximately 450,000 ac-ft/yr).
- Stream gain (cited in the previous bullet) is the largest average annual surface water inflow, followed by the gaged stream inflows at the upper reaches of streams at the edge of the active groundwater model domain (slightly more than 800,000 ac-ft/yr).
- The largest simulated average surface water outflows are to stream diversions (averaging over 1.6 million ac-ft/yr), followed by streamflow out of the model domain in the South Platte River below Julesburg (approximately 400,000 ac-ft/yr).

Two types of model input demands for water are subject to the simulated availability of water in the model. Streamflow diversions are limited to the amount of simulated streamflow and groundwater pumping from wells is limited where the simulated water level drops such that the simulated saturated thickness is relatively small fraction of the total alluvial aquifer thickness. In both cases, where the input demand for diversion or pumping is greater than the water simulated to be available, the model will simulate removal of only the available water. Overall, 98 percent of the streamflow diversion demand volume is met by the model for the 1950 through 2012 simulation period, and 97.6 percent of the groundwater irrigation demand volume is satisfied by the model. In comparison, the original model calibration effort required manually reducing agricultural irrigation pumping to 80 percent of the StateCU demand estimates.

Model calibration is the process of adjusting model input parameters to acceptably match model-simulated values of flows and groundwater levels to their field-measured equivalents. As with the previous effort, the updated model was calibrated to observed groundwater levels measured in wells, measured streamflows at stream gaging locations, and estimates of stream gain/loss. Limited additional calibration was performed during the updated model effort because the main objective was to update and extend the simulation period of the model. The primary calibration efforts focused on adjusting and updating the hydraulic conductivity values assigned to certain portions of the alluvial aquifer system based on additional information and hydrogeologic judgement. Model calibration was improved overall, improving the reliability of the model for performing future predictive simulations and other scenarios. Additional activities undertaken as part of the model update that improved calibration included:

- Minor flow routing corrections and adjustments to streambed elevations were made in some SFR2 streams.
- Estimates of M&I pumping inputs prior to recorded pumping volumes were updated based on water rights and other information.
- Processes for acquiring and inputting data from HydroBase and other data sources were enhanced using a data-centered approach and the information in those data sources were updated. (Of note was the effort by DWR staff to update the irrigation snapshot GIS data to improve the estimated groundwater irrigation pumping rates and spatial distribution of applied irrigation water through improved matching between irrigation wells and irrigated parcels.)

Table ES-3. Average Annual Simulated Groundwater Budget (ac-ft)			
	Groundwater Flow Component	Average Annual	% of Total Inflow or Outflow
Inflow	Groundwater flow in from storage	463,794	19
	Stream loss to aquifer	309,886	13
	Precipitation recharge	103,639	4
	Surface water irrigation return flow recharge	405,918	17
	Groundwater irrigation return flow recharge	143,362	6
	Canal seepage recharge	361,223	15
	Recharge ponds	50,027	2
	Reservoir seepage recharge	31,314	1
	Alluvial underflow in	12,259	1
	Net bedrock flux	15,365	1
	Net lateral boundary flow	503,371	21
Outflow	Groundwater flow out to storage	410,145	17
	Alluvial underflow out below Julesburg	2,665	0
	Stream gain from aquifer	1,353,376	56
	Agricultural irrigation pumping	454,319	19
	M&I pumping	41,056	2
	Augmentation pumping	4,369	0
	Alfalfa ET	16,216	1
	Subirrigated meadow ET	11,698	0
	Phreatophyte ET	105,409	4
Total	Total in	2,400,157	100
	Total out	2,399,253	100
	In minus out	904	N/A
	% mass balance error	0.04	N/A

Table ES-4. Average Annual Simulated Surface Water Budget (ac-ft)			
	Surface Water Flow Component	Average Annual	% of Total Inflow or Outflow
Inflow	Gaged surface water inflows	803,578	30
	Return flow and discharge inflows	223,149	8
	Ungaged surface water inflows	304,532	11
	Stream gain from aquifer	1,353,376	50
Outflow	Physical diversions	1,660,655	62
	Net flow change at selected tributary mouth gages	276,502	10
	Ungaged diversions	37,546	1
	Stream loss to aquifer	309,886	12
	Streamflow out below Julesburg	401,128	15
Totals	Total in	2,686,634	100
	Total out	2,685,717	100
	In minus out	-1,083	N/A
	% mass balance error	-0.04	N/A

To compare the updated model calibration to the initial modeling effort calibration, standard statistics of groundwater-level residuals (observed values minus simulated values) have been calculated for the 1950 to 2006 period. These statistics have been calculated over the entire model domain for all updated observation well locations and for the subset of wells only with surveyed elevation data (see Table ES-5).

Table ES-5. Bulk Groundwater-Level Calibration Statistics Comparison to Initial Model, 1950–2006				
Statistic	Surveyed Wells		Surveyed + Non-Surveyed Wells	
	Updated Model	Initial Model	Updated Model	Initial Model
Residual mean (ft)	0.30	-0.28	0.11	-1.89
Absolute residual mean (ft)	5.87	5.55	8.82	9.58
Residual standard deviation (ft)	8.28	8.33	13.01	14.88
Sum of squared errors (ft)	3.93E+05	3.98E+05	2.46E+06	3.27E+06
Root mean squared (RMS) error (ft)	8.28	8.34	13.01	15.00
Minimum residual (ft)	-25.14	-33.49	-55.28	-71.48
Maximum residual (ft)	39.77	38.57	55.12	74.38

Table ES-5. Bulk Groundwater-Level Calibration Statistics Comparison to Initial Model, 1950–2006

Statistic	Surveyed Wells		Surveyed + Non-Surveyed Wells	
	Updated Model	Initial Model	Updated Model	Initial Model
Number of observations*	5,729	5,729	14,520	14,520
Range in observations (ft)	1906.19	1906.19	2268.23	2268.23
Scaled residual standard deviation (%)	0.43	0.44	0.57	0.66
Scaled absolute residual mean (%)	0.31	0.29	0.39	0.42
Scaled RMS error (%)	0.43	0.44	0.57	0.66
Scaled residual mean (%)	0.02	-0.01	0.00	-0.08

*Note: observations restricted to only those available for 1950-2006.

The average difference in measured versus simulated groundwater-level elevations is less than 1 foot for the updated model, indicating that simulated groundwater levels are overall similar to observed levels and not generally higher or lower then observed levels. Figure ES-2 below presents scatterplots of observed versus simulated groundwater-level elevations. The points on the scatterplot are clustered around the central line (the line of perfect matches between simulated and observed groundwater levels), indicating a close match between simulated and observed values and a lack of overall bias toward simulating high or low values (which is characteristic of a well-calibrated groundwater model).

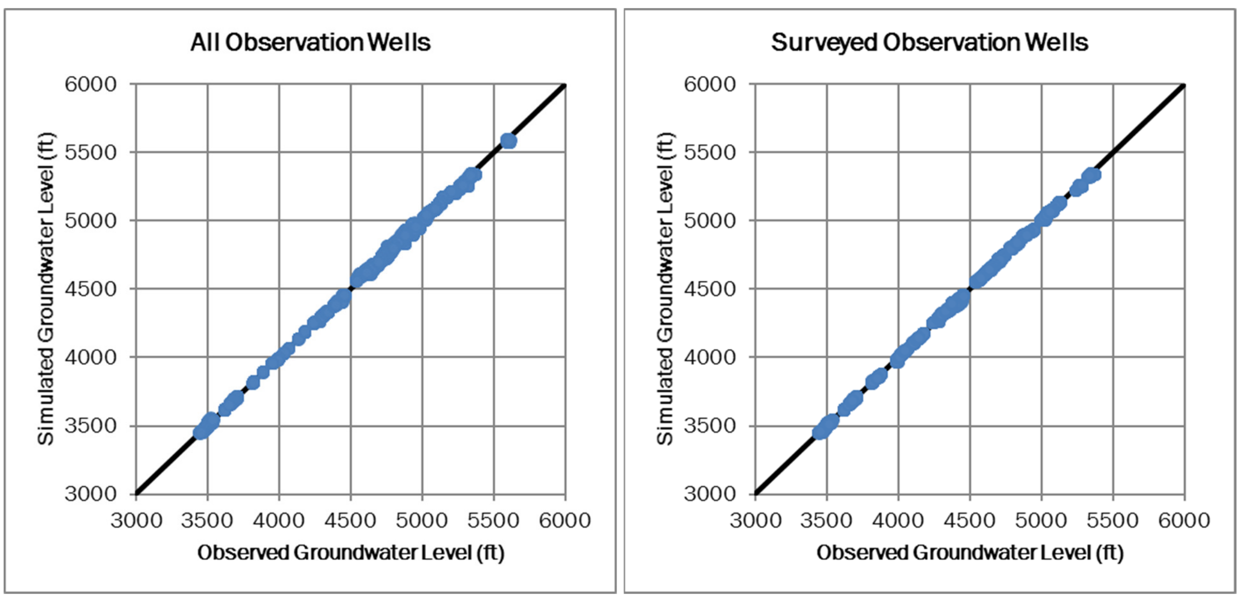

Figure ES-2. Observed vs. Simulated Groundwater-Elevation Scatterplots

The model is also qualitatively calibrated to measured streamflows and estimated stream gain/losses. Figure ES-3 presents comparisons between measured and simulated average annual streamflow volumes and demonstrates reasonable matches, especially along the mainstem of the South Platte River. Stream gains and losses to and from groundwater are not directly measureable and are therefore estimated using mass balance-based approaches. Because of inherent uncertainties in estimating stream gain/loss values, the corresponding simulated values of stream gain/loss are qualitatively compared in terms of overall magnitude and general seasonal patterns. The simulated stream gain/loss values along the South Platte River match reasonably well to the estimated values, and an example comparison graph for the South Platte River between Fort Lupton and Kersey is shown in Figure ES-4.

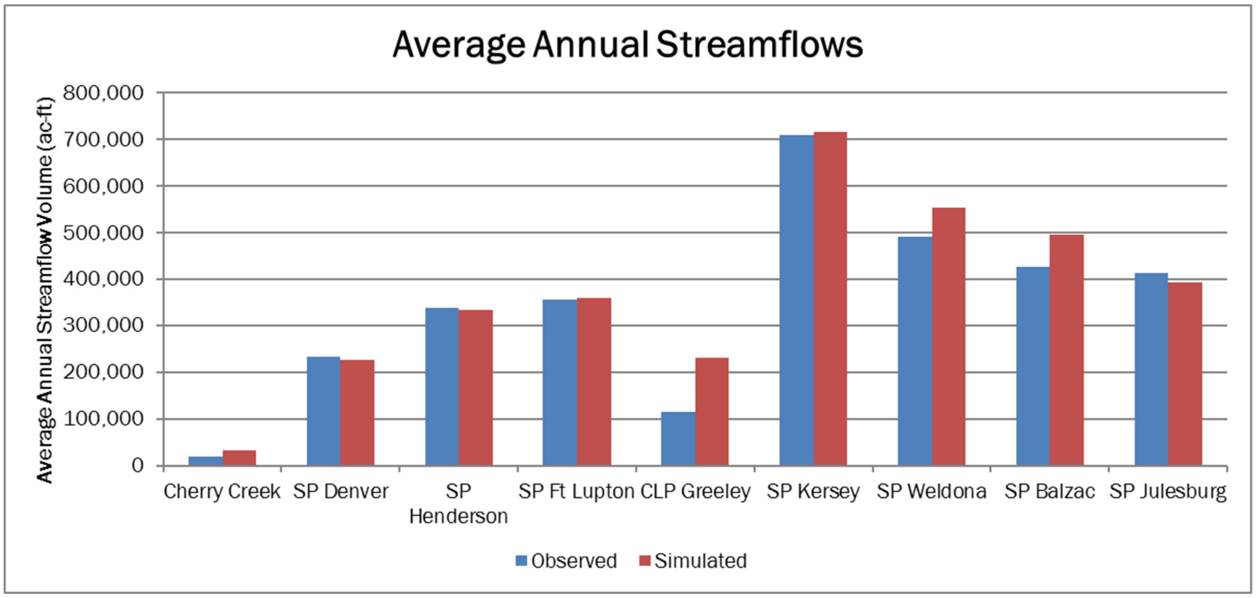

Figure ES-3. Comparison of Simulated and Measured Average Annual Streamflows

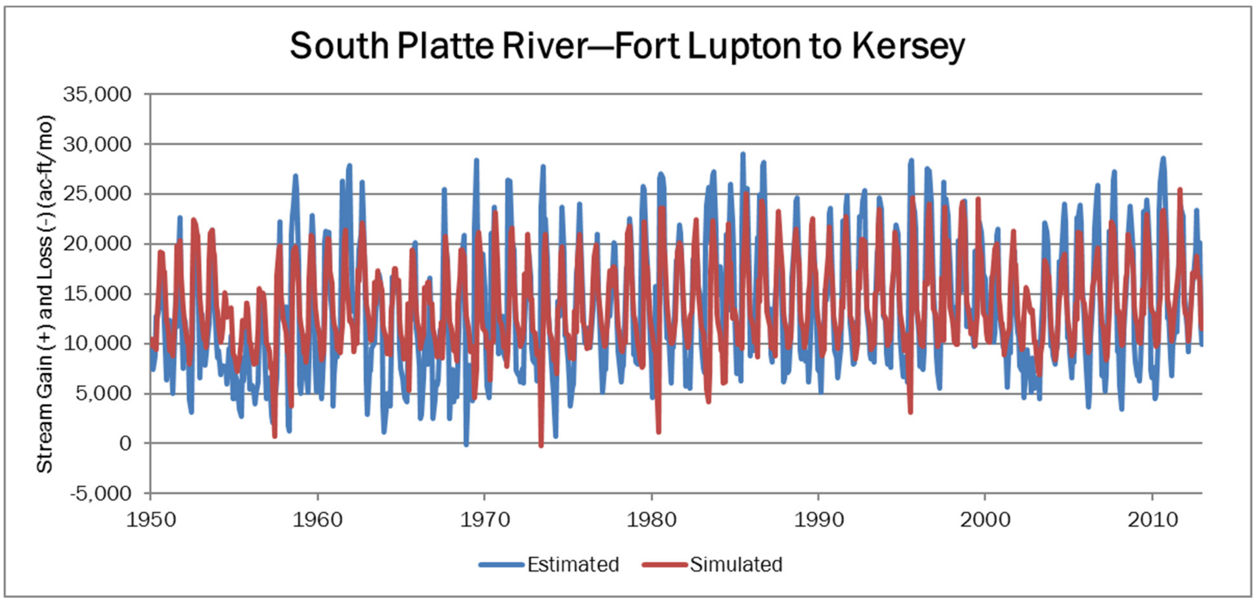

Figure ES-4. Simulated and Estimated Stream Gain/Loss, South Platte River Fort Lupton to Kersey

Summary

The completed update of the model and the model input development processes represents a significant upgrade to the SPDSS that will help to provide a better understanding of basin-scale groundwater flow and groundwater/surface water interactions in the Basin. The model is well calibrated and provides a platform for performing predictive future-casting simulations and other scenarios to help guide potential water management strategies and activities, and it can be utilized as a basis for refined local-scale models.

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List of Abbreviations

2D	two-dimensional
3D	three-dimensional
ac-ft	acre-feet
ac-ft/mo	acre-feet per month
ac-ft/yr	acre-feet per year
BAS	MODFLOW Basic package
Basin	South Platte River Basin
BC	Brown and Caldwell
CCWCD	Central Colorado Water Conservancy District
CDSS	Colorado's Decision Support Systems
CDM	CDM Smith
CDM 2013 Report	*South Platte Decision Support System Alluvial Groundwater Model Report*
CSV	comma-delimited text
CWCB	Colorado Water Conservation Board
DMI	data management interface
DNR	Colorado Department of Natural Resources
DWR	Division of Water Resources
EPA	U.S. Environmental Protection Agency
ET	MODFLOW Evapotranspiration package
ETS	MODFLOW Evapotranspiration Segments package
ft	feet
GAGE	MODFLOW Gage package
GB	gigabyte(s)
GIS	geographic information system
GMG	MODFLOW Geometric Multigrid Solver package
gpm	gallon(s) per minute
GUI	graphical user interface
HB	House Bill
ID	identifier
LPF	MODFLOW Layer Property Flow package
M&I	municipal and industrial
MB	megabyte(s)
model	South Platte Decision Support System Alluvial Groundwater Model
N/A	not applicable
NAD27	North American Datum of 1927
NAD83	North American Datum of 1983
NOAA	National Oceanic and Atmospheric Administration
NRCS	National Resources Conservation Service
NWT	MODFLOW Newton Solver package
PLSS	Public Land Survey System
PSB	MODFLOW Partition Stress Boundaries capability
QA/QC	quality assurance/quality control
RCH	MODFLOW Recharge package
RDGSS	Rio Grande Decision Support System
RMS	root mean square
SFR2	MODFLOW Streamflow Routing 2 package
SPDSS	South Platte Decision Support System
SQL	Structured Query Language
Ss	specific storage
State	State of Colorado
StateCU	State of Colorado's Consumptive Use Model
StateDGI	State Data-Centered Ground Water Interface
StatePP	State Pre-Processor
TIN	triangular irregular network
USGS	U.S. Geological Survey
UPW	MODFLOW Upstream Weighting Flow package
UTM	Universal Transverse Mercator
VBA	Visual Basic for Applications
VB.NET	Visual Basic .NET
WDID	Water District Identification
WEL	MODFLOW Well package
WWTP	wastewater treatment plant

Disclaimer

This report was prepared solely for the State of Colorado (State), Department of Natural Resources/Colorado Water Conservation Board (DNR/CWCB) in accordance with the applicable professional standards in effect at the time the services were performed pursuant to the contract between DNR/CWCB and Brown and Caldwell dated September 23, 2014.

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Section 1

Introduction

The South Platte Decision Support System Alluvial Groundwater Model (model) is a planning-level groundwater model that simulates the effects of regional hydrologic drivers such as pumping and recharge on the South Platte alluvial aquifer and streamflows. The model is a part of the South Platte Decision Support System (SPDSS), which in turn is a component of Colorado's Decision Support Systems (CDSS). CDSS is a joint effort of the Colorado Water Conservation Board (CWCB) and the Colorado Division of Water Resources (DWR) to develop publicly available data sets and analytical tools to assist in water resources management and planning activities within Colorado.

The CWCB, in coordination with the DWR, retained Brown and Caldwell (BC) to update the model to include more recent data. In addition, CDM Smith (CDM) and Wilson Water Group provided assistance in describing the inputs and workflow of the existing model.

The completed update of the model and the model input construction processes represents a significant upgrade to the SPDSS that will help to provide a better understanding of basin-scale groundwater flow and groundwater-surface water interactions in the Basin. The model was updated from the initial version of the model in a number of key ways:

- Simulation period was extended from the end of 2006 through the end of 2012;
- Model inputs were updated through the Data-Centered Approach with improved underlying data from HydroBase and DWR Irrigation Snapshot GIS datasets;
- Several Data-Centered Approach Data Management Interfaces (DMIs) were modernized and improved, including the CDSS Toolbox, the State Data-Centered Ground Water Interface (StateDGI), the State Pre-Processor (StatePP), and the MODFLOW Streamflow Routing 2 Package (SFR2) Generator (SFR2 Generator);
- Model executable code was upgraded to the robust and fully-supported USGS MODFLOW-NWT (Niswonger et al. 2011);
- The Partition Stress Boundaries (PSB) capability was incorporated, which allows for improved and simplified analysis of model inputs and outputs related to the numerous water budget components of the model (Banta 2011);
- Model calibration was improved overall, improving the reliability of the model for performing future predictive simulations and other scenarios.

The model represents a platform for performing predictive future-casting simulations and other scenarios to help guide potential water management strategies and activities. The model can be used for analyzing and finding potential solutions to groundwater challenges in the Basin, such as high water table problems, and it can be utilized as a basis for refined local-scale models.

This report documents the extension of the simulated period of the model—as described in detail in the *South Platte Decision Support System Alluvial Groundwater Model Report* (CDM 2013 Report)—from the end of 2006 to the end of 2012, and describes updates to the processes for generating model input files, executing model simulations, and calibrating the model (CDM 2013).

1.1 Model Update Objectives

The primary objective of this modeling effort was to extend the simulated period of the model from 1950 through 2006 to 1950 through 2012 based on more recent hydrologic and water use data. Additional objectives included upgrading the model execution code from the U.S. Geological Survey's (USGS) MODFLOW-2000 version (MODFLOW-2000 is no longer supported by USGS) to the modern and currently supported MODFLOW-NWT version, incorporating improved simulated water budget accounting using the PSB developed in MODFLOW-CDSS, and providing improvements and updates to data processing procedures used in the generation of model input files.

The main objectives to be implemented under this model update effort were as follows:

- Extend historical time-series data
- Update CDSS Toolbox and StateDGI
- Develop MODFLOW input files
- Run extended model and update calibration

Each of these objectives is described in more detail in Sections 2 through 5. Modeling scenarios were part of the scope of this project and will be documented in a separate report.

1.2 Model Overview

The following section provides a high-level overview of the model. For detailed descriptions of the initial development of the model, please refer to the CDM 2013 Report (CDM 2013).

1.2.1 Model Area and Conceptual Model Description

The area of the model includes the unconsolidated alluvial deposits of the mainstem South Platte River from Chatfield Reservoir downstream to the Colorado-Nebraska border, and the connected, unconsolidated alluvial deposits of several significant tributaries to the South Platte River (see Figure 1-1, below). These alluvial deposits, which consist of predominantly sand and gravel with interbedded finer-grained silty and clayey floodplain deposits, present a contiguous alluvial aquifer system. The alluvial aquifer system is hydraulically connected to surface water streams, diversions, and reservoirs in the model area. The South Platte River Basin (Basin) alluvial aquifer is underlain by the consolidated sedimentary strata of the Denver Basin Group, and relatively minor groundwater flows are exchanged between the Denver Basin aquifer units and the alluvial aquifer.

The sediments of the alluvial aquifer are generally thin (less than 20 feet) in the upper reaches of tributaries and thicken to more than 300 feet farther downstream in the alluvial system along the mainstem South Platte River. Saturated alluvial aquifer thicknesses range from 0 feet to more than 200 feet near the Colorado-Nebraska border. Local hydraulic conductivity values of the most productive sand and gravel deposits may be up to 2,000 feet per day. Hydraulic conductivity values along the South Platte mainstem alluvium generally range from 200 to 600 feet per day, with lower hydraulic conductivity values along the margins of the alluvium and in the tributaries.

The Basin in northeastern Colorado provides the water used for a wide variety of economic activities including agriculture, municipal and industrial (M&I) uses, and recreation. Agricultural irrigation is the leading water use in the Basin and has resulted in the construction and maintenance of a large network of ditches and canals, associated storage reservoirs, and groundwater wells. Both surface water and groundwater resources are used for economic activities in the Basin, and significant groundwater-surface water interactions occur as a result of both natural and human-influenced processes.

Both natural and human-influenced processes contribute to the inflows and outflows of the South Platte alluvial aquifer system. For example, recharge to the alluvial aquifer is provided not only by deep percolation of precipitation, but also irrigation return flows, canal seepage, reservoir seepage, and augmentation recharge ponds. The groundwater inflows and outflows to the alluvial aquifer system are summarized below:

Alluvial Groundwater Inflow:

- Stream loss to groundwater
- Precipitation recharge
- Irrigation return flow recharge
- Augmentation pond recharge
- Canal seepage loss
- Reservoir seepage loss
- Alluvial aquifer underflow into the model domain
- Underflow from bedrock to alluvium

Alluvial Groundwater Outflow:

- Stream gain from groundwater
- Well pumping
- Subirrigated crop evapotranspiration
- Phreatophyte evapotranspiration
- Canal seepage gain from groundwater
- Reservoir seepage gain
- Alluvial aquifer underflow out from the model domain
- Underflow from alluvium to bedrock

The model accounts for each of these inflows and outflows as well as changes in groundwater storage. Additionally, the model accounts for surface stream inflows where the South Platte River and tributaries enter the active model domain and stream outflows where the South Platte River exits the model near the Colorado-Nebraska border. Estimating these groundwater inflows and outflows for the extended modeling period of 2007–12 represents one of the main tasks of the model update effort.

1.2.2 Data-Centered Approach

CDSS employs a “data-centered approach” to the use of analytical and numerical tools (including the model) in which data management interfaces (DMIs) enable connections between data sources such as DWR’s HydroBase (DWR 2015) and geographic information system (GIS) data sets (DWR 2016). The data-centered approach allows updated data sets to be efficiently incorporated into tools such as the model.

For this update effort, the CDSS Toolbox, StateDGI, HydroBase, State of Colorado's Consumptive Use Model (StateCU) (DNR 2010), TSTool (DNR 2016) and StatePP all were used to extend the period simulated by the model. In some cases these tools were improved in their efficiency, functionality, and/or accuracy.

1.2.3 Numerical Model Description

The model was developed using MODFLOW, the industry standard groundwater flow-modeling code produced by USGS. The model is constructed using a MODFLOW grid of a single vertical layer, 655 rows and 848 columns aligned north–south and east–west with a uniform grid cell spacing of 1,000 feet that overlays the alluvial aquifer system as shown in Figure 1-1. The GIS horizontal location coordinate of the origin (southwest corner) of the model grid in Universal Transverse Mercator (UTM) coordinates in the North American Datum of 1983 (NAD83) in feet is X=1,579,065, Y=14,264,407, or in meters is X=481,300, Y=4,347,800. The model was previously based on a version of MODFLOW-2000 modified to better handle simulation of dewatered model cells (Harbaugh et al. 2000; Doherty 2001). USGS now considers MODFLOW-2000 to be superseded, and it no longer provides support for the code. The Doherty method of handling dewatered model cells, while being generally effective, was never formally adopted by USGS (Doherty 2001). As described in Section 4 below, the updated model is now based on MODFLOW-NWT (Niswonger et al. 2011). MODFLOW-NWT is a modern and supported version of MODFLOW that uses the Newton method and robust model solution techniques to handle dewatered model cells.

The initial construction and calibration of the model was documented in the CDM 2013 Report (CDM 2013). The CDM 2013 Report describes how model inputs were generated, including geometry of the base of the alluvium used as the bottom elevation of the model, distribution of hydraulic conductivity and storage parameter (i.e., specific yield) values, stream configuration and routing, and incorporation of previously mentioned groundwater and surface water inflows and outflows. Many of these groundwater and surface water flows are highly transient in nature and require the assembly of large amounts of time-series data.

1.3 Report Overview

For the updated model, the extension of time-series data from 2006 to 2012 is described in Section 2, below. Section 3 presents a description of updates to the CDSS Toolbox and StateDGI, and Section 4 includes a description of the development of the MODFLOW input files. A summary of the updated model calibration is presented in Section 5, and recommendations for further work are outlined in Section 6.

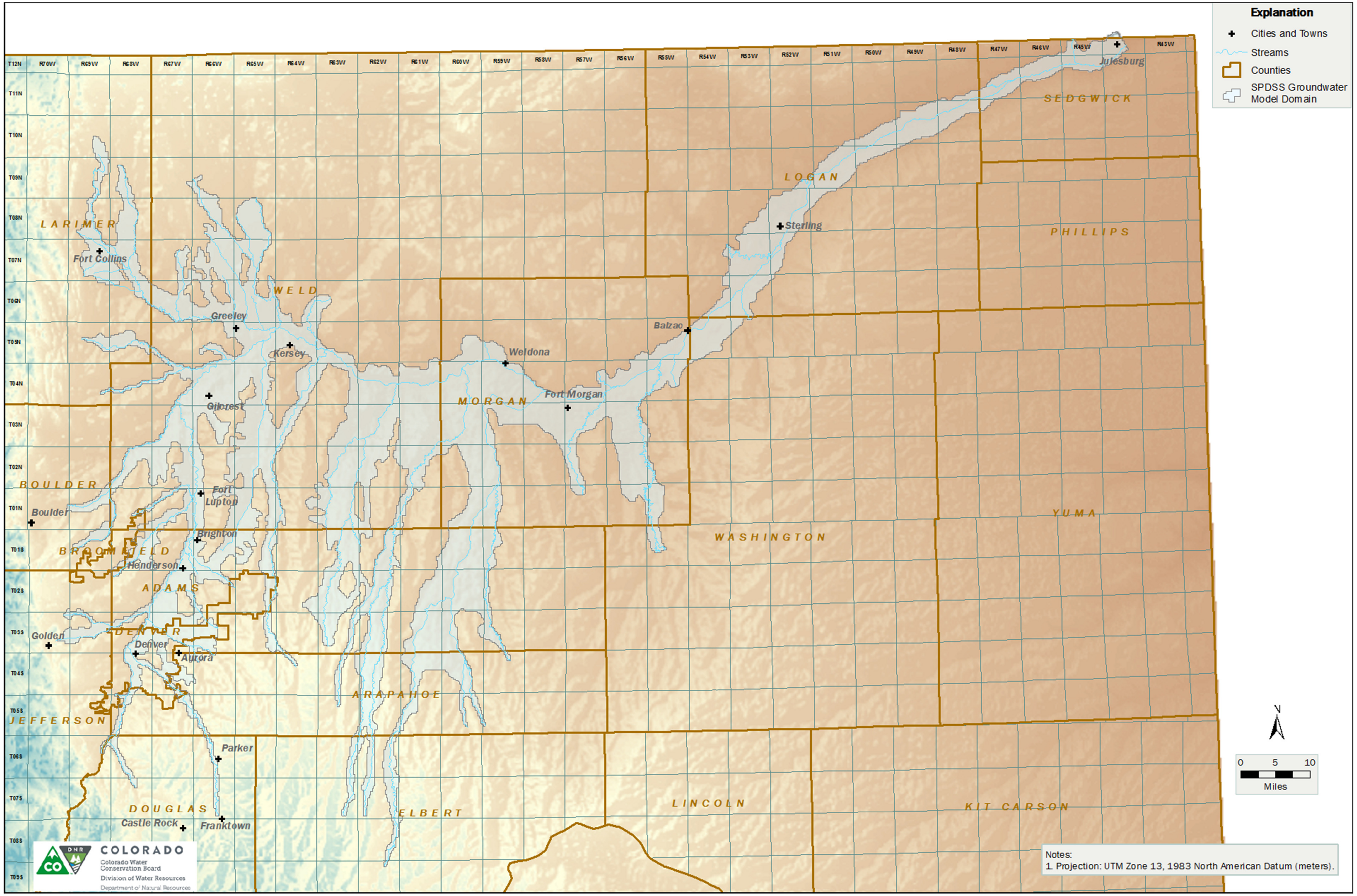


Figure 1-1. Model Study Area

Section 2

Extension of Historical Time-Series Data

The initial task for the model update was to extend the time-series data sets used to develop model input files with the most recent available data. A number of factors were considered when determining the end date for the extension period. The availability of flow, diversion, discharge, and climate data was investigated, in addition to considering the modeling periods for current SPDSS consumptive-use and surface water modeling efforts. To make all of the modeling efforts under SPDSS as cohesive as possible, the extended modeling period was set to align with the most recent consumptive-use and surface water models, which both ended in 2012. The SPDSS consumptive use modeling update is complete, and the surface water modeling effort should be finalized by December 2016.

In general, the time-series data update was focused on gathering post-2006 data to add to the previously developed 1950 to 2006 data. For some modeling input data sets, historical data were not available during the initial modeling effort conducted by CDM (hereinafter referred to as the "initial modeling effort"), but some historical data are now available, or major revisions to the historical data were conducted and are now available for use. In these instances, the newly acquired data were used to replace the existing time-series data for the entire period of record (1950 to 2012).

The extension of time-series data sets primarily on existing tools and approaches from the initial modeling effort. For some data sets, data-centered enhancements were implemented to streamline the previous data generation workflow. In these cases, workflows were modified to use standard tools and data sources and remove dependence on proprietary tools, user-edited data, and data formats incompatible with standard SPDSS processes.

This section provides a description of the data, data-processing steps, and approach used to extend time-series data sets. Workflow diagrams showing the entire process to generate MODFLOW input files, including the necessary input data, were also developed and are presented in this section.

2.1 Approach and Process

Existing tools and previously developed approaches for collecting and processing time-series data were used for the extension effort. The tools used for the initial and current modeling efforts include standard CDSS tools such as TSTool and StateDGI, as well as other common tools such as Excel spreadsheets and Access databases. StateDGI is a DMI specifically designed to store and output data for the StatePP tool that pre-processes data for MODFLOW and generates several MODFLOW input files. In addition to those tools, the original model development included a number of software tools for specific modeling processes that integrate into the workflow. A number of these existing processing tools were replaced and new processing tools were developed in an effort to improve and simplify certain workflows. Where possible, greater emphasis was focused on using TSTool and other data-centered approaches. Modified or new tools developed during the model update are described herein. The unmodified tools and processes developed during the initial modeling effort are described in detail in the CDM 2013 Report (CDM 2013).

2.1.1 Data Sources and Background

The primary source for hydrologic and spatial data for the model was the HydroBase database maintained by DWR (DWR 2015). The version of HydroBase used throughout the data-collection process was issued on March 4, 2015. Historical data collected from HydroBase included streamflow records, diversion records, climate data, M&I pumping records, recharge pond deliveries, irrigated areas, groundwater levels, soil types, land use, and demographic information.

The model is also closely integrated with other SPDSS basin-wide modeling efforts. The current basin-wide consumptive-use model (StateCU) was developed as a part of ongoing surface water model (StateMod) development efforts (DNR 2015). For the model, output from StateCU was used to estimate irrigation recharge, canal seepage, and irrigation well pumping. Wilson Water Group, the contractor managing the StateCU model, provided this output for use in the model. Therefore, the input data sets for both the SPDSS groundwater and surface water models have been prepared using consistent sources and data.

Some of the time-series data, such as M&I discharges and bedrock fluxes, were collected from non-decision support system data sources or models. Discharge data were collected from the U.S. Environmental Protection Agency (EPA) database, and bedrock fluxes were based on output from the USGS Denver Basin groundwater model (EPA 2015, Paschke 2011).

Data-centered enhancements were implemented during data collection and processing. These enhancements include increasing the use of TSTool commands to retrieve data stored in HydroBase, eliminating reliance on data not stored in HydroBase, and developing detailed workflow diagrams to explain the processing steps for each time series.

2.1.2 Approach Summary

In general, the extension of time-series data for each component was completed separately using individual approaches and processes. Table 2-1 provides a summary of the approaches and processes used to generate the time-series data for each component. Additional details for various components are provided in Appendix A of this report.

Table 2-1. Time-Series Data Set Extension Approach

Time-Series Data Set	Extension Approach
Alluvial underflow into model	The rates of monthly alluvial groundwater inflow entering the model domain at modeled tributary branches were calculated during the initial modeling effort and are constant year-to-year. The same values were used for the extended modeling period.
Bedrock fluxes	Bedrock fluxes were calculated using the USGS Denver Basin model. The USGS model simulation period of record ended in 2003. The 2003 fluxes were repeated for subsequent years of the model, including the extended modeling period period.
Reservoir seepage	Reservoir seepage rates were assumed to be constant for a given soil type underlying the reservoirs. The seepage rates already in the initial model were used for the extended modeling period.

Table 2-1. Time-Series Data Set Extension Approach

Time-Series Data Set	Extension Approach
Streamflow routing components: streamflow, M&I discharges, and diversions	Historical streamflows and diversion records for the extended modeling period were collected from HydroBase by Wilson Water Group and were provided. Incomplete records were filled using regression or other suitable methods as described in the SPDSS Task 2 technical memorandum (Leonard Rice Engineers 2007). Tributary inflows at the edge of the model domain were estimated using the nearest downstream gage and then adding diversions occurring between the gage and the model boundary. See Appendix A for details on the data collection efforts. M&I discharge data were collected from the EPA database.
Precipitation	Historical monthly precipitation data from the key climate stations identified in the initial modeling effort were retrieved from HydroBase by Wilson Water Group and were provided. Missing data were filled using linear regression. The climate station weights used to distribute precipitation across the model domain and the percentages used to determine the amount of precipitation that becomes recharge (based on land use and soil types) were not changed from the initial modeling effort.
Consumptive-use model output: agricultural pumping, canal seepage, and irrigation recharge	Agricultural pumping, canal seepage, and irrigation recharge time-series data were estimated using the StateCU model output. The consumptive-use modeling was completed by Wilson Water Group and provided. The model output contained monthly values for each parameter. See Appendix A for details on the data-collection efforts.
M&I pumping	The historical M&I pumping data were extended using a combination of data retrieved from HydroBase and data provided by the well users. HydroBase data were preferred to user-supplied data. Missing or incomplete records were filled using similar methods from the initial modeling effort. The availability of HydroBase data was limited during the initial modeling effort. Estimated values prior to 2006 were replaced with newly available HydroBase records when possible. See Appendix A for details on the data-collection efforts and filling procedures.
Augmentation and recharge	Recharge areas: Augmentation recharge was estimated using recharge pond delivery records. Delivery records were retrieved from HydroBase and provided by Wilson Water Group. New recharge facilities that came on line during the extended modeling period were added to the model as part of the model update. Recharge and augmentation pumping: Historical recharge pumping records were compiled by Wilson Water Group and provided. Appropriate wells were identified with the help of the Division 1 Engineer's office. Pumping records were retrieved from HydroBase. Historical augmentation pumping records were also collected from HydroBase by Wilson Water Group and provided. The Division 1 Engineer's office assisted in identifying the appropriate wells. See Appendix A for details on the data-collection efforts.
Lateral boundary inflow fluxes	Lateral boundary inflow fluxes represent a combination of precipitation recharge, irrigation recharge, canal seepage, and pumping that occur outside the active model domain and that generate groundwater flux across the active model domain boundary. Existing tools were updated and used to combine the component fluxes and generate lagged boundary inflow values.

Table 2-2 below provides a summary of the approaches taken to extend the time-series data used to develop the calibration data sets.

Table 2-2. Calibration Data Set Extension Approach	
Calibration Data Set	**Extension Approach**
Observation water levels	Measurements of groundwater-level elevations were retrieved from HydroBase for monitoring well sites that were identified during the initial modeling effort.
Stream gain/loss estimates	Daily streamflow, diversion, and discharge data for the extension period (2007–12) were retrieved from HydroBase and added to existing stream mass balance spreadsheets for each identified reach. The new estimates of daily gain/loss for each reach were processed using the pilot point spreadsheets developed during the initial modeling effort and documented in the Task 46.2 technical memorandum (CDM 2008).
Streamflow at relevant gages	Streamflow gage data for the gages used in calibration were retrieved from HydroBase by Wilson Water Group and provided. Missing data were filled using linear interpolation.

2.2 Results

Extended time-series data were compiled in a number of formats. Most data were uploaded to the model database and geodatabase. StateCU model output was kept in its original format because it is read directly by the MODFLOW model input file pre-processor (StatePP). Some time-series data consisted of monthly values that were repeated for each year of the modeling period. Those data were extended by modifying a flag in the existing MODFLOW input files that indicated to the model that the current values are to be used for the extended modeling periods.

2.2.1 Data Descriptions and Processes for Extending Data Series

The following is a brief summary of the data collected for each time series in the model. Some time-series categories were lumped together because of their similarity and because similar processes were used to extend the data.

Detailed workflow diagrams for each time series, or group of time series, were developed to show the entire process of creating the extended time series and developing the MODFLOW input files. The diagrams show the source data and the final MODFLOW package that receives or uses the time-series data. Figure 2-1 below shows a generalized overview of the workflow for generating all of the time-series data. Some processing steps for certain time series are not shown for clarity.

2.2.1.1 Constant Time-series data: Alluvial Underflow, Bedrock Fluxes, and Reservoir Seepage

Data representing alluvial underflow, bedrock fluxes, and reservoir seepage are constant on a year-to-year basis, with monthly variation. These time series were updated by modifying the existing MODFLOW model input files to indicate that the previous values are to be repeated for stress periods in the extended model. The bedrock fluxes in the model from 2003 onward use the values from the last year of output from the USGS Denver Basin groundwater model, which ends in 2003 (Paschke 2011).

Reservoir seepage and alluvial underflow are constant monthly values repeated each stress period for the entire modeling period. Because no new data were introduced for the extension, an individual workflow diagram was not generated for these time series. However, their processes are shown in general terms on the workflow overview diagram in Figure 2-1, below.

The methodologies used to determine reservoir seepage and process bedrock fluxes are discussed in further detail in Appendix B of the CDM 2013 Report, while alluvial underflow is discussed in Appendix D of that report (CDM 2013).

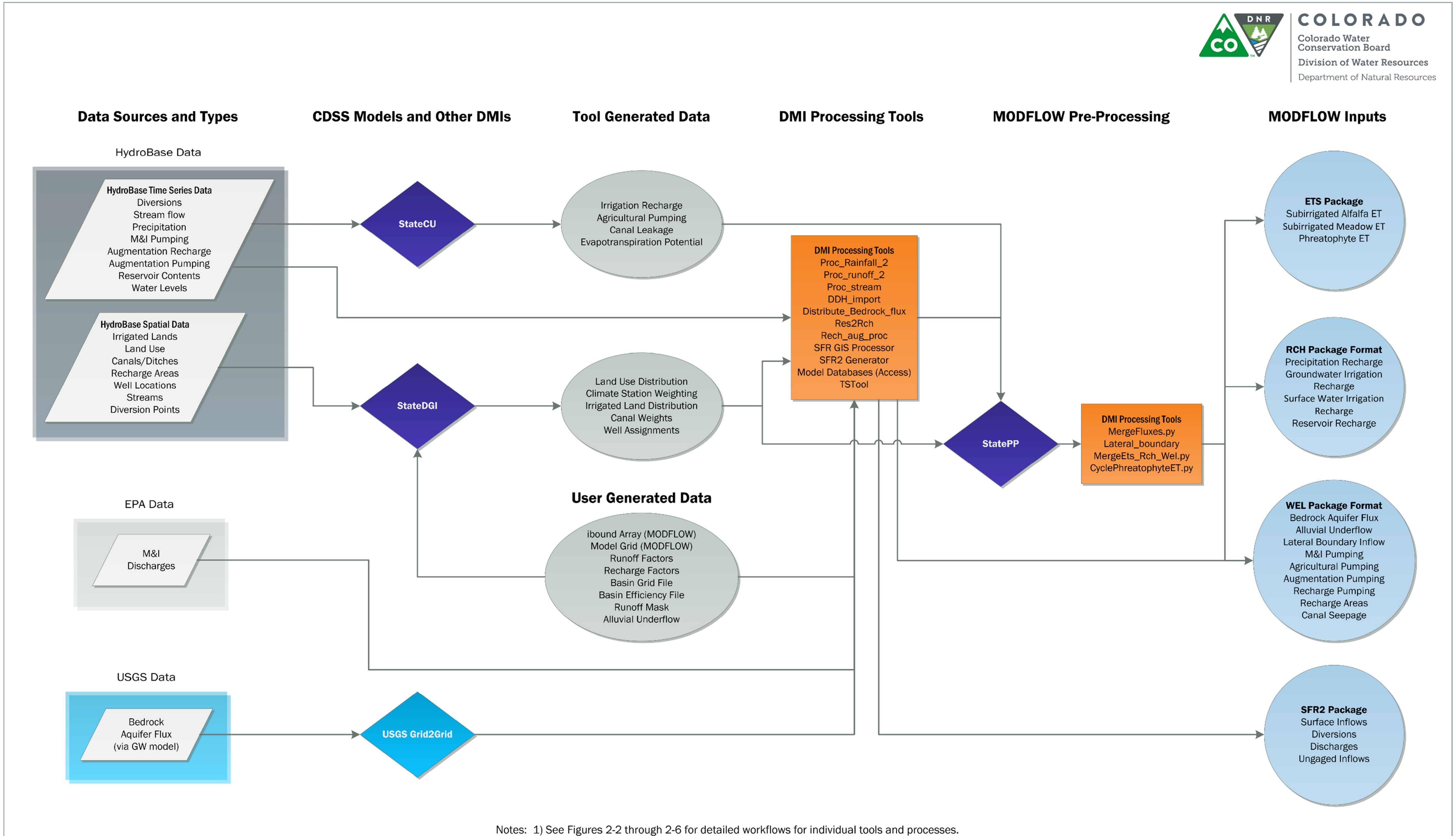


Figure 2-1. Model Workflow Overview

2.2.1.2 Streamflow Routing Components

SFR2 is used by the model to route surface water in stream channels and simulate the discharge from the aquifer to the stream (gaining stream) or discharge from the stream to the aquifer (losing stream). SFR2 uses a combination of streamflow gage data, stream diversions, discharges to the stream (e.g., municipal wastewater treatment effluent), and estimates of runoff from precipitation to calculate the flow and stage of the stream. A description of the data collection and time-series extension efforts for the components of SFR2 are highlighted below. Precipitation runoff is discussed near the end of Section 2.2.1.3, below. The complete SFR2 workflow, including all components, is shown on Figure 2-2, below. Additional background information about the components of SFR2 can be found in Appendices F and G of the CDM 2013 Report (CDM 2013).

2.2.1.2.1 Streamflow

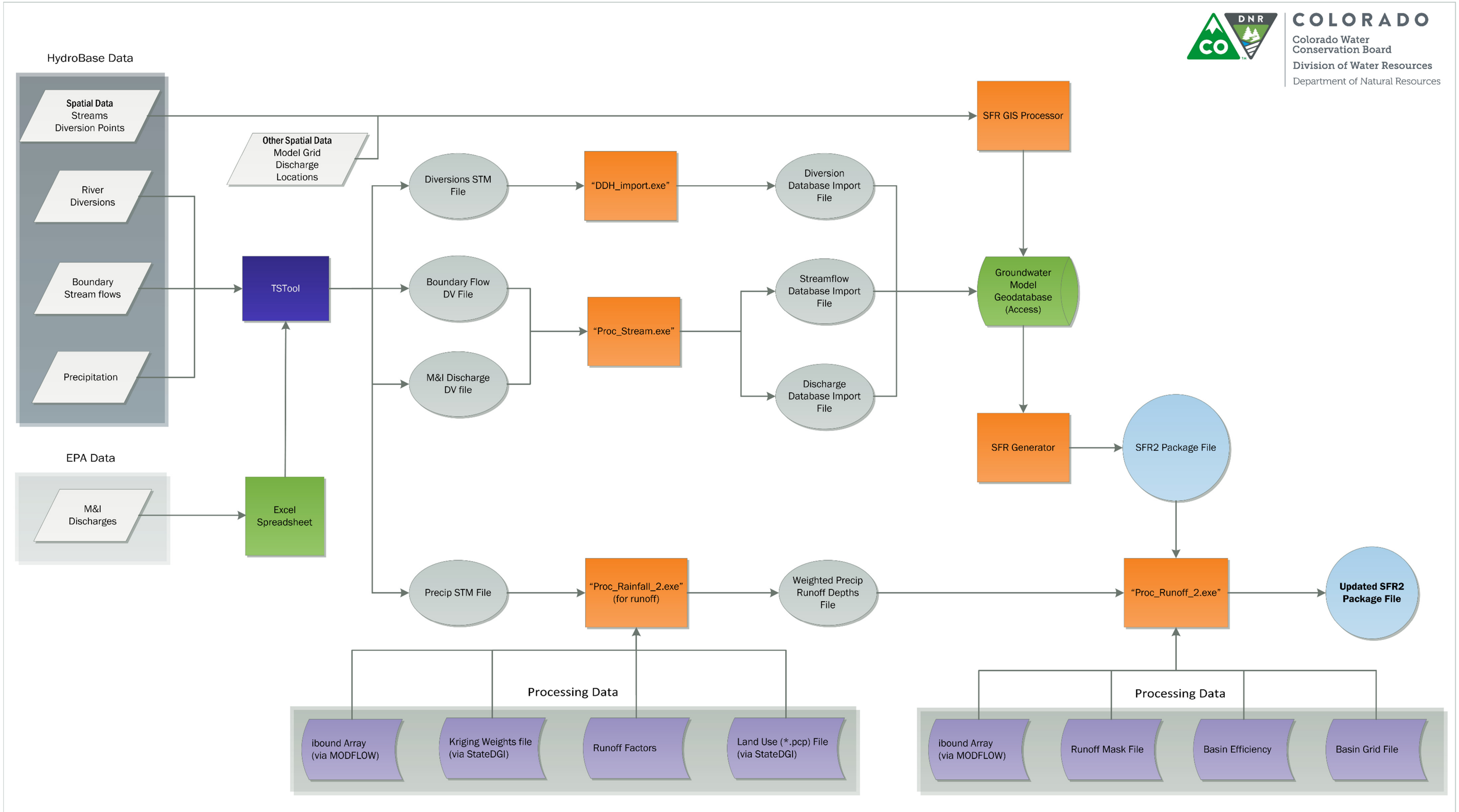
Streamflow data are used in the development of SFR2 and are based on USGS gage measurements at gages located near the model boundary on the South Platte River and major tributaries. Streamflow data were also used in the development of stream gain/loss estimates applied as calibration targets and discussed in Section 2.2.1.9.2, below. These data were retrieved from HydroBase using a TSTool command file. Missing data were filled using linear regression relationships with nearby gages. The regression relationships used to fill data for the model were the same as the relationships used in the SPDSS StateMod model that is currently under development. The filled data were uploaded to the model geodatabase and then processed with the SFR2 Generator to create the MODFLOW input files. Figure 2-2 below shows the complete workflow process for generating MODFLOW input files from streamflow data and the other components of SFR2.

2.2.1.2.2 Diversions

Canal diversions are also a component in SFR2. The diversion records are stored in HydroBase and were acquired and compiled using TSTool commands. Between 2006 and 2012, there were very few missing values in the records. Missing data were filled using an approach consistent with current StateCU and StateMod modeling efforts. The data-filling process uses a wet-dry-average pattern based on historical flow patterns at a nearby stream gage. The pattern file assigns a wet, dry, or average attribute for each month, and then—for any given month with missing data—the average monthly value corresponding to the pattern assignment is used to fill the data gap. Final data were uploaded to the SPDSS geodatabase for SFR2 Generator processing. The workflow for processing diversion data is a part of Figure 2-2.

2.2.1.2.3 Municipal and Industrial Discharges

Major M&I discharges from wastewater treatment plants (WWTPs) and power plants to the South Platte River and major tributaries are also included in SFR2. Unlike the streamflow and diversion data, discharges from M&I sources are not stored in HydroBase. Data were retrieved from the EPA database. Records were mostly complete for the extension period; however, some sites required filling. For small, intermittent data gaps, average monthly values were used to fill missing values. When data for municipal discharges were missing for longer consecutive periods, the values were filled using per-capita use and population data. This is the same approach used in the initial modeling effort to fill missing data prior to 2006 (CDM 2013). Missing industrial discharge data were filled with monthly average values. The processing steps for discharge data are also shown on Figure 2-2, below.



Notes: 1) Proc_rainfall_2.exe generates either weighted runoff depths or weights precipitation recharge depths, depending on what type of factors are read as inputs. For SFR2 purposes, runoff depths were generated.

Figure 2-2. SFR2 Development Workflow

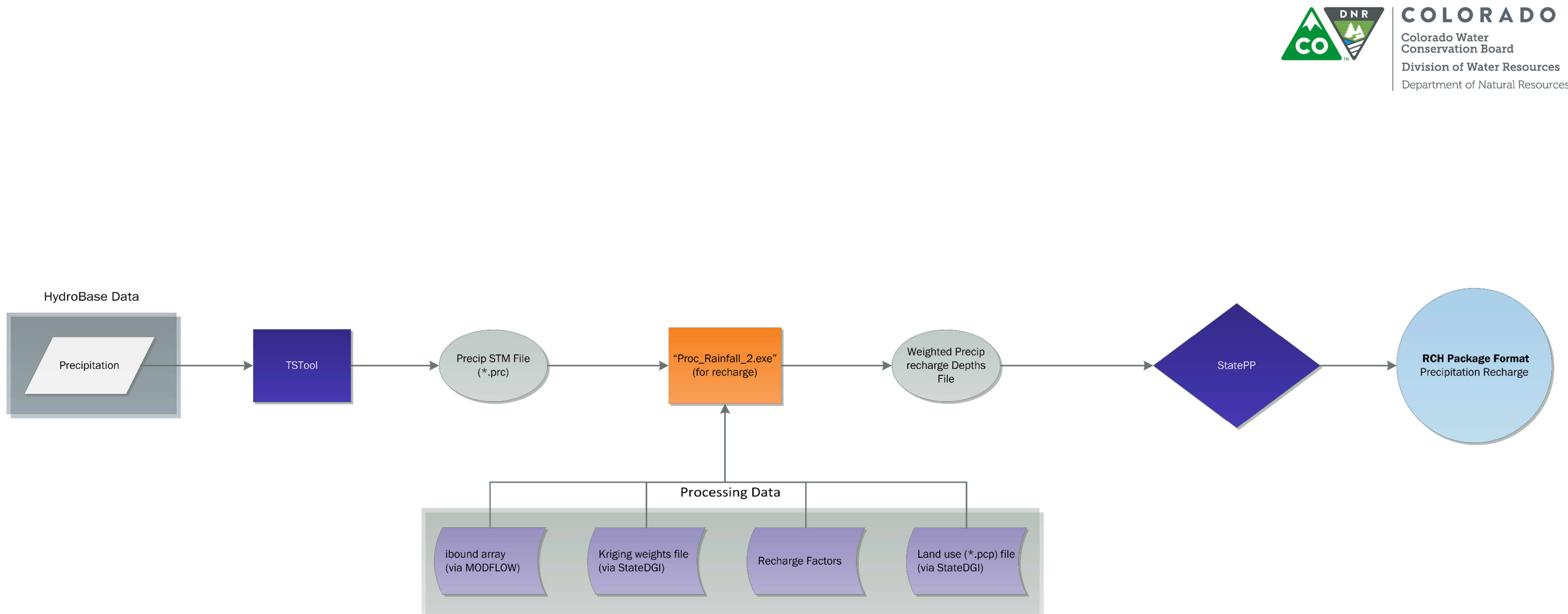
2.2.1.3 Precipitation

Precipitation data were collected from HydroBase using TSTool commands for 29 weather stations located throughout the Basin. The weather stations are operated by the National Oceanic and Atmospheric Administration (NOAA) and are the same locations used in the initial modeling effort. Precipitation data collected from the stations were distributed across the model grid based on a set of weighting files, which indicated the relative weight that a particular weather station had for any given model cell. A weighting file was generated for each station using a kriging interpolation method. The farther the model cell was from a particular weather station, the lower the weight was for that station. The precipitation assigned to any given model cell represented the weighted sum of precipitation for multiple surrounding weather stations. The weather station weighting and precipitation distribution methods were developed during the initial modeling effort and were unchanged during the update process.

The recharge component resulting from precipitation was determined by using recharge factors that represent the percentage of precipitation that recharges the alluvial aquifer. The percentages are based on land cover types, soil classifications, and season. The recharge percentages used for the extended modeling period were the same as the percentages used in the initial modeling effort. The workflow for processing precipitation recharge data is shown in Figure 2-3, below. Further background information can be found in Appendix B of the CDM 2013 Report (CDM 2013).

The runoff component of precipitation was calculated in a similar way, but using a different set of percentages. The runoff percentages used for the extended modeling period were the same as the percentages used in the initial modeling effort. The runoff percentages were based on the same land cover and soil types as the recharge percentages. Precipitation runoff is a component of SFR2. The workflow diagram shown in Figure 2-2 includes the runoff processing. More information about SFR2 components can be found in Appendix G of the CDM 2013 Report (CDM 2013).

Missing or incomplete precipitation data were filled using linear regression relationships with nearby stations. The regression relationships are consistent with the initial modeling effort as well as the current StateCU and StateMod modeling efforts.



Notes: 1) Proc_rainfall_2.exe can be run with recharge factors to generate weighted recharge arrays or with "runoff" factors to generate weighted runoff arrays. Recharge arrays are used in the recharge package workflow.

Figure 2-3. RCH Development Workflow: Precipitation Recharge

2.2.1.4 Consumptive-Use Model Output

A number of model input time series are based on the output from the StateCU consumptive-use model. These include irrigation pumping, irrigation recharge, and canal seepage. An updated version of the basin-wide StateCU model was developed in support of SPDSS StateMod modeling efforts, in addition to other efforts. The model output was provided by Wilson Water Group, the consumptive-use model contractor for CWCB. The StateCU model uses GIS-based irrigated acreage "snapshots" (i.e., mapping) from HydroBase to determine the appropriate amount of irrigated area for each diversion structure in the model, and to determine which irrigation wells correspond to the particular parcels. The snapshots provide a quantification of the irrigated area and the crop types on a parcel-by-parcel basis for a given year. Snapshots are available from HydroBase for 1956, 1976, 1987, 2001, 2005, and 2010. The 2010 snapshot was added to the StateCU model for the model extension effort.

Additionally, all snapshots have been revised since completion of the initial groundwater modeling effort, with a focus on improving the well-to-parcel assignments. As a result, the current StateCU output is slightly different from the output used in the initial groundwater modeling effort. For consistency with the other modeling efforts in the Basin, the older StateCU output used in the initial groundwater modeling was replaced with the new StateCU output for the entire simulation period (1950 to 2012). The monthly values of irrigation pumping, irrigation recharge, and canal seepage are calculated by the StateCU model, and there are no missing or incomplete data. The data are read directly from the detailed water balance output from StateCU into the MODFLOW model pre-processor, StatePP, and converted into MODFLOW input files. The complete workflow for StateCU generated data is shown in Figure 2-4, below. Appendix B from the CDM 2013 Report provides additional information on methodologies and processes use for recharge data collection (CDM 2013).

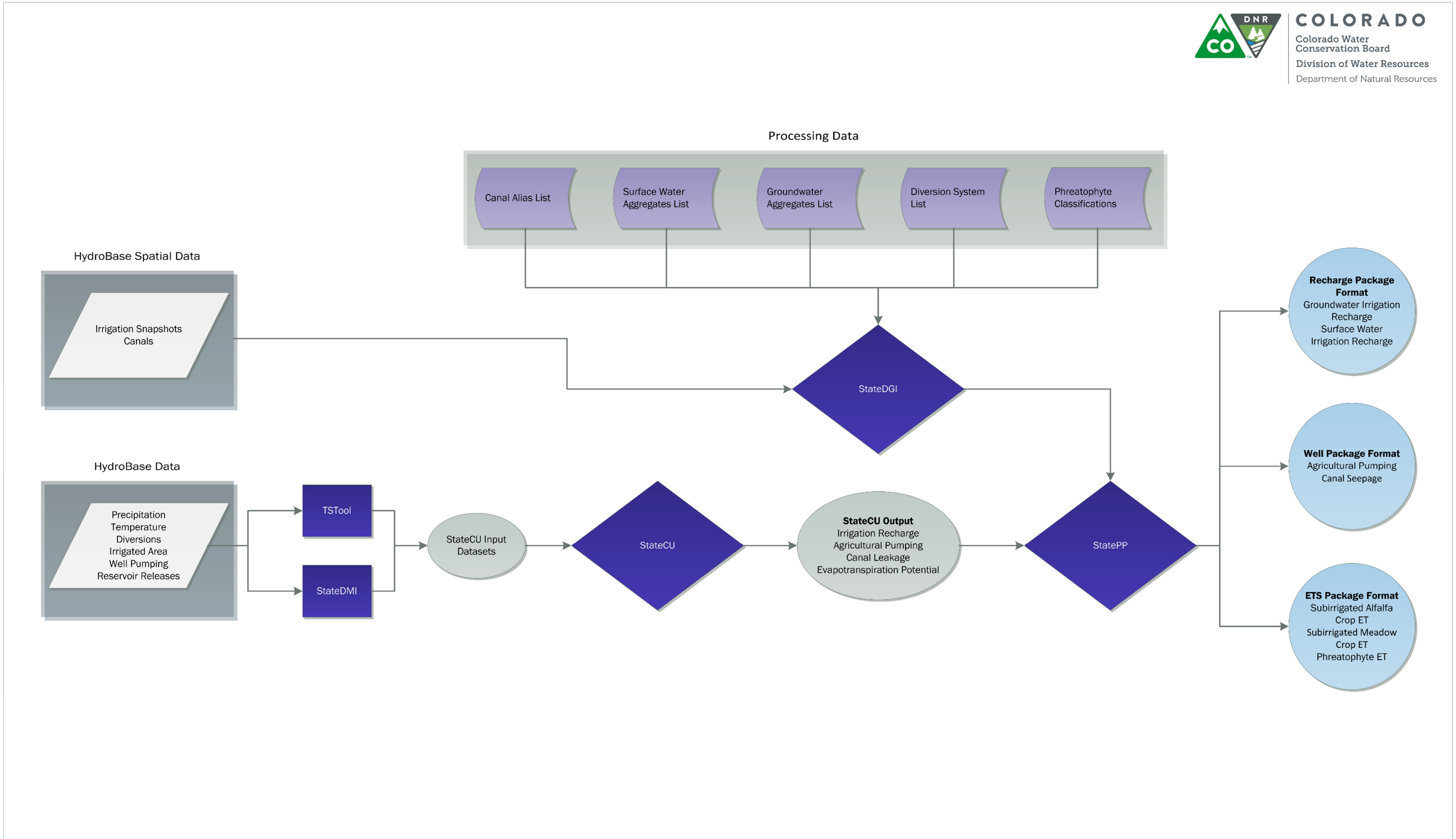


Figure 2-4. MODFLOW Package Development Workflow: Consumptive-Use Model Components

2.2.1.5 Municipal and Industrial Pumping

M&I pumping data were gathered from both HydroBase (using TSTool commands) and well users. Data from HydroBase were preferred for two reasons when both sources were available. One was to maintain a data-centered approach. The other was that the user-supplied data were often in annual pumping forms or were generalized, lumping pumping records from individual wells into a total pumping record for an entire wellfield. Data from HydroBase and the well users were generally in agreement. Larger discrepancies were investigated and addressed on a case-by-case basis. A detailed overview of the data collection and approach for filling missing or incomplete data is provided in Appendix A.

Because of the variation in the quality and completeness of available data, missing values were filled on a case-by-case basis for each well user. Pumping data were uploaded to the model database and exported in the appropriate format to be read by StatePP. The workflow for extending M&I pumping data is relatively straightforward and shown with sufficient detail on the workflow overview in Figure 2-1, above. Additional background information about the collection of M&I pumping can be found in Appendix C of the CDM 2013 Report, and the Task 41.3 technical memorandum (CDM 2006, 2013).

2.2.1.6 Recharge Areas

Intentional recharge of the alluvial aquifer for augmentation purposes occurs in recharge ponds and in canals throughout the Basin. The time-series data reflecting augmentation recharge were collected from HydroBase using TSTool commands. The data, which were compiled by Wilson Water Group, are consistent with current SPDSS consumptive-use and surface water modeling efforts. The number of recharge areas included in the extended version of the model has increased since the initial modeling effort. This is primarily a result of the rapid development of recharge areas that occurred in the Basin since 2006.

The data-collection efforts for recharge areas during the initial modeling effort relied on data that were either never in HydroBase (e.g., data from augmentation plan accounting forms) or data that have since been removed from HydroBase. The current augmentation recharge time series rely exclusively on data found in HydroBase. A comparison of historical augmentation recharge data from both the initial modeling effort and the current StateMod model revealed discrepancies at nearly all recharge sites. Most of the data discrepancies were small and were likely a result of rounding of the delivery record values. Some differences were much larger and could not be easily explained. However, the sum of augmentation recharge at all sites in the model was very similar.

After consultation with Wilson Water Group (the surface water model contractor) and a thorough review of the data, the augmentation recharge data set was used from the surface water model and replaced the existing data from the initial modeling effort for the entire modeling period. This approach offers two advantages. First, it is data-centered and easily repeatable. Second, the augmentation recharge data set is consistent with the current surface water model.

The workflow for extending the augmentation recharge time series is shown Figure 2-5, below. Appendix M of the CDM 2013 Report provides more details on the process used to generate the augmentation recharge time-series data (CDM 2013).

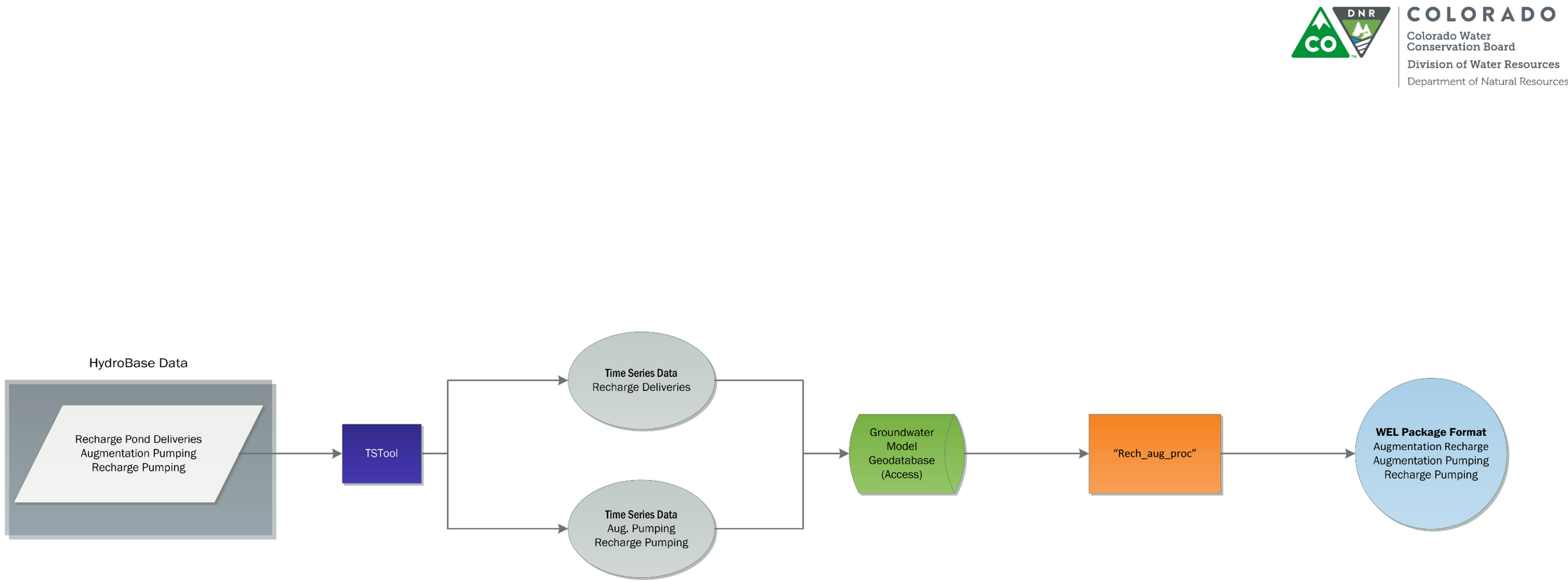
2.2.1.7 Recharge and Augmentation Pumping

Recharge pumping represents water pumped from the alluvial aquifer that is delivered to recharge ponds. Augmentation pumping is water periodically pumped from the alluvial aquifer and delivered directly to the river to replace streamflow depletions from well pumping associated with augmentation plans. The time series for both types of pumping were retrieved from HydroBase using

TSTool commands. The list of wells used for recharge or augmentation purposes was provided by Wilson Water Group, which also consulted with DWR to determine the proper list of wells for each type of use.

The updated list of wells was different from the list of wells used in the initial modeling effort, which was a result of the different approach taken to identify recharge or augmentation wells. The initial modeling effort considered all wells with a decreed use of either recharge or augmentation and collected any records corresponding to the pumping under those uses. This resulted in a number of wells being identified that were used for recharge or augmentation pumping for a brief period and then never operated under that use again. Most of the pumping from these wells was in very small quantities and the pumping records were not always available in HydroBase. The updated approach identified wells that are used for augmentation or recharge on a regular or semi-regular basis. The goal was to create a data set that represents both past and potential future use of augmentation or recharge wells. After consultation with Wilson Water Group, BC adopted the updated data-collection approach and replaced the data from the initial modeling effort for the entire period of record. The updated approach is more data-centered and is consistent with the other modeling efforts in the Basin.

The workflow for recharge and augmentation pumping time-series extension is also shown on Figure 2-5, below. Additional information about the methodology used to collect augmentation and recharge pumping data can be found in Appendix M of the CDM 2013 Report (CDM 2013).

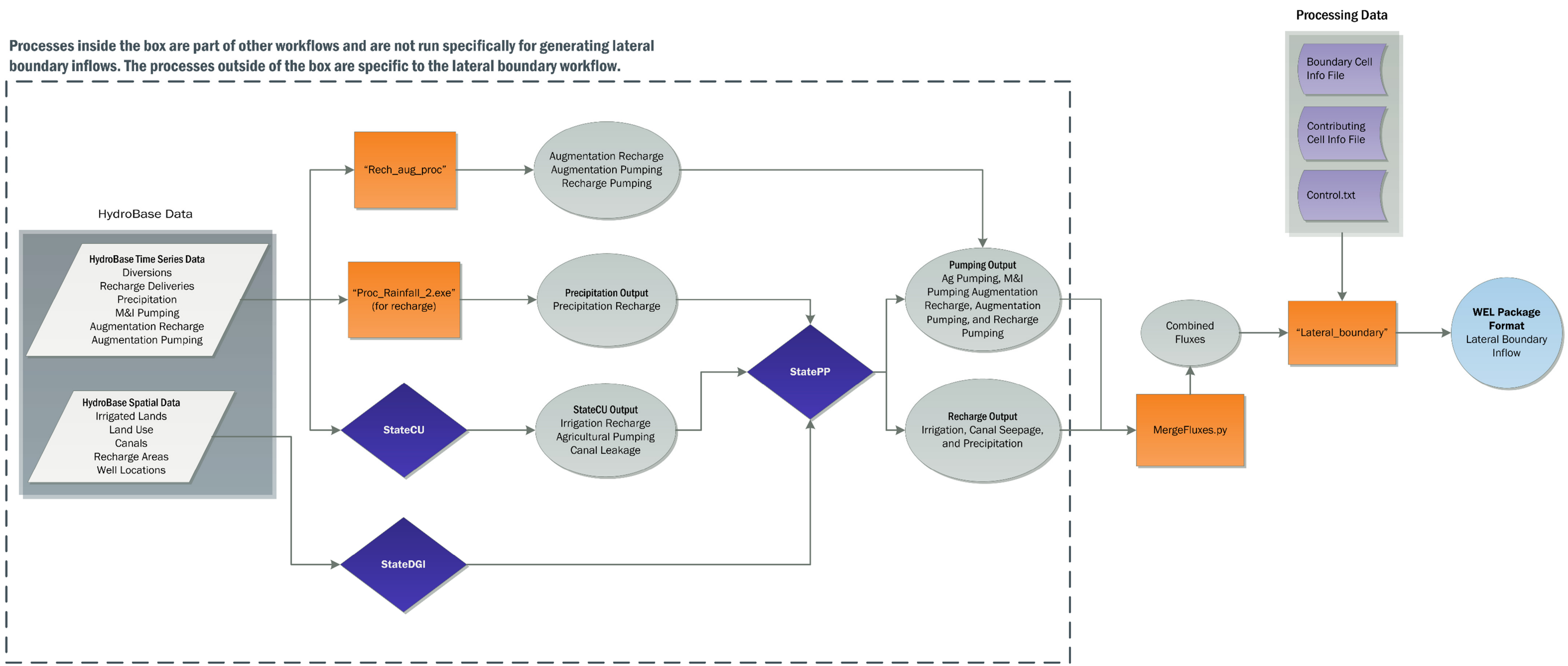


Recharge areas (ponds) are now modeled using a WEL package format file, which is better suited to represent their relatively sparse spatial distribution.

Figure 2-5. WEL Development Workflow: Augmentation Components

2.2.1.8 Lateral Boundary Inflow Fluxes

Lateral boundary fluxes are a composite of a number of individual time series that represent groundwater flux at the boundary of the active model domain. The fluxes at the model boundary are a result of irrigation, canal seepage, precipitation, augmentation recharge, and pumping that occur outside of the active model domain. The net flux from these inputs at the boundary is estimated with a software tool developed in the initial modeling effort. This tool uses output from StatePP for irrigation recharge; irrigation pumping; M&I well pumping; canal seepage, and precipitation, as well as values of augmentation recharge, and augmentation/recharge pumping occurring outside the active model domain. The locations of the inputs listed above are used to determine the shortest distances between individual inputs and the active model boundary. The distances are used to identify the boundary model cells that will receive the lateral inflow fluxes and to derive parameters for estimating the timing of the fluxes. The analytical Glover Equation is used to generate the timing of the fluxes (Glover and Balmer 1954). The tool uses this information to generate MODFLOW input files reflecting lateral boundary inflow fluxes. A detailed workflow diagram for the lateral boundary fluxes is shown on Figure 2-6, below. Further information regarding lateral boundary inflows can be found in Appendix D of the CDM 2013 Report (CDM 2013).



Notes: 1) See Figure 2-3 for complete precipitation workflow.
2) See Figure 2-4 for complete StateCU workflow.
3) See Figure 2-5 for complete augmentation recharge, augmentation pumping, and recharge pumping workflow.

Figure 2-6. Lateral Boundary Inflow Workflow

2.2.1.9 Calibration Data

The primary data used for model calibration include groundwater-level measurements, estimates of stream gain/loss on a reach-by-reach basis, and streamflow measurements. A description of the methods and approach used to generate each data set is provided below. Additional background information regarding the calibration data can be found in Appendix K of the CDM 2013 Report (CDM 2013).

2.2.1.9.1 Observation Water Levels

Groundwater-elevation data were retrieved from HydroBase for 560 wells located throughout the Basin. A comparison of groundwater-elevation data obtained from the most recent version of HydroBase and data collected during the initial modeling effort indicated that the measuring-point elevations have been updated for a number of the wells. The update in measuring-point elevations resulted in changes to observed groundwater elevations for these wells. A number of SPDSS and USGS monitoring wells have had water-level measuring points surveyed since the initial modeling effort, and these surveyed measuring-point elevations were incorporated into the observed water-level elevation data (Everett and Char 2015). Additionally, water-level measuring-point elevations at non-surveyed wells were checked against the 1/3 arc-second USGS three-dimensional (3D) Elevation Program Seamless DEM, and the measuring-point elevations were updated to the DEM elevation value for nine of the non-surveyed wells based on professional judgment (USGS 2015). For these wells where measuring-point elevation data were updated, groundwater-elevation data for the entire modeling period were calculated to ensure that the data reference a consistent measuring-point elevation.

Some water-level observation wells also have had horizontal location coordinates updated. First, 63 wells were updated with the horizontal location coordinates from the DWR irrigation snapshot GIS data sets. Second, 106 wells appeared to have had horizontal location coordinates that were UTM coordinates in the North American Datum of 1927 (NAD27), but had been reported as being in the NAD83. The difference between these two types of datum is approximately 600 feet on the ground. The discrepancy was noted when several wells from the Central Colorado Water Conservancy District (CCWCD) did not plot in locations that matched the Public Land Survey System (PLSS) information. After a review of well locations, the discrepancy between the UTM coordinates and the PLSS information clearly indicated that the UTM coordinates had a simple error in the datum, and the UTM coordinates were re-projected into the correct values for the NAD83 datum using GIS methods.

A number of monitoring well locations have been equipped with water-level transducers and continuously recording data-logging equipment. Datalogger measurements from these wells are available from HydroBase on a daily or average daily basis. To avoid biasedo weighting of water-level calibration statistics through the sheer volume of the data available for these wells, only the data point nearest to the end of each month were used in the water-level calibration data set. If applicable, water-level measurements prior to the installation of transducers and data-logging equipment at these wells were preserved in the water-level calibration data set.

2.2.1.9.2 Stream Gain/Loss Estimates

Estimates of stream gain and loss were calculated on a reach-by-reach basis using a mass balance approach developed during the initial modeling effort. Streamflow gage data were used along with measured diversions and M&I discharges to determine the net unmeasured gain or loss of flow along a particular stream reach on a daily time scale. The streamflow and diversion data were retrieved from HydroBase and the discharge data were collected from the EPA (see Section 2.2.1.2.3 for more detail).

The reaches are defined by the location of the stream gages. The daily net gain/loss value computed with the mass balance approach was constrained by a number of factors using the mass balance-based approach developed in initial modeling efforts. The process for quantifying gains/losses included an initial constraint that limits the daily gain/loss by the capacity of the aquifer to transmit water to and from the stream. The constrained daily values were then averaged over a multi-day period to account for the expected travel time in the reach. A longer moving average was then derived from the daily data to account for runoff events that can produce rapid but temporary 1- or 2-day increases in stream gains. The cumulative monthly constrained and averaged values were then used as the calibration targets for the stream gain/loss calculated by the model in SFR2. A more detailed description of the methodology and approach for estimating stream gain/loss is provided in Appendix E of the CDM 2013 Report (CDM 2013).

2.2.1.9.3 Streamflow at Relevant Gages

Streamflow data used for calibration were collected by Wilson Water Group and provided using the same procedures outlined in Section 2.2.1.2.1, above. The gage locations used for calibration are within the model domain and were used to check simulations of streamflow generated by SFR2. The same 13 sites identified during the initial modeling effort were used for calibration of the updated model. Additional background information regarding the calibration data can be found in Appendix K of the CDM 2013 Report (CDM 2013).

2.2.2 QA/QC Procedures

The procedures for quality assurance and quality control (QA/QC) were tailored to the individual data sets being reviewed. The following is an overview of the QA/QC that was conducted on the various types of data:

- Data received from Wilson Water Group: Data provided by Wilson Water Group included StateCU modeling output, precipitation time series, streamflow measurements, canal diversions, augmentation deliveries, and augmentation and recharge pumping. Excluding the StateCU output, these data were provided in the form of TSTool command files and TSTool output, and had undergone a level of QA/QC by Wilson Water Group prior to being delivered. Each TSTool command file was tested to make sure they ran without errors. All of the StateCU and TSTool outputs were examined for outliers and inconsistent trends.
- Constant time-series data: Time-series components that were constant from year to year were not changed during the extension effort. A brief review of the existing data was conducted and did not identify any issues with values used in the model.
- M&I pumping: Most of the M&I pumping data for the extended period were collected from HydroBase using TSTool commands. The command files were reviewed and checked for consistency. The extended data were compared to the data from the initial period of record to check for consistency and continuity. Unreasonably large increases or decreases in pumping were investigated on a case-by-case basis. Detailed descriptions of the development of M&I pumping data can be found in Appendix A of this report.
- Augmentation and recharge: Augmentation recharge in ponds and augmentation and recharge pumping data were retrieved from HydroBase using TSTool commands provided by Wilson Water Group. The commands and TSTool output were reviewed for consistency.
- Lateral boundary fluxes: The lateral boundary fluxes are represented by a combination of input sources including data from StateCU. QA/QC was conducted for the individual components prior to processing the lateral boundary fluxes as described in this section. The computed lateral boundary fluxes were spot-checked for consistency after processing.

- Processing tool output: The workflow to convert time-series data into MODFLOW model input files involves using processing tools developed by CDM. BC conducted an evaluation of each tool, which included a review of the source code and a review of the output files focusing on consistency and verifying expected results.

The methods described above represent the first round of QA/QC for the time-series data. Additional QA/QC was conducted after the MODFLOW input files were generated and model testing was initiated. The testing process provided an opportunity to discover data inconsistencies that were previously undetected.

2.3 Conclusions

The time-series data sets for the model were extended from the initial period of 1950 to 2006 to include data through 2012. Most of the effort was focused on developing the data for the extension period (2007–12); however, some time series were updated for the entire modeling period because of improvements to the available data and approach. This effort also included the extension of time-series data to be used for model calibration.

In general, the approach and tools used to extend the time series relied on concepts and tools from the initial modeling effort. The intent of the project approach was to streamline the extension effort using previous methods. To aid in understanding the existing tools and processes, detailed workflow diagrams were developed, and they are included with this report. The goal in creating the diagrams was to clarify the overall workflows, identify necessary input files and tools, and provide guidance for future users to develop time-series data sets. The refinement and clarification of the workflows and approaches used to develop time-series data for the model are intended to improve the quality and accuracy of the data used in the model and to reduce the effort required to generate time-series data in the future.

Section 3

CDSS Toolbox and StateDGI Updates

The CDSS Toolbox is a set of GIS DMIs implemented using Python scripts that provide users with a graphical user interface (GUI) for each tool within Esri's ArcToolbox™ software environment. Python is an open-source, high-level computer programming language with clear syntax that has been incorporated in ArcGIS for performing geoprocessing tasks and also has proved to be a powerful tool in performing several model input file processing tasks outside of ArcGIS. The CDSS Toolbox DMIs perform operations to process GIS data sets for use with other CDSS tools and DMIs, notably StateDGI, StateCU, StateMod, and StatePP. The CDSS Toolbox is intended to provide consistent, automated, and reproducible methods of developing the input files required for other CDSS tools.

StateDGI is a DMI specifically designed to store, process, and output data for StatePP. StateDGI is implemented via an Access-based geodatabase that also contains several additional data tables, forms, stored queries, and Visual Basic for Applications (VBA) scripts that generate input files for StatePP. StateDGI performs several spatial data processing tasks including locating the groundwater model cells containing irrigation wells, calculating the partial areas of irrigated parcels within individual groundwater model cells, and calculating the partial lengths of irrigation canals within individual groundwater model cells.

3.1 CDSS Toolbox Update

The primary objective of the CDSS Toolbox update was to update the scripts to operate within ArcGIS version 10.1, with additional objectives of reading both geodatabase feature classes and shapefiles as input, removing redundant code, checking the logic of geoprocessing operations, checking for consistent input data schema requirements, and ensuring that the scripts process data correctly.

The original CDSS Toolbox Python scripts were written for ArcGIS version 9.1. Python support within ArcGIS has evolved over the past several years, and a brief technical history is provided here. ArcGIS 9.1 (and thus the CDSS Toolbox) used the non-standard PythonWin (rather than standard open-source Python) package and accessed the ArcGIS geoprocessing components using the PythonWin win32com COM interface. Later versions of ArcGIS version 9 used standard versions of Python and accessed ArcGIS geoprocessing components using the Python-native arcgisscripting module. ArcGIS version 10 (all sub-versions) continues to use standard versions of Python, and includes the newer ArcPy module while continuing to support the older arcgisscripting module.

Because the Python scripting syntax between the PythonWin and arcgisscripting is virtually the same, updating the previous scripts to operate in ArcGIS version 10.1 requires only very minor code changes. However, after consultation with CWCB and DWR, the CDSS Toolbox scripts were updated to the newer ArcPy syntax because of the likelihood that Esri will end support for and remove the older arcgisscripting from ArcGIS in future versions. Performing the transition to ArcPy at this stage led to performing several of the additional objectives such as searching for redundant code, checking the logic of geoprocessing operations, and ensuring that the scripts process data correctly.

During the process of updating the CDSS Toolbox scripts, any updates to the original code that were not a simple conversion of arcgisscripting syntax to the equivalent ArcPy syntax were left in place but commented out to illustrate the changes and preserve a record of the previous code. Also, supplemental explanatory comments were added to the Python script source code to describe the flow of processing operations, and improved the messages output to users during execution of each tool.

An updated CDSS Toolbox user manual is included as Appendix B.

3.2 StateDGI Updates

The StateDGI Access database includes a series of linked queries to assist in determining the locations of groundwater wells, fractional areas, and lengths of irrigated parcels and irrigation canals. The queries serve as the basis for creating files that can be used as input to StatePP. These linked queries are in some cases very complex. As part of the scope of this model update effort, BC reviewed these queries for logical consistency and accuracy. During this review, two major inconsistencies that produced incorrect input files for StatePP were identified and corrected.

First, an issue was identified and resolved for the series of linked queries that produces files for StatePP that contain the Water District Identifier (WDID) of a canal and the partial length of the canal within each groundwater model cell to appropriately distribute canal seepage recharge. In some cases the WDIDs in StateDGI needed to be aliased to another WDID for StatePP to be able to appropriately match canal seepage estimates from StateCU. These situations occurred when multiple WDIDs for some canals were “aggregated” under a single WDID (e.g., multiple canals under a single ditch system may be aggregated to the WDID of the system’s main canal). Separate alias WDIDs are necessary to split seepage from the portion of a canal that carries water to a storage reservoir from the portion of the canal that carries water from the reservoir to irrigated lands because the timing and volumes of seepage are different in the supply and demand sections of the canal. The original StateDGI queries for canal lengths applied the aliased WDIDs one process step too soon in the chain of queries such that the lengths of any canals with aliased WDIDs had not been written to the canal file for StatePP, ultimately resulting in canal seepage recharge related to those canals not being added to the model.

Second, issues were found and resolved for the series of linked queries that produce files for StatePP that contain the WDID for an irrigation well, the acreage irrigated by the well, and the pumping capacity of the well. Irrigated parcels may receive water from a combination of surface water sources and groundwater wells, including instances of multiple surface water sources and multiple groundwater wells. In addition, many individual wells have the potential to supply water to multiple irrigated parcels. The series of linked queries is intended to calculate the proportions of irrigated acreage of each model cell to be irrigated by each well and the proportion of each well’s pumping capacity that can be applied to each irrigated parcel in each model cell. A Python script developed for QA/QC to sum the irrigated acreage for each parcel and pumping capacity for each well revealed that the previous versions of these linked queries had been incorrectly proportioning both irrigated acreage and pumping capacity. After reviewing the initial results from the Python QA/QC script, adjustments were made to many of these queries, and additional helper queries were added. StateDGI now produces well input files for StatePP that generate well pumping capacities and irrigated acreages that are correct and consistent with the values loaded into StateDGI from the irrigated lands GIS data sets.

Other minor updates to StateDGI included changes to data table field names to be consistent with current DWR data schema and compliance with current Access standards. Some stored queries still used a former standard (e.g., “WD_ID_7”) field name, and these were changed as appropriate to current standard field names (e.g., "SW_WDID"). Many data tables and stored queries related to wells used the field name "TOP" for the depth of the top of well screen. The word TOP is a reserved word and statement in Structured Query Language (SQL) and is not accepted by ArcPy as a field name. All tables and queries in StateDGI with the field name TOP have now been changed to use the field name "TOP_" to avoid any possible confusion with the SQL TOP statement. Finally, in consultation with CWCB and DWR staff, the queries that return well pumping capacities are now limited to 2,000 gallons per minute (gpm) total for each individual well to reflect likely physical limits on pumping capacity.

Section 4

Development of Extended Model Input Files

The development of the model input files for the extended period is a multi-step process involving multiple DMIs and processing tools. During the development of model input files, several DMIs and data processing tools were updated and improved in terms of accuracy, efficiency, and functionality. This section describes the improvements to these DMIs and data processing tools as well as the development of the model files themselves.

4.1 File Directory Structure

Using a cohesive file directory structure was an overarching theme in the development of the model files. The use of an organized file and directory structure assists in tracking the flow of raw input data through the calculations and processing of the various CDSS DMIs and analysis tools through to the final MODFLOW input files.

The irrigated lands GIS data sets in CDSS are major data input sources to the model. The GIS data sets include the locations and areas of irrigated parcels, including the associated sources of water for irrigation and the locations and pumping capacities of irrigation wells. The irrigated lands GIS data sets prior to 2010 data sets were produced for the State by Riverside Technology, Inc. as "snapshots" for specific years based primarily on detailed aerial photograph interpretation (Riverside Technology 2007). The spatial information from irrigated lands snapshots was applied through time as described in Table 4-1.

Table 4-1. Irrigation Snapshot Years and Simulation Periods

Snapshot Year	Simulation Period
1956	1950–75
1976	1976–86
1987	1987–96
1997	1997–2000
2001	2001–04
2005	2005–09
2010	2010–12

StateDGI is capable of processing data from only one irrigated lands GIS data set snapshot at a time to produce input files for StatePP. By necessity, then, the StateDGI and StatePP processing must be performed separately for each simulation period corresponding to a snapshot. This results in one StateDGI subdirectory for each snapshot's simulation period. StatePP can also read in only a single set of input files from StateDGI. Additionally, the most straightforward method of producing separate evapotranspiration input files for subirrigated meadow, subirrigated alfalfa, and riparian phreatophyte vegetation for PSB from StatePP is to perform separate StatePP processes. The spatial distribution of subirrigated crops is determined from the irrigated lands GIS data set snapshots and thus changes with each snapshot's simulation period. The spatial distribution of riparian phreatophyte vegetation used in the model remains constant through time, and the same annual cycle of monthly maximum evapotranspiration rates is applied each year. Consequently, a single StatePP run can be used for the entire simulation period to create the evapotranspiration input file for riparian phreatophyte vegetation.

Table 4-2 presents the file directory structure used for the model and generation of model input files for each simulation period through the StateDGI/StatePP process. Folder names below are in bold and descriptions are in italics. Closed circles denote primary subfolders, and open circles and closed squares denote subfolder secondary and tertiary hierarchy, respectively.

Table 4-2. Model File Directory Structure
StateDGI
○ **Snap1956**: *StateDGI output from 1956 irrigated lands GIS data set*
○ **Snap1976**: *StateDGI output from 1976 irrigated lands GIS data set*
○ **Snap1987**: *StateDGI output from 1987 irrigated lands GIS data set*
○ **Snap1997**: *StateDGI output from 1997 irrigated lands GIS data set*
○ **Snap2001**: *StateDGI output from 2001 irrigated lands GIS data set*
○ **Snap2005**: *StateDGI output from 2005 irrigated lands GIS data set*
○ **Snap2010**: *StateDGI output from 2010 irrigated lands GIS data set*
StatePP
○ **1950-1975a**: *StatePP output for 1950–75 including recharge, pumping, and alfalfa evapotranspiration*
○ **1950-1975m**: *StatePP output for 1950–75 including meadow evapotranspiration*
○ **1976-1986a**: *StatePP output for 1976–86 including recharge, pumping, and alfalfa evapotranspiration*
○ **1976-1986m**: *StatePP output for 1976–86 including meadow evapotranspiration*
○ **1987-1996a**: *StatePP output for 1987–96 including recharge, pumping, and alfalfa evapotranspiration*
○ **1987-1996m**: *StatePP output for 1987–96 including meadow evapotranspiration*
○ **1997-2000a**: *StatePP output for 1997–2000 including recharge, pumping, and alfalfa evapotranspiration*
○ **1997-2000m**: *StatePP output for 1997–2000 including meadow evapotranspiration*
○ **2001-2004a**: *StatePP output for 2001–04 including recharge, pumping, and alfalfa evapotranspiration*
○ **2001-2004m**: *StatePP output for 2001–04 including meadow evapotranspiration*
○ **2005-2009a**: *StatePP output for 2005–09 including recharge, pumping, and alfalfa evapotranspiration*
○ **2005-2009m**: *StatePP output for 2005–09 including meadow evapotranspiration*
○ **2010-2012a**: *StatePP output for 2010–12 including recharge, pumping, and alfalfa evapotranspiration*
○ **2010-2012m**: *StatePP output for 2010–12 including recharge, pumping, and alfalfa evapotranspiration*
○ PhreatET: *StatePP output for 1 year of annual cycle of monthly riparian phreatophyte vegetation ET then extended*

Table 4-2. Model File Directory Structure
MODFLOW
◦ **SFR2_Generator**: *SFR2 input files created by the SFR2 Generator ArcToolbox tool including sample ArcMap file, SFR2 Generator Python script, and ArcToolbox .tbx file* ◦ **Simulations** ▪ **Input files**: *MODFLOW input files from StatePP outputs combined for entire 1950–2012 simulation period + MODFLOW input files for performing warm-up simulation to produce initial heads for 1950–2012 simulation period* ▪ **SP2016_GW_Final**: *MODFLOW Name files and model outputs for warm-up and 1950–2012 South Platte Alluvial Groundwater Model simulations* ▪ **Tools**: *Python utilities for extracting initial heads from end of the warm-up simulation and writing binary input files to plain text for inspection and QA/QC.*

4.2 Source Code Updates to StatePP and Other DMIs

During the course of the development of model input files, updates were made to StatePP and several of the CDSS DMIs used in the model development process. In the case of some DMIs, non-standard Fortran syntax specific to a proprietary compiler software was replaced with standard Fortran syntax to allow the Fortran source code to be portable to any standard Fortran compiler, including open-source compilers. The remaining updates to DMIs generally include improvements in functionality, accuracy, and efficiency.

4.2.1 StatePP

The StatePP is a Fortran-based software package that is designed to receive input from StateCU, StateDGI, and other CDSS DMIs and to then produce MODFLOW input files for the Recharge package (RCH), Evapotranspiration package (ET), Evapotranspiration Segments package (ETS), and Well package (WEL). The StatePP Fortran source code was reviewed and tested as part of this model update effort. Additional code comments were added to better document the flow of the code in some places, and minor changes were made to the flow of the code to improve efficiency and speed of execution of StatePP. Two major additions to the functionality of StatePP were also completed during this model update effort, as described in Sections 4.2.1.1 and 4.2.1.2 below.

4.2.1.1 Partition Stress Boundaries Capability Support

First, support was added to StatePP to produce MODFLOW input files that can be used with PSB to separate and individually track different water budget components. The initial version of the model included several water budget components in a single WEL—not only agricultural and M&I pumping, but also augmentation recharge pumping, lateral boundary fluxes, bedrock fluxes, and alluvial underflow. As such, WEL included most of the total simulated fluxes in and out of the initial model construct, and tracking each of these fluxes was extremely difficult. With PSB, several WEL input files may be specified, one for each of these separate water budget components.

PSB facilitates creation of multiple input files for several other MODFLOW boundary condition packages. For example, instead of recharge from precipitation, canal seepage, surface water irrigation return flows, and groundwater irrigation return flows being lumped into a single RCH input file, each these different sources of recharge can be tracked and accounted through the entire MODFLOW simulation. When the user invokes the new StatePP option to produce separate MODFLOW input, separate RCH input files are produced for precipitation, canal seepage, surface water irrigation return flows, and groundwater irrigation return flows. For ET and ETS input files that are separate for phreatophyte vegetation versus individual subirrigated crops, the user must execute separate StatePP runs for each ET/ETS vegetation type.

4.2.1.2 MODFLOW Input File Size Reduction

Second, StatePP was updated through several different measures to generate MODFLOW electronic input files that are of smaller and more manageable sizes. The previous version of StatePP produced very large MODFLOW files for the model. For example, the 1950 to 2006 model ETS input file produced by the previous StatePP is slightly over 40 gigabytes (GB), a size that is very difficult to read and verify for correctness. The updated ETS input files now total less than 2 GB in file size, and each main ETS input file is less than 1 megabyte (MB) while each external array file is 2.1 MB in size such that each file can be read and reviewed easily. The reductions to MODFLOW input file sizes produced by StatePP were achieved through multiple methods, some of which are options the StatePP user can select. The two-dimensional (2D) arrays required in RCH, ET, and ETS represent the greatest proportion of the file size reductions. A new Fortran subroutine was added to StatePP to produce the 2D arrays. This subroutine checks internally whether an array is a constant value (e.g., zero irrigation recharge during non-irrigation season) and, if the values are constant, instead of writing out the entire array, the subroutine employs the MODFLOW “CONSTANT” keyword. This subroutine is also capable of writing the 2D arrays as external files in a binary format that is smaller than a plain text format. Because these binary files cannot be read directly, a Python script (bin2csv.py) is utilized that converts these binary files to comma-delimited text (CSV) files that can be read and array values checked.

Additionally, the decimal precision of array values written by StatePP was reduced to more appropriately reflect the likely precision of the input data. Another option allows the user to specify that canal seepage recharge is written using the WEL format rather than the RCH format. Equivalent values of canal seepage recharge can be entered into MODFLOW through either WEL or RCH because both represent specified flux boundary conditions. However, because in general canal seepage recharge is generally not spatially distributed very widely (i.e., is spatially confined along canal lengths), there is no canal seepage recharge over most model cells. As such, specifying the canal recharge fluxes at individual model cell locations with non-zero values using only WEL requires less overall data than specifying a 2D array of mostly zero values.

4.2.1.3 Recharge Spatial Weighting Corrections

Two minor issues were identified and corrected in the StatePP code during this effort. First, the application of user-specified spatial weighting of canal seepage was corrected. The previous version of the code was found to apply no weighting to the canal seepage recharge even if the user specified weighting values to certain canal lengths. For example, the North Sterling Canal has some sections that were assumed to have greater seepage, but that weighting was not previously applied. With the code fix, weighting of the seepage along those lengths is now being applied.

The second issue that was identified and corrected is the distribution of irrigation return flow recharge both volumetrically and spatially across each group of irrigated parcels that receive water from a structure. Note that in both cases of these issues, the previous version of StatePP was applying the appropriate volumetric fluxes of recharge, and the corrections are only for the spatial distribution (locations) of the recharge.

4.2.1.4 Additional StatePP User Input Flags

Additional flags were added to the StatePP Control File to allow users to specify whether the newly added options such as external binary array input files or PSB-compatible input files will be produced. If these new input flags are not included in a StatePP Control File, the updated StatePP executable will ignore these new options. As a result, older StatePP Control Files will still be compatible with the updated executable.

The input new flags and values include:

- PSB options:
  - "ipsb" flag: specifies whether StatePP should produce PSB-compatible input files (value of 1) or not (value of 0).
  - "iwelcan" flag: specifies whether StatePP should produce canal seepage recharge in WEL format (value of 1) or RCH format (value of 0).
  - "cetid" flag: single-character value to append to end of output filename of ETS files to identify which vegetation type is represented in the file (e.g., "a" = alfalfa, "m" = meadow, "p" = phreatophyte).
- "binarray" flag: specifies whether StatePP should produce external binary arrays (value of 1) or not (value of 0).
- "ispoffset" flag: allows user to specify the initial overall model stress period number for a snapshot in data array headers and external binary array file names (e.g., the 1976 irrigation snapshot starts in stress period 133 of the model, so ispoffset = 133 would be used for processing the 1976 irrigation snapshot).
- An additional value of 2 is now allowed for the previously existing "no_alloc_recharge" flag to employ the new methodology to allocate recharge correctly both spatially and volumetrically; the previous values of 0 and 1 are still allowed to provide backward compatibility with previous StatePP runs.

4.2.2 SFR2 Generator and Precipitation Runoff Processor

The SFR2 Generator is a DMI that is designed to read SFR2 information from the SPDSS geodatabase (e.g., model cell locations of streams with information about stream geometry, inflows at the active model boundary, WWTP discharge inflows, etc.) and produce an SFR2 input file for MODFLOW. The previous version of the SFR2 Generator was translated from the older Visual Basic .NET (VB.NET) source code to an ArcPy-based Python script that can be executed in ArcGIS. An ArcToolbox (.tbx) file for the SFR2 Generator ArcPy script has also been created that provides a GUI to execute the script with the appropriate input parameters (Figure 4-1). The SFR2 input file produced by the new ArcPy script was compared to the equivalent SFR2 input file produced by the older VB.NET executable to verify that the contents are both equivalent and correct. The SFR2 Generator ArcPy script was further modified to write the SFR2 input file using appropriate and consistent numeric formats and spacing to allow for easier reading and checking of values written to the SFR2 input file.

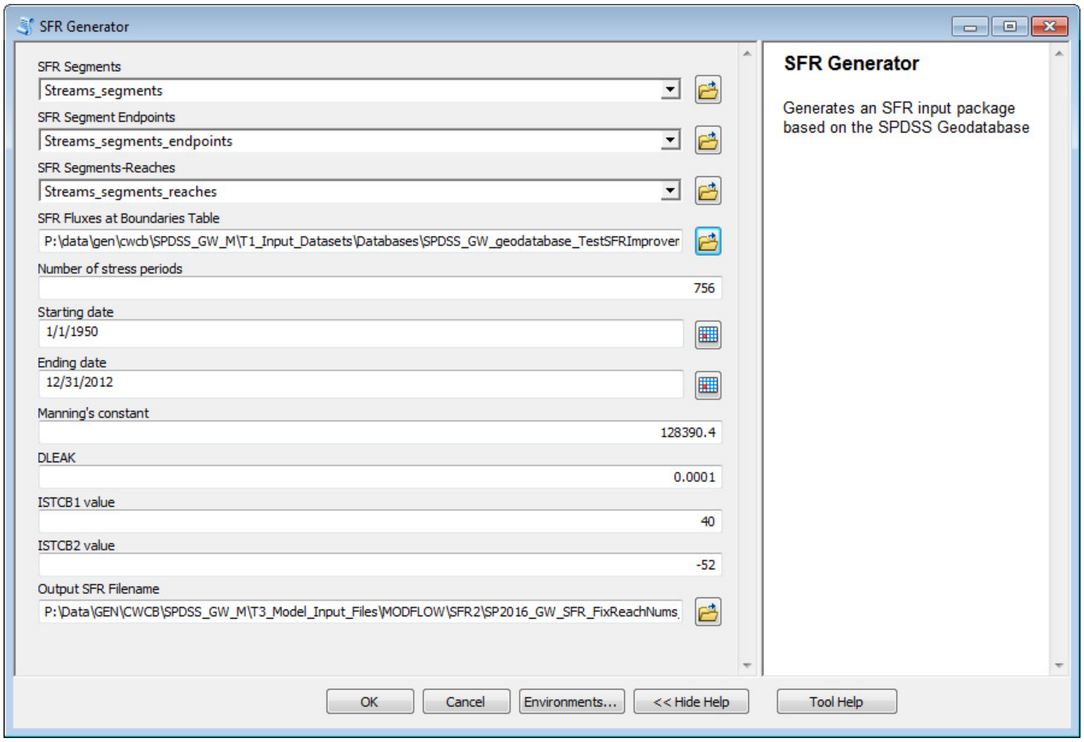


Figure 4-1. Example GUI to the SFR2 Generator DMI

The precipitation runoff processor “proc_runoff” DMI is a Fortran-based executable that reads values of precipitation runoff produced by the “proc_rainfall” DMI that processes precipitation into estimates of precipitation recharge and runoff (ungaged surface flow). The “proc_runoff” DMI reads in both the runoff estimates and the SFR2 input file produced by the SFR2 Generator, and then writes a new SFR2 input file that includes the runoff estimates to streams in SFR2. The “proc_runoff” DMI was updated to add the runoff estimates to the SFR2 “RUNOFF” input variable for each stream segment rather than the “FLOW” variable. The SFR2 “FLOW” input variable is intended to be used for inflow or outflow to or from a stream, such as discharges to the stream from a WWTP or water piped out of a stream for use (Niswonger and Prudic 2005). The SFR2 “RUNOFF” input variable is intended to be used for diffuse runoff (ungaged surface flow) entering a stream (Niswonger and Prudic 2005). The previous “proc_runoff” DMI added the precipitation runoff estimates to the “FLOW” input variable for stream segments including those streams with WWTP discharges or other inflows. This commingling of stream inflows and runoff did not allow the user to easily read and check that the correct inflow and runoff values are present in the SFR2 input file. The updated methodology of adding the runoff values to the “RUNOFF” input variable allows the user to check the values in the input file as well as track the runoff in MODFLOW output files. Finally, the “proc_runoff” code was improved to use the same numeric formats and spacing as the updated SFR2 Generator in the final SFR2 input files to allow the user to more easily check the values that have been written.

4.2.3 Lateral Boundary Processor

The Lateral Boundary Processor is a Fortran-based DMI that accumulates the effects of recharge and pumping from locations outside but tributary to the active model domain. These accumulated fluxes are applied at the active model cell nearest to the location of the flux with a lag time approximated using an approach based on the Glover Method, similar to how timing of stream depletions from pumping are calculated in Colorado (Glover and Balmer 1954). To allow an estimation of lagged flows originating before the model simulation period, but entering the active domain during the simulation period, the fluxes from the simulation period are used during a “warm-up” period. Following the convention from the initial modeling effort, this warm-up period length was set at 80 years. To fill the flux data for this 80-year period, the model simulation period (1950 to 2012) fluxes are read by the code. Because the 63-year length of the model simulation period is less than the warm-up period length, the code returns to the data from the beginning of the simulation period and continues from the beginning to finish filling the warm-up period with data.

The original Lateral Boundary Processor code required more than ten hours to process these flows for the updated model. After a review of the Fortran source code, several coding inefficiencies were found and improved. The previous version of the code contained several time-consuming instructions to read and write data between disk and memory that were unnecessary. The flow of the previous version of the code in looping through data and performing calculations was also inefficient. Several of these loops were combined or reordered in the updated code to improve efficiency. These updates to the Lateral Boundary Processor code resulted in the execution time being reduced from more than ten hours to approximately one hour, and testing of the updated code versus the previous code revealed that both produce equivalent final output.

4.3 Model Input File Generation

Following the aforementioned updates to DMIs and other tools, updated MODFLOW input files for the model were developed using the process described below.

StateDGI. A copy of the initial updated StateDGI database was populated using the CDSS Toolbox with GIS data that do not change through time with each irrigation snapshot (i.e., the model grid, canal locations, and land cover for phreatophyte vegetation). The resulting StateDGI database was copied to a separate directory for each irrigation snapshot, and then the CDSS Toolbox was employed to upload the GIS information of irrigated parcels and wells for each irrigation snapshot. Finally, the StateDGI database file for each irrigation snapshot was opened in Access, and input files for StatePP were generated using the StateDGI main menu.

StatePP. For the periods corresponding to each irrigation snapshot, two StatePP runs were made. First, StatePP was run to generate PSB-compatible MODFLOW input files for precipitation recharge, surface water irrigation return flow recharge, groundwater irrigation return flow recharge, canal seepage recharge, irrigation pumping, M&I pumping, and alfalfa ET. Input files were created in RCH format for precipitation and irrigation return flow recharge, while an input file was created in WEL format for canal seepage recharge because of the narrow spatial extent of canal seepage. Input files were created in WEL format for groundwater pumping, and an input file was created in ETS format for alfalfa. A second StatePP run was executed for each irrigation snapshot period to create an ETS input file for subirrigated meadow ET.

In addition to the two StatePP runs described above, a third StatePP was run for one year (1950) to create the ETS input file for phreatophyte vegetation ET, because the spatial distribution of phreatophyte vegetation is assumed to not change through time, and the estimated monthly ET rate factors are cycled through each year without changes. A Python script (CyclePhreatophyteET.py) was used to create a final phreatophyte vegetation ETS input file that extends the annual cycle of monthly ET rates through the entire simulation period of 1950 through 2012. Table 4-3 summarizes the StatePP processing runs.

Table 4-3. Summary of StatePP Processing Steps		
StatePP Run Type	Period(s)	Water Budget Components (MODFLOW Package Type)
1	All irrigation snapshots	Precipitation recharge (RCH) Surface water irrigation return flow recharge (RCH) Groundwater irrigation return flow recharge (RCH) Canal seepage recharge (WEL) Groundwater pumping for irrigation (WEL) Groundwater pumping for M&I (WEL) ET from alfalfa (ETS)
2	All irrigation snapshots	ET from meadow subirrigation (ETS)
3	1 year	ET from phreatophyte vegetation (ETS)

StatePP was run with the new control flags for employing PSB, canal seepage recharge in WEL format, RCH and ETS arrays in external binary format files to reduce file sizes, and the new methodology to allocate recharge correctly both spatially and volumetrically. The "cetid" flag to identify the vegetation type of each ETS input file uses "a" for alfalfa, "m" for subirrigated meadow, and "p" for phreatophyte vegetation. The value of "ispoffset" was set to correctly identify the initial MODFLOW stress period of each irrigation snapshot.

Following these StatePP runs, a Python script was written to combine the MODFLOW input files from each irrigation snapshot period to single input files that cover the entire simulation period of 1950 through 2012.

Lateral Boundary Processor. The Lateral Boundary Processor reads the flux values from the unconsolidated materials outside the active model grid from a single input file in RCH format for the entire simulation period. A Python script (mergeFluxes.py) was written that reads each final recharge and pumping input file generated by StatePP through the process previously described, sums the fluxes in each MODFLOW stress period, and then writes out the fluxes in RCH format. The updated Lateral Boundary Processor code was used with this flux input and the existing input files (e.g., list of model cells at the edge of the active model domain) from the initial modeling effort.

SFR2. The SFR2 input file was created using the updated SFR2 Generator ArcPy Python script, and precipitation runoff estimates were added using the "proc_runoff" DMI as previously described.

Bedrock, Reservoir Seepage, and Alluvial Underflow Fluxes. Because these fluxes are assumed to remain constant from the end of the initial modeling effort's simulated period, the MODFLOW flags to reuse data from the initial model's final stress period were extended through the end of 2012.

Augmentation Recharge and Pumping. Pumping for recharge and streamflow augmentation was extracted from HydroBase as described in the previous sections, and the DMI "recharge_aug_proc" was used to format the pumping rates into WEL format. Recharge applied in recharge ponds was extracted from HydroBase as described in the previous sections. To reduce input file size by using the WEL input format rather than the RCH input format, the DMI "recharge_aug_proc" was used to format these recharge rates into WEL format, instead of the "proc_recharge_areas" DMI that produces much larger RCH formatted files.

MODFLOW Upstream Weighting Flow Package (UPW). UPW of MODFLOW-NWT replaces the Layer Property Flow package (LPF) from previous versions of MODFLOW when using the Newton Solver package (NWT). The input format of UPW is nearly identical to the format of the LPF input file (Niswonger et al. 2011). Minor updates were made to the UPW file used in the updated model:

- Layer inter-cell transmissivity terms are now calculated using harmonic mean rather than logarithmic mean (Goode and Appel 1992)
- The specific storage (Ss) and specific yield terms are now specified as constant values rather than as arrays for simplicity and to reduce input file size
- Hydraulic conductivity values are now referenced from an external text file with appropriate numeric format

Discretization File. The updated discretization file now references external text files for model layer top and bottom elevations with appropriate numeric formats, and stress period time discretization for monthly model stress periods for 2007–12 have been added.

Output Control Package. The keyword "COMPACT BUDGET" was added to Data Set 1 of the Output Control package input file to reduce the total size of the output cell-by-cell budget file, and output specifications for the model stress periods for 2007–12 were added.

NWT Solver File. The NWT solver replaces the MODFLOW Geometric Multigrid Solver package (GMG) with the Doherty method of handling dewatered model cells used in the initial model (Doherty 2001). The input parameters for NWT were selected through a combination of professional judgment and experimentation for model solution stability and speed as well as overall model mass balance results.

Name File. The Name File lists the references to all the input and output files to be used in a MODFLOW simulation including the Fortran file unit numbers. The Name File was updated to reference input files from the "inputfiles" subdirectory as specified in Section 5.2, below. The updated Name File now references multiple WEL, RCH, and ETS input files for use with PSB identifiers for each water balance component represented by the input file.

MODFLOW Basic Package (BAS). The BAS input file contents remain as they have been from the initial modeling effort, but some numeric formats have been updated.

MODFLOW Gage (GAGE) Package. The GAGE input file contents remain unchanged from the initial modeling effort.

4.4 Model Code Executable Updates

The updated model uses MODFLOW-NWT, a version of MODFLOW that uses the Newton method to solve nonlinear equations such as those governing unconfined groundwater flow (Niswonger et al. 2011). The initial model used MODFLOW-2000 with modifications that prevent drying of model cells by maintaining a minimal simulated saturated thickness and transmissivity (Harbaugh et al. 2000; Doherty 2001). The Newton-based solution method represents a much improved method of avoiding these numerical instabilities and oscillations because of model cell drying and rewetting through a more mathematically rigorous yet efficient solution procedure. Furthermore, the MODFLOW-NWT code is fully supported by USGS.

An additional modification was made to the MODFLOW-NWT executable used for the model through the incorporation of PSB. PSB was originally included with a specialized version of MODFLOW known as MODFLOW-CDSS that was developed by USGS for CWCB as part of the overall CDSS effort (Banta 2011). MODFLOW includes several different types of boundary condition packages such as WEL, RCH, and ETS. Using PSB, the simulated groundwater flows through each of these boundary condition package types is tracked separately by MODFLOW, but all flows within each boundary condition package type are combined during the simulation. PSB allows MODFLOW to use multiple input files for each boundary condition package type and track the flows from the boundaries specified in each individual input file separately. In the model, several different water budget components are included in each MODFLOW boundary condition package type. For example, WEL input includes well pumping for agricultural irrigation, well pumping for M&I use, well pumping for streamflow augmentation, well pumping for recharge re-timing, lateral boundary flows, alluvial underflow into the model, and bedrock fluxes. Without PSB, it is difficult to assess the impact of each individual water budget component on model results because WEL aggegates all the fluxes into a single flux for each model cell. With PSB, the simulated water budget for WEL is separated out into each individual contributing component and is much easier to understand, evaluate, and check for correctness.

One minor issue in the MODFLOW-NWT code's UPW and NWT packages was found and resolved during the course of the model update effort. The issue is related to speed of the model solution rather than an appreciable difference in final model solution results. The problem is related to the calculation of the derivative of the smoothing function used for model cell-to-cell conductance terms (Niswonger et al. 2011). This issue was resolved in the modified MODFLOW-NWT executable used for the updated model. The code issue and proposed correction have been communicated to the USGS code author, and the USGS code author confirmed both the code issue and the resolution (Niswonger 2016). Both the USGS code author and BC tested the corrected MODFLOW-NWT code on several models and confirmed that model outputs change insignificantly, but that the corrected code solves models more quickly. The next USGS release version of MODFLOW-NWT will contain this corrected code (Niswonger 2016).

Section 5

Extended-Period Model Simulation and Calibration Updates

The updated transient model input files for the extended model simulation period of 1950 through 2012 were used to develop a base model for simulation. The following subsections describe the updates to the MODFLOW executable used for the model, the simulated water budget results, and the updated model calibration.

5.1 Model Execution

The updated model is executed in two stages. First, the warm-up period simulation is executed to balance pre-1950 component fluxes, and the final head output array is extracted to a separate file using the Python utility “ExtractHdsAtSP_TS.py.” Second, the 1950 to 2012 simulation is executed using the final head output from the warm-up period as the initial heads.

Model files are stored in two separate directories. The “SP2016_GW_Final” directory contains the MODFLOW-NWT executable and the MODFLOW Name files for each simulation, and this directory is also where all model outputs will be written. The “inputfiles” directory contains all other MODFLOW input files. This directory structure separating input and output files serves to create clear demarcation between model inputs and outputs, is easier to navigate, reduces file sizes by not having multiple copies of input files, and will allow for clear and straightforward model-predictive-scenario execution in the future. The command line batch file “batchrun.bat” will perform all of these operations.

5.2 Simulated Water Budget

The simulated water budget for the updated model was tabulated and evaluated for the entire 1950 to 2012 simulation period for both groundwater and surface water components. Evaluation of the simulated water budget for groundwater components was streamlined and improved through the incorporation of PSB to track these components individually through MODFLOW itself. Table 5-1 below summarizes the average monthly and annual simulated groundwater flow budget components. While groundwater moving in and out of storage throughout the model domain is more than 400,000 acre-feet per year (ac-ft/yr) on average, the average annual net change in groundwater storage is approximately 53,000 ac-ft/yr of groundwater flow into groundwater sinks (e.g., wells, evapotranspiration) from storage. Note that for MODFLOW-based groundwater models, flow from groundwater storage (i.e., a lowering of the water table or potentiometric surface) is accounted as an inflow to the model because flows from groundwater storage satisfy the outflow at a groundwater sink (such as a well), which is then accounted for as an outflow from the model. The largest average annual simulated inflow to the alluvial aquifer system is from the lateral boundary inflows (approximately 500,000 ac-ft/yr), followed by recharge from both irrigation return flows (more than 400,000 ac-ft/yr for irrigation from surface water sources and 140,000 ac-ft/yr for irrigation from groundwater) and canal seepage (approximately 360,000 ac-ft/yr). The largest average annual simulated groundwater outflow is to the surface water system as stream gain (more than 1.3 million ac-ft/yr), followed by agricultural irrigation pumping (approximately 450,000 ac-ft/yr). Appendix C of this report summarizes the simulated groundwater budget for each month of the entire model simulation period.

Table 5-2 below summarizes the average monthly and annual simulated surface water flow budget components. The largest simulated surface water inflow is stream gain from groundwater discharge as stream baseflow (more than 1.3 million ac-ft/yr), followed by the gaged stream inflows at the upper reaches of streams at the edge of the active groundwater model domain (slightly more than 800,000 ac-ft/yr). Note that after accounting for stream loss in those reaches where surface water is simulated to be flowing to the aquifer, the simulated net groundwater discharge to stream baseflow still averages slightly more than 1.0 million ac-ft/yr. The largest simulated average surface water outflows are to stream diversions (averaging over 1.6 million ac-ft/yr), followed by streamflow out of the model domain in the South Platte River below Julesburg (approximately 400,000 ac-ft/yr). Appendix D of this report summarizes the simulated surface water budget for each month of the entire model simulation period.

Table 5-1. Average Monthly and Annual Simulated Groundwater Budgets (ac-ft)

	Groundwater Flow Component	January	February	March	April	May	June	July	August	September	October	November	December	Average Annual	% of Total Inflow or Outflow
Inflow	Groundwater flow in from storage	38,551	32,147	29,870	15,601	15,758	37,067	61,125	53,219	46,104	43,138	48,006	43,209	463,794	19
	Stream loss to aquifer	22,086	19,849	23,064	28,579	36,569	34,029	29,097	27,434	24,105	23,301	20,234	21,538	309,886	13
	Precipitation recharge	1,402	1,424	3,606	12,221	19,530	16,106	15,818	12,864	9,422	7,391	2,318	1,538	103,639	4
	Surface water irrigation return flow recharge	2,325	2,107	2,942	18,450	55,105	71,879	95,784	83,897	47,458	20,148	3,451	2,371	405,918	17
	Groundwater irrigation return flow recharge	0	0	20	1,482	8,982	24,555	41,270	39,639	22,513	4,857	45	0	143,362	6
	Canal seepage recharge	11,116	11,802	15,334	20,950	41,393	55,664	61,153	53,557	34,893	23,991	17,537	13,832	361,223	15
	Recharge ponds	3,528	3,929	7,478	7,586	4,680	5,003	1,261	1,465	2,519	6,541	3,212	2,824	50,027	2
	Reservoir seepage recharge	2,658	2,422	2,658	2,572	2,658	2,572	2,658	2,658	2,572	2,658	2,572	2,658	31,314	1
	Alluvial underflow in	1,040	948	1,040	1,007	1,040	1,007	1,040	1,040	1,007	1,040	1,007	1,040	12,259	1
	Net bedrock flux	1,307	1,191	1,307	1,264	1,305	1,262	1,303	1,302	1,260	1,302	1,260	1,302	15,365	1
	Net lateral boundary flow	42,909	38,574	41,702	39,919	41,162	40,201	42,438	43,382	42,652	44,270	42,598	43,565	503,371	21
Outflow	Groundwater flow out to storage	16,219	13,155	17,022	33,458	73,004	72,283	59,712	38,070	18,400	26,726	23,416	18,680	410,145	17
	Alluvial underflow out below Julesburg	253	234	259	265	298	283	198	144	138	169	192	231	2,665	0
	Stream gain from aquifer	103,043	93,437	100,778	97,150	106,133	111,701	136,731	136,380	125,856	123,019	111,463	107,685	1,353,376	56
	Agricultural irrigation pumping	0	0	79	5,348	30,380	80,306	128,329	121,492	71,966	16,271	149	0	454,319	19
	M&I pumping	2,379	2,277	2,526	3,122	3,826	4,454	5,564	4,916	4,132	3,163	2,359	2,338	41,056	2
	Augmentation pumping	720	676	545	435	282	125	142	212	266	192	218	555	4,369	0
	Alfalfa ET	0	0	5	327	1,302	3,394	4,196	4,008	2,242	739	3	0	16,216	1
	Subirrigated meadow ET	0	0	13	358	784	1,815	2,763	2,730	2,100	1,118	16	0	11,698	0
	Phreatophyte ET	4,065	4,349	7,581	9,243	12,315	15,088	15,278	12,411	9,309	7,200	4,339	4,232	105,409	4
Total	Total in	126,922	114,394	129,020	149,631	228,182	289,344	352,946	320,457	234,505	178,638	142,240	133,877	2,400,157	100
	Total out	126,679	114,128	128,808	149,707	228,325	289,448	352,914	320,362	234,409	178,599	142,154	133,720	2,399,253	100
	In minus out	243	267	211	-75	-142	-104	32	95	97	39	85	157	904	N/A
	% mass balance error	0.19	0.23	0.16	-0.05	-0.06	-0.04	0.01	0.03	0.04	0.02	0.06	0.12	0.04	N/A

Table 5-2. Average Monthly and Annual Simulated Surface Water Budgets (ac-ft)

	Surface Water Flow Component	January	February	March	April	May	June	July	August	September	October	November	December	Average Annual	% of Total Inflow or Outflow
Inflow	Gaged surface water inflows	17,984	16,935	22,193	45,109	156,839	225,329	128,163	82,095	41,329	27,332	21,597	18,671	803,578	30
	Return flow and discharge inflows	14,097	12,886	14,601	16,264	19,279	20,010	28,645	30,898	22,310	16,932	13,559	13,667	223,149	8
	Ungaged surface water inflows	5,868	6,468	14,783	36,969	54,742	43,217	42,208	35,878	26,762	21,593	9,581	6,462	304,532	11
	Stream gain from aquifer	103,043	93,437	100,778	97,150	106,133	111,701	136,731	136,380	125,856	123,019	111,463	107,685	1,353,376	50
Outflow	Physical diversions	54,106	55,394	70,734	93,169	189,300	259,809	272,082	231,540	155,139	120,290	90,922	68,169	1,660,655	62
	Net flow change at selected tributary mouth gages	23,963	20,466	24,279	28,439	26,114	23,002	13,870	13,793	24,376	28,347	25,598	24,257	276,502	10
	Ungaged diversions	1,619	1,678	2,583	5,755	9,995	4,495	2,452	2,170	1,594	1,726	1,793	1,686	37,546	1
	Stream loss to aquifer	22,086	19,849	23,064	28,579	36,569	34,029	29,097	27,434	24,105	23,301	20,234	21,538	309,886	12
	Streamflow out below Julesburg	39,873	32,760	31,864	38,518	70,896	74,943	20,408	12,162	12,337	16,600	18,915	31,853	401,128	15
Totals	Total in	140,991	129,727	152,356	195,493	336,993	400,257	335,747	285,251	216,257	188,877	156,200	146,485	2,684,634	100
	Total out	141,646	130,148	152,524	194,460	332,873	396,278	337,909	287,100	217,550	190,264	157,462	147,503	2,685,717	100
	In minus out	-655	-421	-168	1,033	4,120	3,979	-2,162	-1,848	-1,293	-1,387	-1,262	-1,019	-1,083	N/A
	% mass balance error	-0.46	-0.32	-0.11	0.53	1.23	1.00	-0.64	-0.65	-0.60	-0.73	-0.80	-0.69	-0.04	N/A

The mass balance errors of a model's simulated water budgets may indicate potential problems with the model solution or issues with model input or conceptual design. The overall mass balance error of a model should be less than 1 percent in all cases and approximately 0.5 percent or less in most cases (Anderson et al. 2015). Tables 5-1 and 5-2 above present simulated mass balances for groundwater and surface water averaged for each calendar month as well as averaged annually. Appendices D and E of this report present the simulated groundwater and surface water mass balances for each individual month and the total cumulative mass balance results. The total cumulative simulated groundwater mass balance error is 0.04 percent, and the groundwater mass balance errors are all less than 1 percent in each month. The total cumulative simulated surface water mass balance error is 0.03 percent. However, the surface water mass balance errors range from 0 to 3 percent in each month.

The likely explanation for the higher surface water simulated mass balance errors in some months is the transient nature of the flows in the model and the distance flows travel through the model domain such that surface water flows have not fully equilibrated by the end of each stress period. The low total cumulative mass balance error in the simulated surface water budget indicates a very reasonable overall simulated surface water mass balance error, as does the fact that the cumulative mass balance errors remain under 0.1 percent after the third year of simulation.

Two types of model input demands for water are subject to the simulated availability of water in the model. First, streamflow diversions are limited to the amount of streamflow simulated by SFR2 (Niswonger and Prudic 2005). Second, the MODFLOW-NWT code reduces pumping from WEL at model cells where the simulated water level drops such that the simulated saturated thickness is a small fraction of the total model thickness (Niswonger et al. 2011). In both cases, where the input demand for diversion or pumping is greater than the water simulated to be available, the model will simulate removal only of that available water.

Figure 5-1 below shows the percentage of streamflow diversion demand simulated to be met each year of the extended simulation period, and Figure 5-2 shows only 1999 through 2005 for comparison to the CDM 2013 Report Figure 4-32 (CDM 2013). The percentages of diversions met are generally lower in non-irrigation months when both streamflow and diversion rates are low. Because the overall diversion demand is low during these months, a small amount of diversion demand not being met at one location may lead to a lower percentage of diversion demand being met. On an annual basis, the model meets diversion demands at 95 percent or more each year (Figure 5-1).

Table 5-3 below presents volumes of average monthly diversion demand and diversions simulated by the model, showing that the non-irrigation season months have the lowest percentages of diversion demands met by the model while the irrigation season months of April through October have the highest percentages of diversions met. Overall, 98 percent of the input streamflow diversion demand volume is met by the model for the 1950 through 2012 simulation period.

Figure 5-3 below shows the percentage of agricultural irrigation groundwater pumping input demand that is satisfied by the model annually for the entire simulation period. The percentage of demand met by the model is nearly 100 percent in the early portion of the model simulation period, but declines slightly from the 1950s through the mid-1970s, and then generally stabilizes. Over the entire simulation period, 97.6 percent of the input groundwater irrigation demand volume is satisfied by the model. In comparison, the initial model calibration effort required manually reducing agricultural irrigation pumping to 80 percent of the StateCU demand estimates (CDM 2013).

Figure 5-4 below shows the percentage of M&I groundwater pumping input demand that is satisfied by the model annually for the entire simulation period. Over the entire simulation period, 95.6

percent of the input groundwater irrigation demand volume is satisfied by the model. During the 1950 through 2012 simulation period, 99.8 percent of the augmentation pumping demand is met by the model.

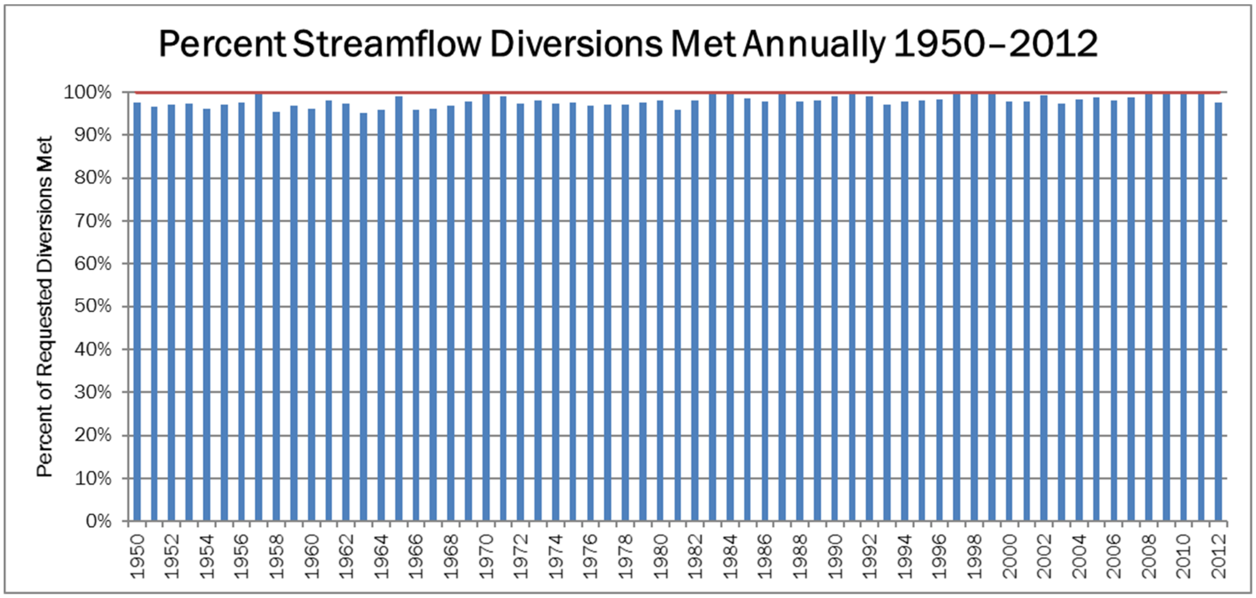


Figure 5-1. Percentage of Streamflow Diversions Met Annually by Updated Model 1950–2012

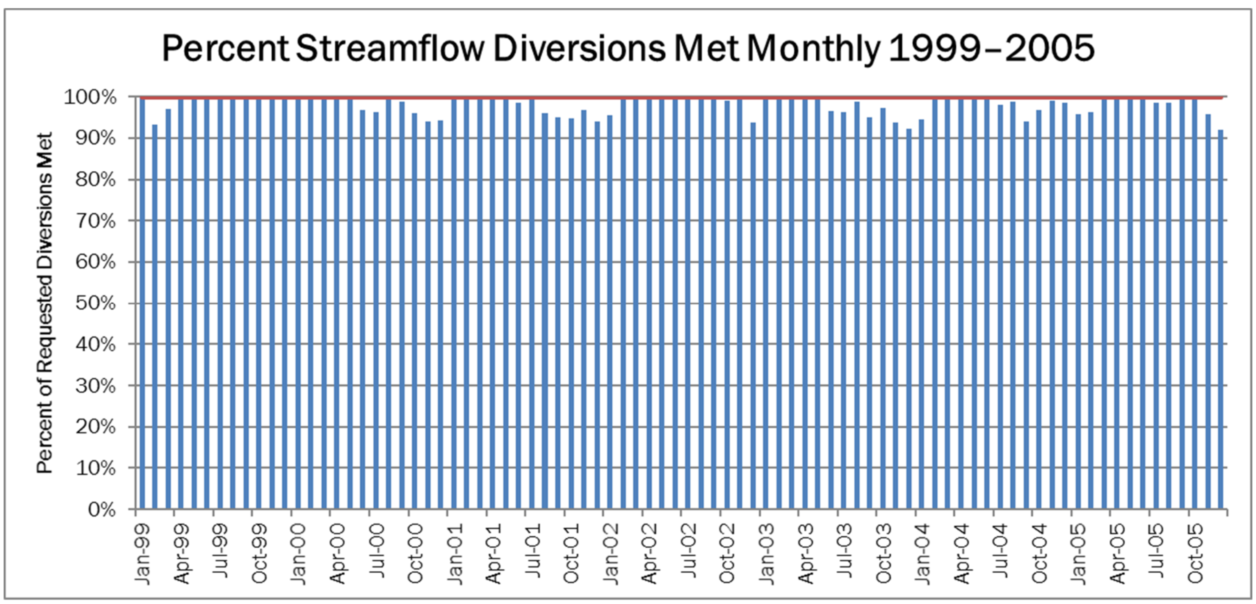


Figure 5-2. Percentage of Streamflow Diversions Met Monthly by Updated Model 1999–2005

Table 5-3. Summary of Streamflow Diversion Demand and Simulated Diversions

Month	Average Diversion Demand (ac-ft/mo)	Average Simulated Diversions (ac-ft/mo)	% Diversion Demand Simulated to Be Met
January	58,063	54,106	93.2
February	58,554	55,394	94.6
March	74,157	70,734	95.4
April	93,580	93,169	99.6
May	189,482	189,300	99.9
June	261,356	259,809	99.4
July	274,988	272,082	98.9
August	235,117	231,540	98.5
September	156,524	155,139	99.1
October	123,822	120,290	97.1
November	95,481	90,922	95.2
December	73,129	68,169	93.2
Average annual	141,188	138,388	98.0

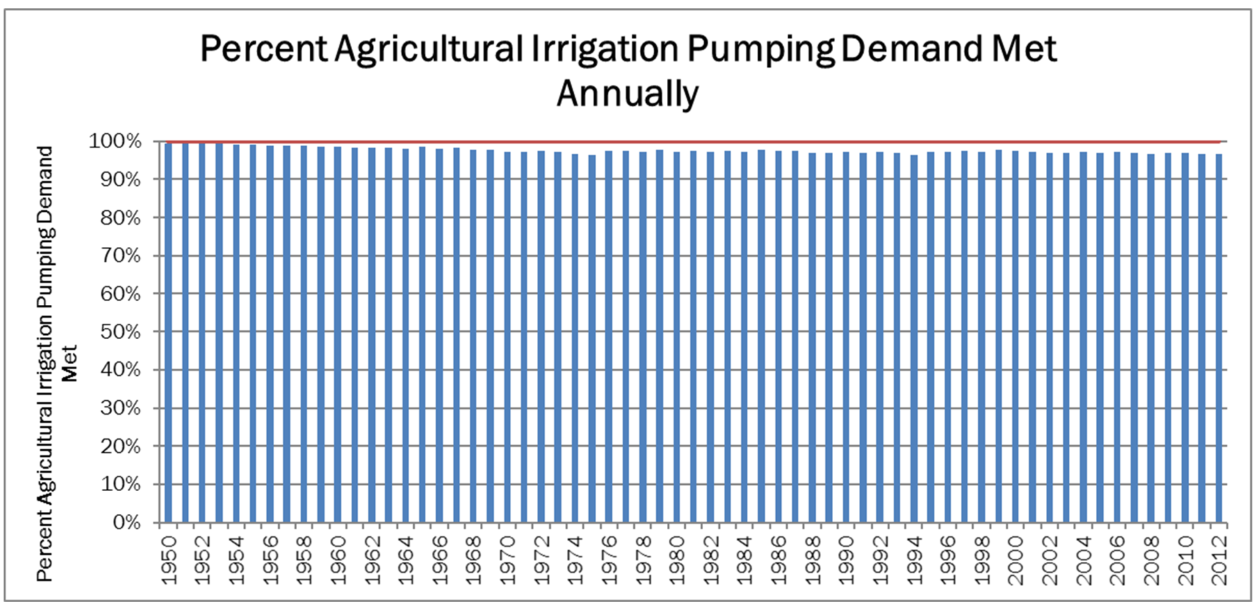


Figure 5-3. Percentage of Agricultural Irrigation Pumping Demand Met Annually

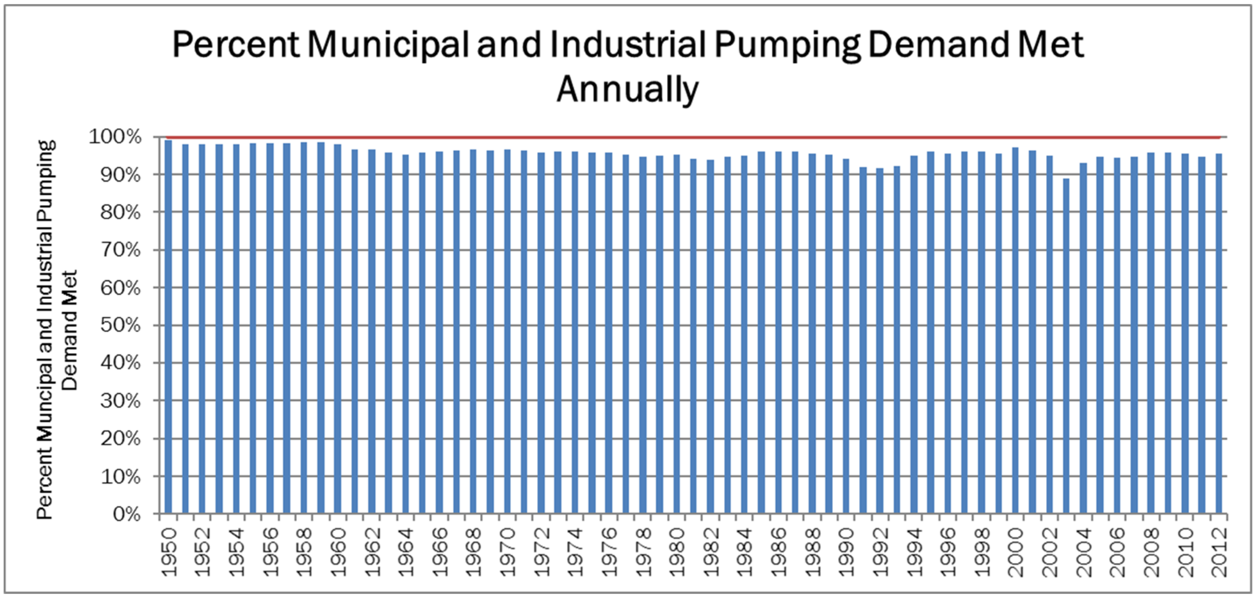


Figure 5-4. Percentage of M&I Pumping Demand Met Annually

5.3 Model Calibration

Model calibration is the process of adjusting model input parameters such that the model reasonably simulates field-measured values of surface flows and groundwater levels. The initial model effort performed limited model calibration on a steady-state version of the model, then more comprehensive calibration on the transient version for the 1999 to 2005 period, and finally a "validation" of the model's calibration for the 1950 to 2006 period. Because the primary objective of the model update effort was to update and extend the model simulation period, only limited additional calibration was performed during this effort. For the updated model effort, the simulated flows and groundwater levels were compared to field-measured values for the full extended 1950 to 2012 simulation period.

5.3.1 Model Input Changes

Several updates were made during the updated model calibration process. The primary calibration efforts focused on adjusting and updating the hydraulic conductivity values assigned to certain portions of the alluvial aquifer system based on additional information and hydrogeologic judgement. Additional activities undertaken as part of the model update also improved calibration. This section describes those updates to the model.

5.3.1.1 Hydraulic Conductivity

The model hydraulic conductivity values were modified in the following areas (see Figure 5-5):

- The vicinities of Gilcrest and Sterling based on information gleaned from evaluations of high water table conditions in these areas (BC 2015)
- Lost Creek Basin based on the calibrated hydraulic conductivity values from the USGS Lost Creek Designated Basin model (Arnold 2012)
- Model active domain margins where lower hydraulic conductivity values would be expected because of the presence of finer-grained alluvial deposits
- Areas showing large discrepancies between simulated and observed groundwater-level elevations

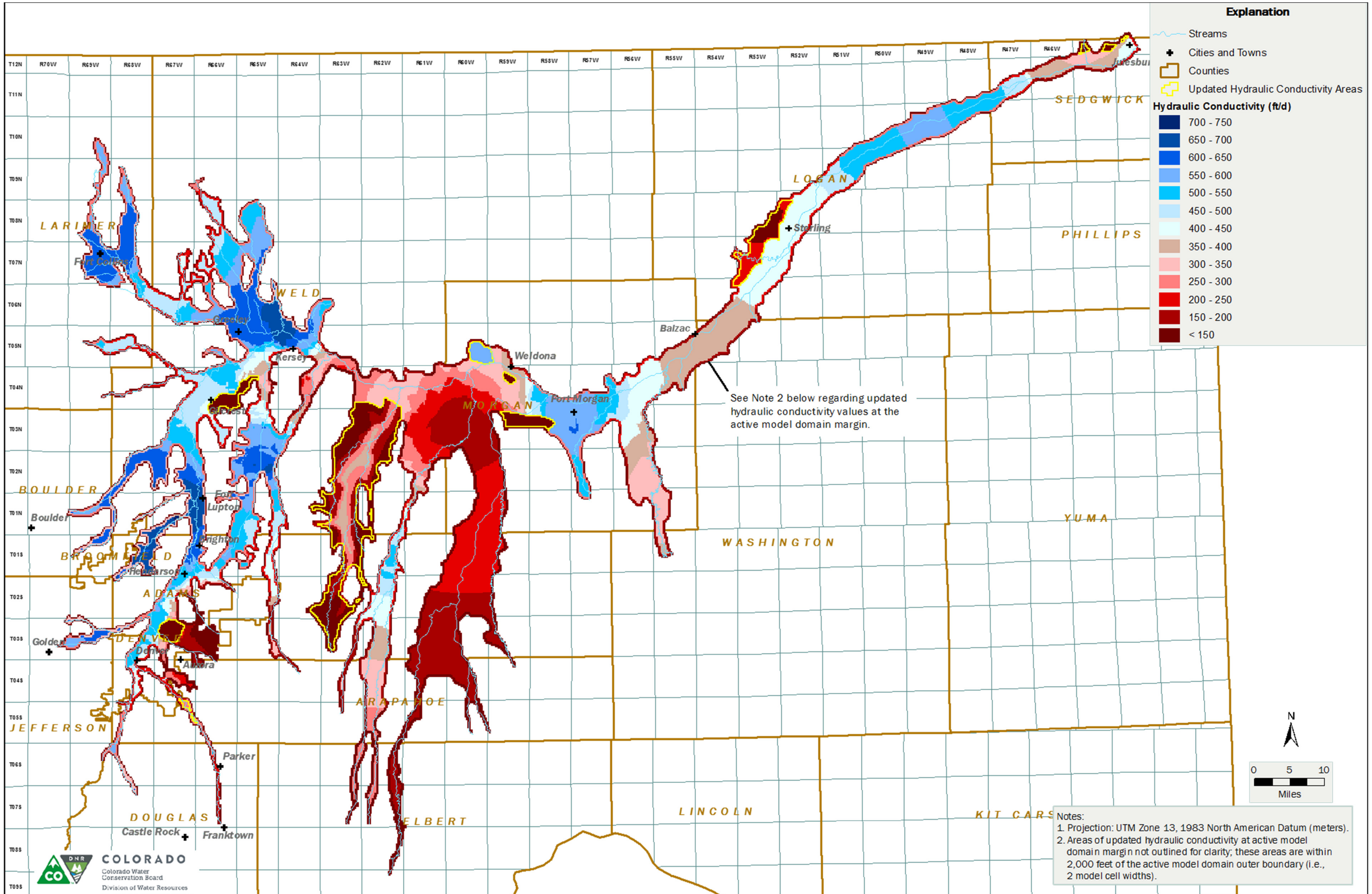


Figure 5-5. Updated Model Hydraulic Conductivity Distribution

5.3.1.2 SFR2 Updates

SFR2 was updated with minor fixes to the stream reach numbering (i.e., routing) of reaches in 4 (of the total 774) SFR2 segments and adjustments to stream top elevation values for some SFR2 segments based on observed groundwater levels in adjacent wells and updated USGS 1/3 arc-second resolution digital elevation models.

5.3.1.3 Municipal and Industrial Pumping

The groundwater pumping demand for M&I wells was reviewed and updated following the results of automated pumping reductions by the MODFLOW-NWT code during early model simulations. The input pumping demands at certain M&I wells have been reduced following review of well permits, available pumping records, well drilling logs, and other documentation as follows:

- Aurora: Wells 1, 2, 3, and 4 were drilled in July and August 1956; Wells 5 and 6 were drilled in December 1955, and Well 7 was drilled in August 1963. Pumping for each of these wells is now simulated to begin the month following the drilling of the well rather than January 1950. Further, after review of reported pumping rates for these wells 1990 through 2012, the estimated pumping rates for 1950-1989 have been reduced by 50 percent in the model inputs.
- COLO State W 4: Based on the well drilling log for the well, the well is screened in bedrock rather than alluvium, and pumping at this well was removed from the model.
- Klausner: A review of the well permits and decree for these wells indicates a total annual allocation of 145.3 ac-ft/yr rather than the 1,311 ac-ft/yr total pumping demand previously used in the model. The pumping rates for these wells have been adjusted to be 145.3 ac-ft/yr total with the same relative allocation of pumping among the four wells.
- Walker Well 3: A review of the well permit for this well indicates that it is an irrigation well, and this well is included in the DWR irrigation GIS data sets. As such, pumping demand for this well is appropriately simulated in the agricultural irrigation pumping demands, and this well was removed from the M&I pumping data sets.
- Wiggins Well 1: A review of the well permit for this well indicates that it was an agricultural irrigation well until 1994, when it was converted to municipal use. The annual appropriation for municipal use is 170.3 ac-ft/yr; therefore, starting in 1994, the simulated municipal pumping demand at this well is specified as 170.3 ac-ft/yr allocated evenly per month.

5.3.1.4 Additional Changes

Precipitation recharge in urban irrigated lands such as golf courses and parks is now assumed to follow the same pattern as precipitation recharge on agricultural irrigated lands. Previously, all urban land use GIS classifications were placed in a single category for precipitation processing.

The elevation of the bottom of the model (i.e., the bottom of alluvial materials) was adjusted upward in the area south of Gilcrest based on review of well logs and observed water levels.

Other model groundwater and surface water flow rates have changed because of updates in underlying data that feed into the model through the data-centered approach. Updates and improvements have been made to HydroBase, which provides streamflow, surface water diversion, climate, groundwater level, and other data to many of the inputs to the model through StateCU, StatePP, SFR2 Generator, and other DMIs. Also, DWR staff have performed updates and improvements to the irrigation snapshot GIS data sets, most notably improving the matching between irrigation wells and irrigated parcels, which in turn improves the estimated groundwater irrigation pumping rates and spatial distribution of applied irrigation water.

5.3.2 Groundwater-Level Calibration

Calibration of the model to observed groundwater levels was evaluated through both statistical and graphical assessments of simulated versus observed groundwater levels. As described in Section 2 above, the observed groundwater-level data set used for the model calibration evaluation was updated from the initial modeling effort to include additional wells, updated well datum surveyed elevations, and updates to well spatial locations. To compare the updated model calibration to the initial modeling effort calibration, standard statistics of groundwater-level residuals (observed values minus simulated values) have been calculated for the 1950 to 2006 period. These statistics have been calculated over the entire model domain for all updated observation well locations and for the subset of wells only with surveyed elevation data (see Table 5-4).

Table 5-4. Bulk Groundwater-Level Calibration Statistics Comparison to Initial Model, 1950–2006

Statistic	Surveyed Wells		Surveyed + Non-Surveyed Wells	
	Updated Model	Initial Model	Updated Model	Initial Model
Residual mean (ft)	0.30	-0.28	0.11	-1.89
Absolute residual mean (ft)	5.87	5.55	8.82	9.58
Residual standard deviation (ft)	8.28	8.33	13.01	14.88
Sum of squared errors (ft)	3.93E+05	3.98E+05	2.46E+06	3.27E+06
Root mean squared (RMS) error (ft)	8.28	8.34	13.01	15.00
Minimum residual (ft)	-25.14	-33.49	-55.28	-71.48
Maximum residual (ft)	39.77	38.57	55.12	74.38
Number of observations*	5,729	5,729	14,520	14,520
Range in observations (ft)	1906.19	1906.19	2268.23	2268.23
Scaled residual standard deviation (%)	0.43	0.44	0.57	0.66
Scaled absolute residual mean (%)	0.31	0.29	0.39	0.42
Scaled RMS error (%)	0.43	0.44	0.57	0.66
Scaled residual mean (%)	0.02	-0.01	0.00	-0.08

*Note: observations restricted to only those available for 1950-2006.

The residual mean is an indicator of whether the model is simulating water levels within the domain too high or too low on average, compared to the measured water levels. The updated model residual mean values are well within 1.0 foot for both the populations of all wells and surveyed wells only, indicating that the model is, on average, simulating water levels with virtually no bias toward higher or lower water levels for the 1950 to 2006 period. The absolute residual mean is an indicator of how well the model is matching measured values regardless of whether simulated values are higher or lower than the accompanying measured values. The updated model shows a very slight increase in the absolute residual mean for the surveyed wells, but an improvement in the absolute residual mean for the population of all wells. The residual standard deviation, sum of squared errors, and root mean squared error are measures of variability between the simulated and measured groundwater levels. Each of these statistics has improved for the updated model over the initial model. Scaling these statistics by the range in measured groundwater levels provides an indication of whether the discrepancies between the simulated and measured values are a small part of the overall model response (Anderson and Woessner 1992). These scaled values are all less than 1 percent for both the initial and updated models, indicating that discrepancies between simulated and measured groundwater levels are a very small part of the model response.

The same suite of bulk calibration statistics was calculated for the updated model for the entire 1950 through 2012 simulation period, and these statistics are presented in Table 5-5 for both the population of surveyed observation wells and the population of all observation wells.

Table 5-5. Bulk Groundwater-Level Calibration Statistics for Updated Model 1950–2012

Statistic	Surveyed Wells	All Wells
Residual mean (ft)	0.80	0.80
Absolute residual mean (ft)	5.85	8.64
Residual standard deviation (ft)	8.53	12.84
Sum of squared errors (ft)	6.24E+05	3.03E+06
Root mean squared error (ft)	8.57	12.86
Minimum residual (ft)	-25.14	-55.28
Maximum residual (ft)	40.58	72.68
Number of observations	8,509	18,312
Range in observations (ft)	1,938.1	2,268.23
Scaled residual standard deviation (%)	0.44	0.57
Scaled absolute residual mean (%)	0.30	0.38
Scaled RMS error (%)	0.44	0.57
Scaled residual mean (%)	0.04	0.04

The residual mean values for the entire simulation period are within 1.0 foot, continuing to indicate very low bias toward simulating groundwater levels—on average either too low or too high. The absolute residual mean values for both observation well populations for the full 1950 to 2012 simulation period improved slightly compared to the initial 1950-2006 period. The statistics that are measures of variability between simulated and observed values increased slightly for the population of surveyed observation wells, but decreased slightly for the population of all observation wells. Overall, the bulk groundwater-level calibration statistics indicate that the updated model remains well calibrated to observed groundwater levels compared to both the initial model construct and the extended period of the updated model.

Graphical measures of groundwater model calibration to observed water levels include scatterplots of observed versus simulated groundwater-level elevations, maps of average groundwater-level residual value at each observation well location, and simulated versus observed hydrographs for transient models. Figure 5-6 below presents scatterplots of observed versus simulated groundwater elevations. A well-calibrated groundwater model should have the points of an observed versus simulated scatterplot cluster along the central line (dark black line of Figure 5-6), with the points tightly clustering around the central line indicating a close match between observed and simulated values. The scatterplot points should also not consistently plot above or below the central line, indicating a lack of bias toward simulating groundwater levels higher or lower than the observed values.

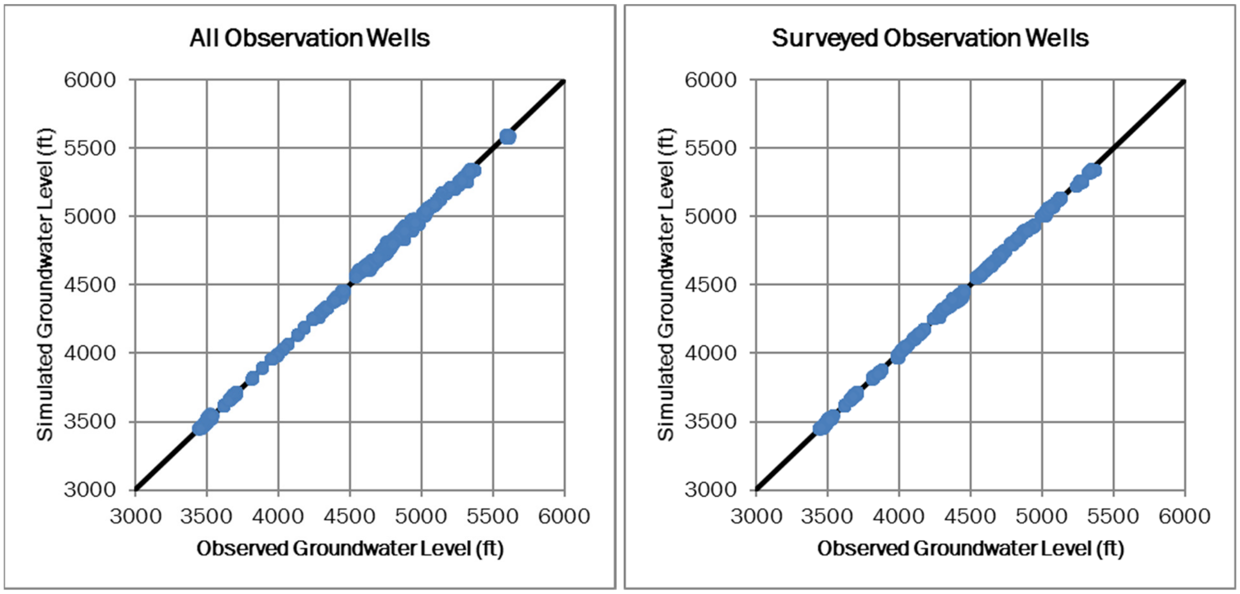


Figure 5-6. Observed vs. Simulated Groundwater-Elevation Scatterplots

Figure 5-7 below presents a map of average groundwater-level residuals at individual wells throughout the model domain. Figure 5-7 indicates that the updated model calibration has generally smaller positive and negative residuals and thus better calibration along the mainstem of the South Platte River, while larger positive and negative residuals occur along tributaries of the South Platte River, especially the designated groundwater basins to the east of Greeley and south of the river. Figure 5-8 shows a sample of observed versus simulated hydrographs, and Appendix E contains similar calibration groundwater-level hydrographs for all observation wells with 10 or more measured water levels. Overall, these measures demonstrate that the model is well calibrated to long-term observed groundwater levels.

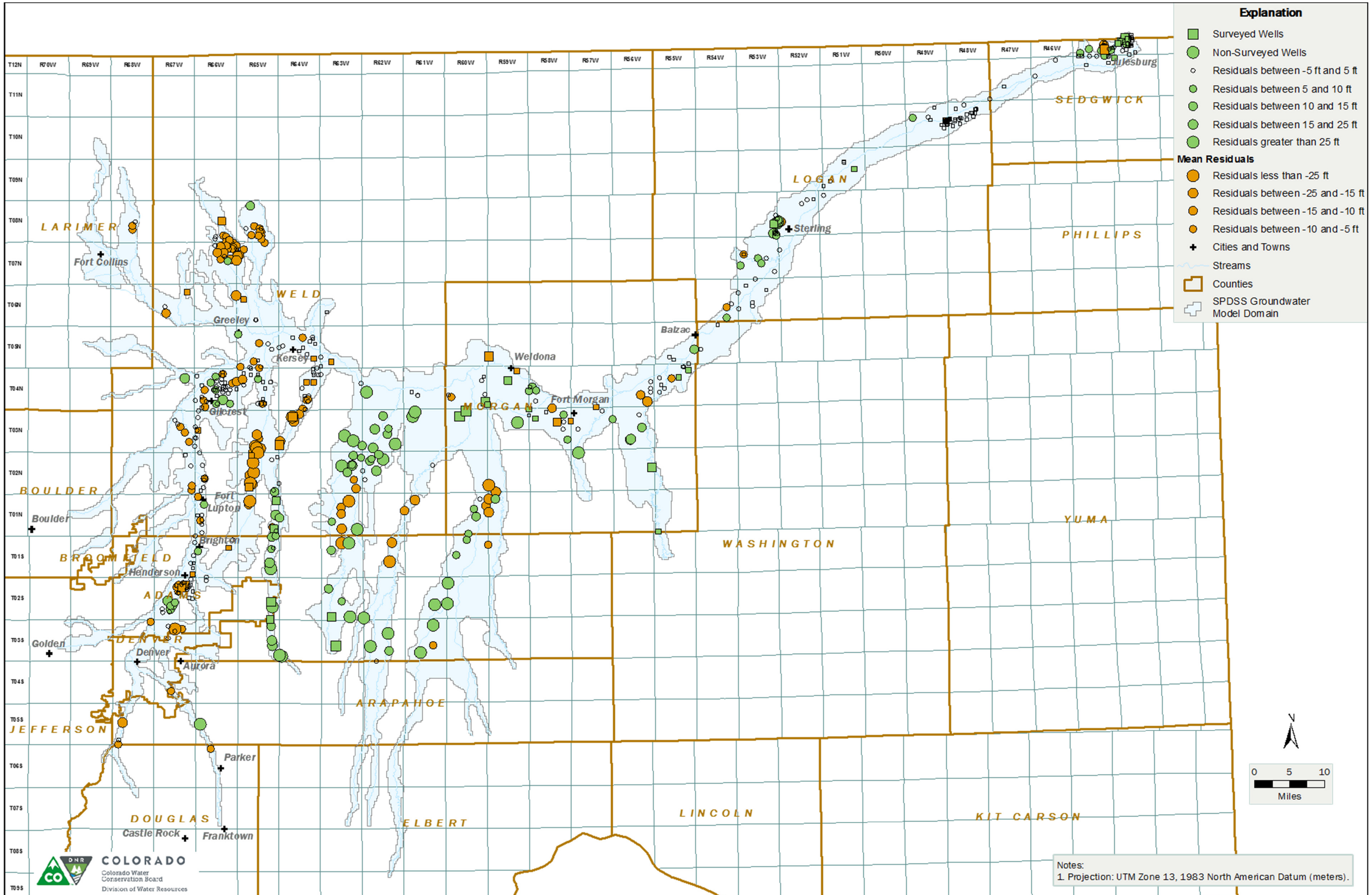


Figure 5-7. Mean Residuals at All Wells

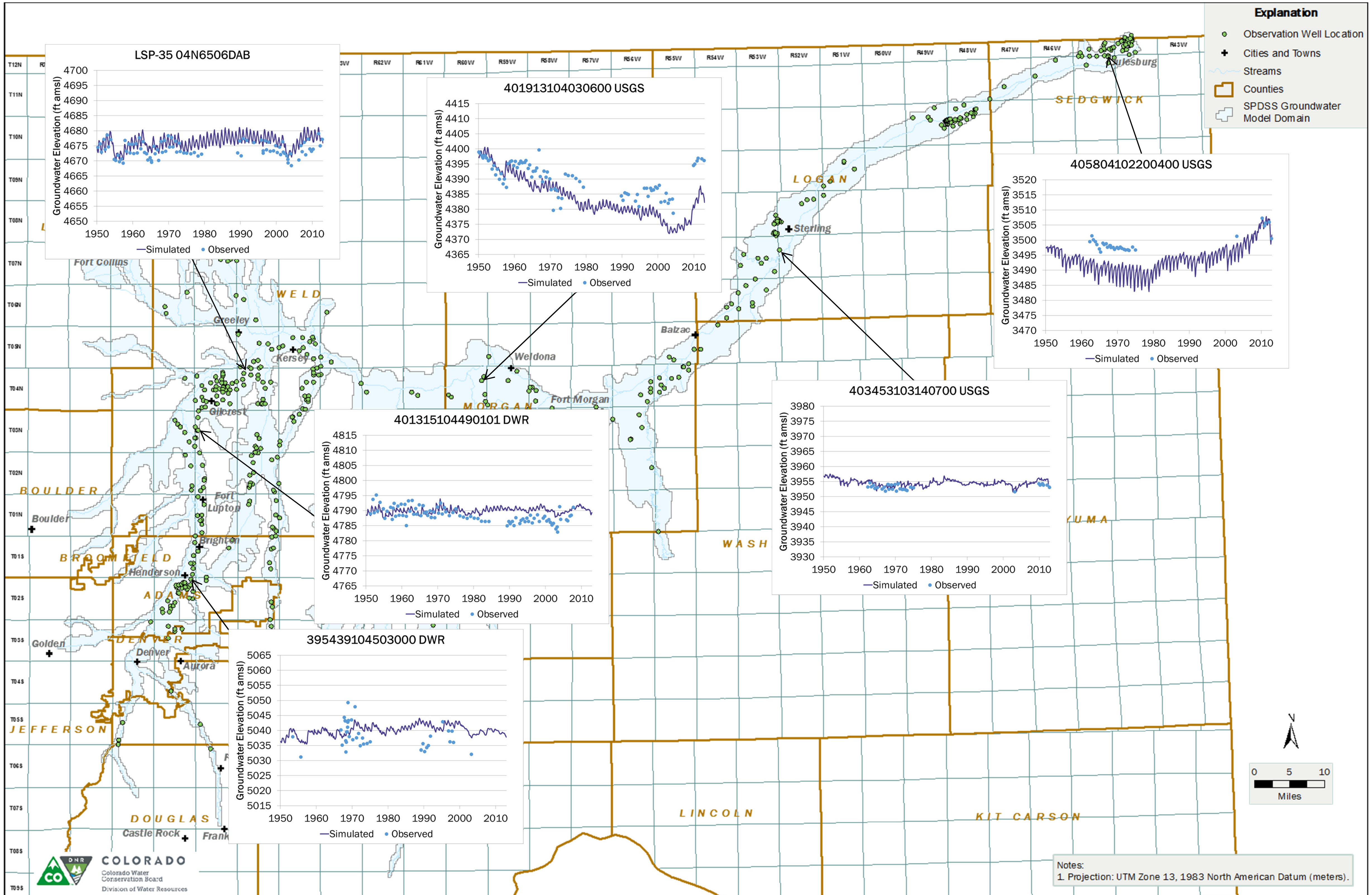


Figure 5-8. Sample Calibration Hydrographs

5.3.3 Streamflow Calibration

The model calculates streamflow within the domain and accounts for inflows, diversions, discharges, and simulation of stream gains/losses to and from the alluvial aquifer. Streamflows simulated by the model are compared to streamflow measurements at nine gages within the model domain:

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

Figure 5-9 compares the measured and simulated average annual streamflows at these stream gaging locations for the 1950 through 2012 simulation period. Similar to the initial modeling effort, average annual simulated streamflows from the updated model are significantly higher than those measured for Cherry Creek at Denver (75 percent higher than measured) and the Cache la Poudre at Greeley (99 percent higher than measured) (CDM 2013). The updated model is simulating average annual streamflows slightly higher than measured for the South Platte River at both Weldona (13 percent higher than measured) and Balzac (16 percent higher than measured). At the remaining five stream gaging locations, the simulated average annual streamflows are within 5% of the measured average values. Figures 5-10 through 5-18 present annual total streamflow volumes for each of the streamflow gaging locations. In general, the streamflows simulated in the updated model match measured streamflow values better at later times in the simulation period. This trend may be the result of improved accuracy in water-rights administration records during the later periods.

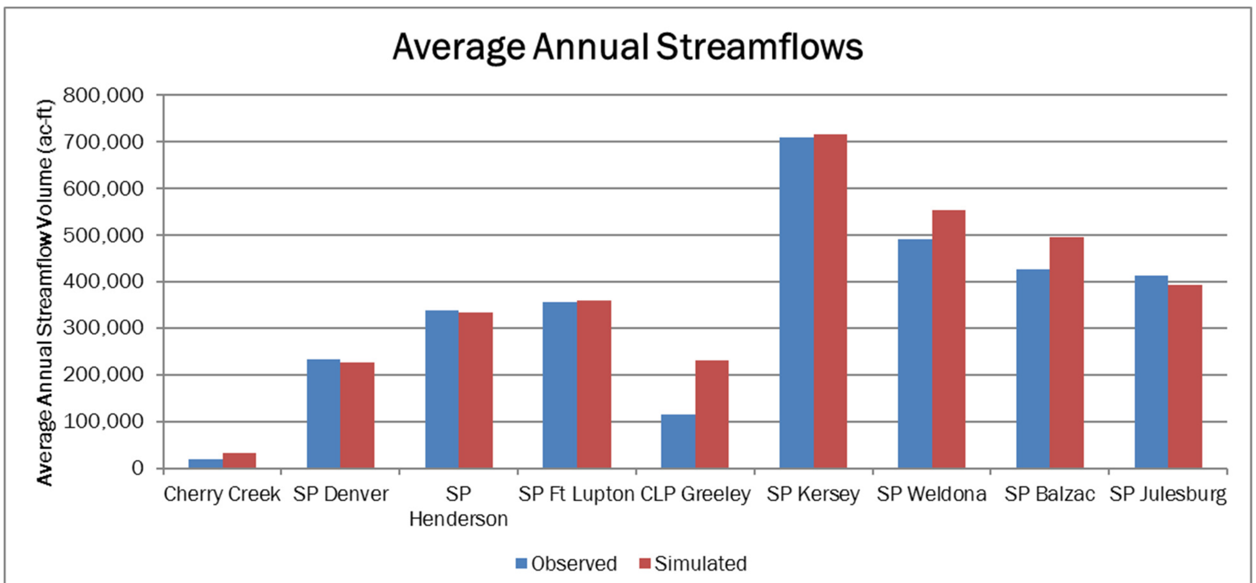


Figure 5-9. Comparison of Simulated and Measured Average Annual Streamflows

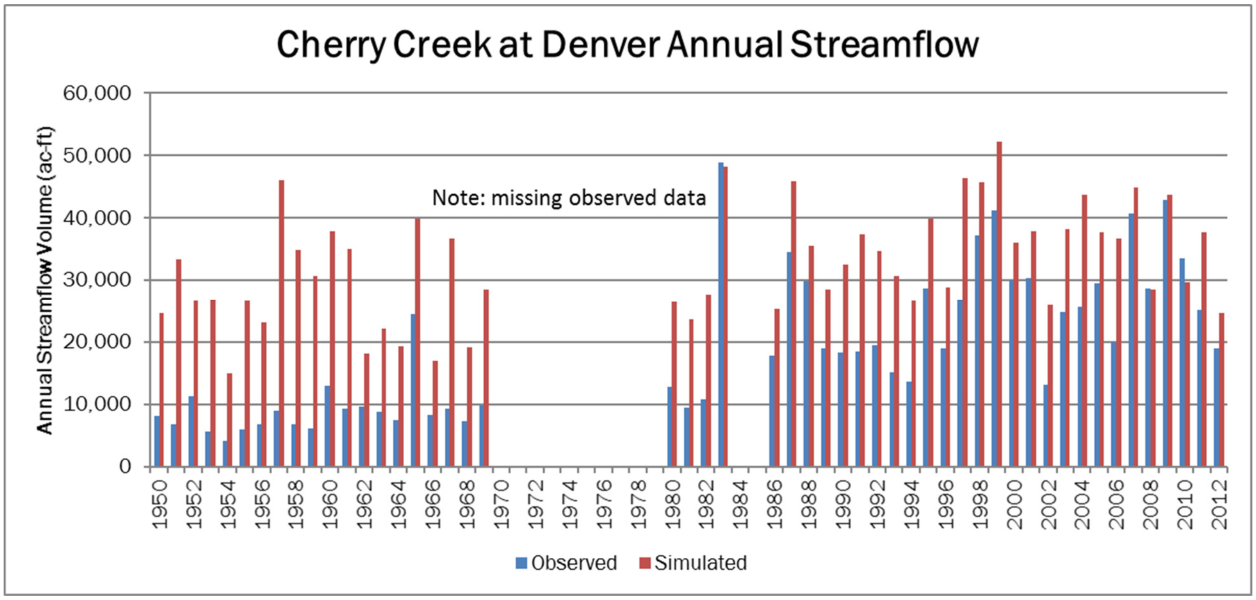


Figure 5-10. Simulated and Measured Annual Streamflow in Cherry Creek at Denver

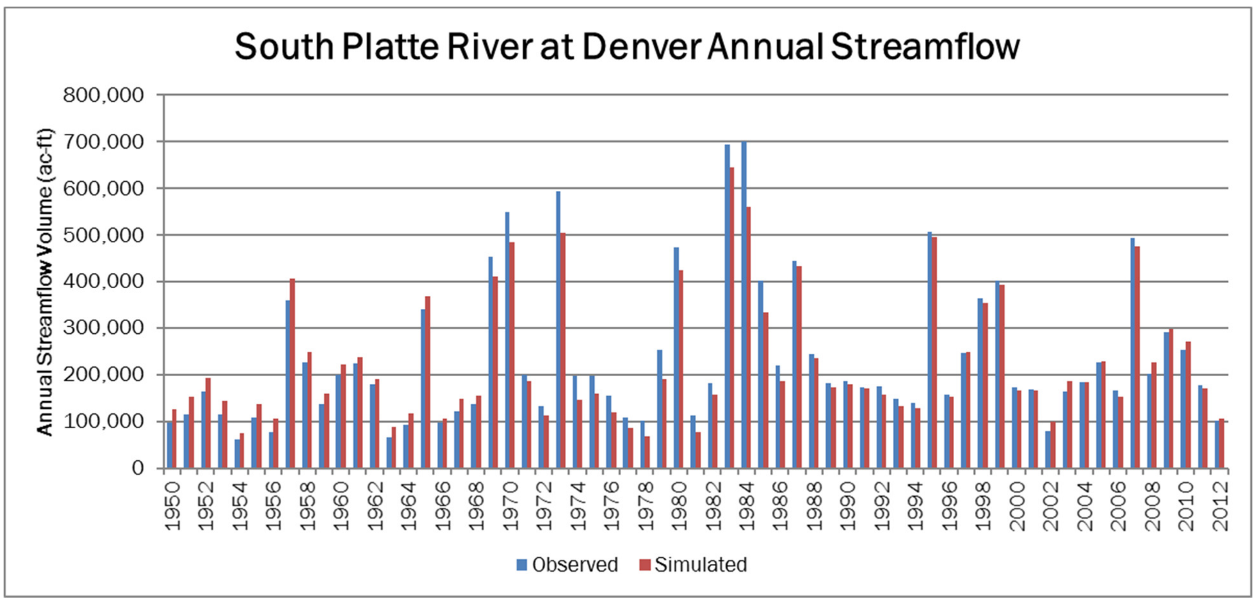


Figure 5-11. Simulated and Measured Annual Streamflow in the South Platte River at Denver

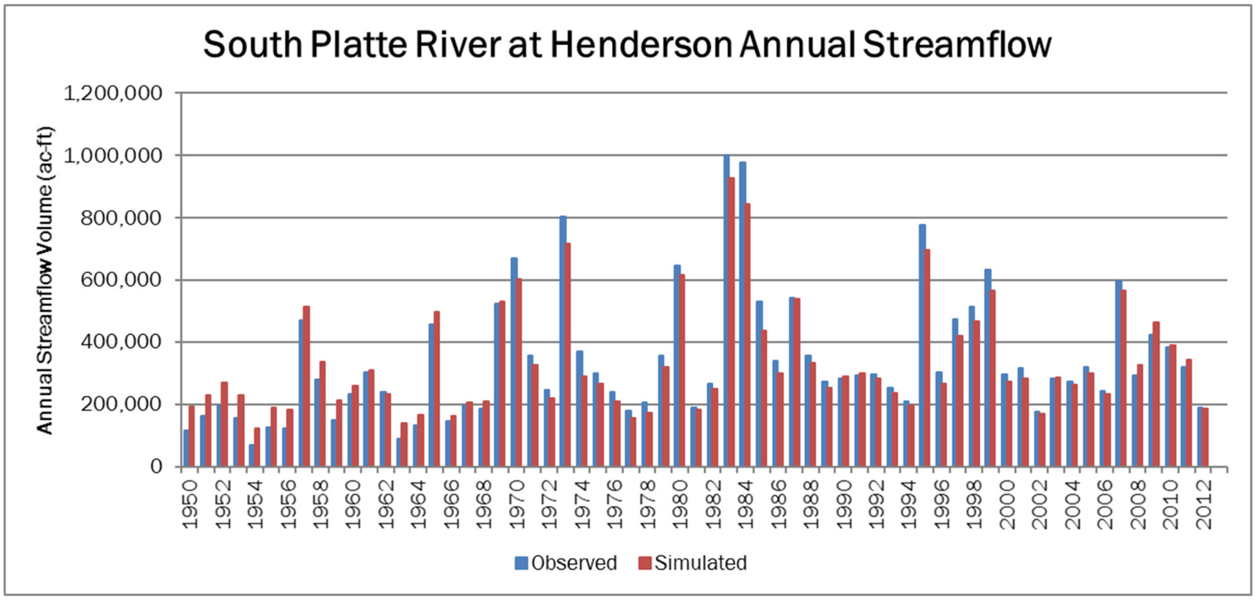


Figure 5-12. Simulated and Measured Annual Streamflow in the South Platte River at Henderson

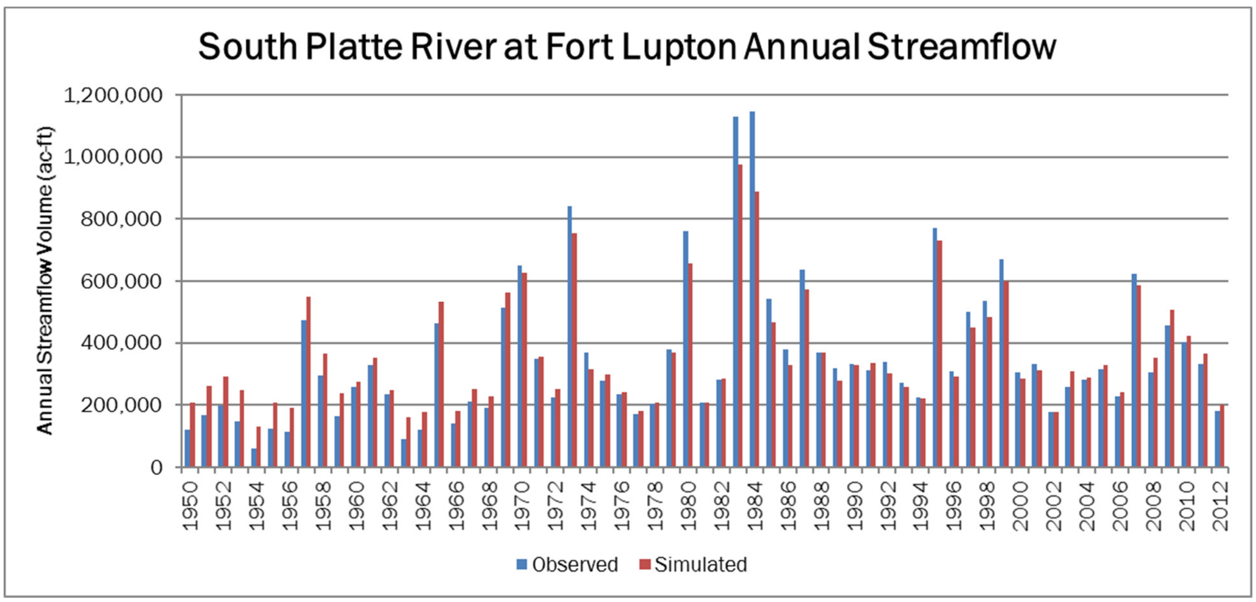


Figure 5-13. Simulated and Measured Annual Streamflow in the South Platte River at Fort Lupton

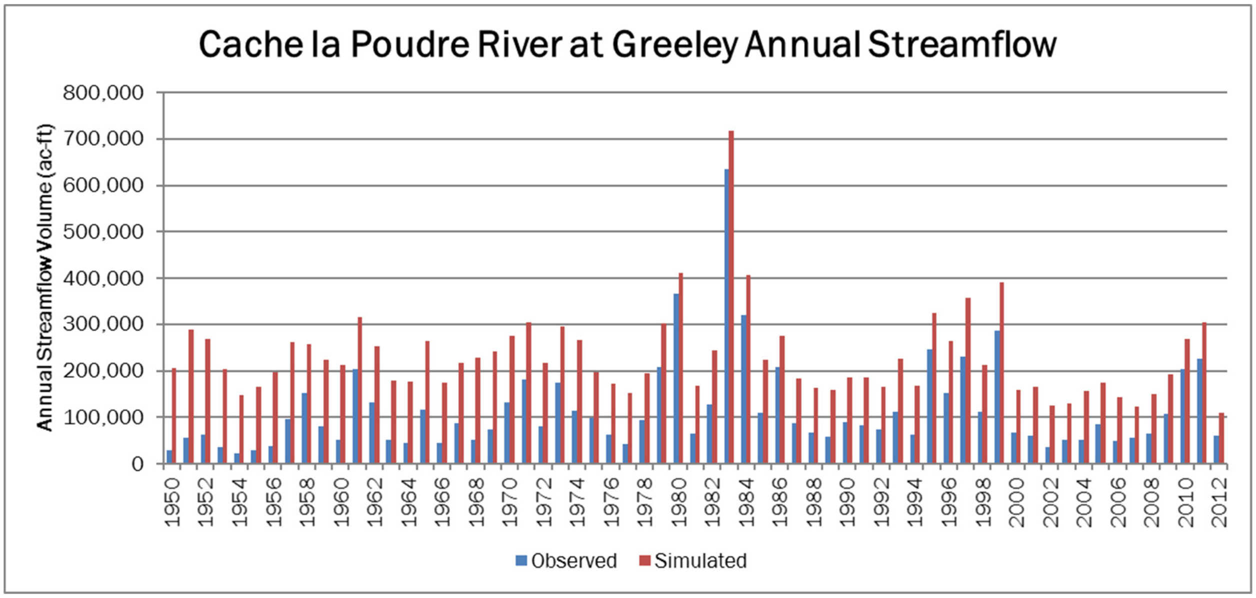


Figure 5-14. Simulated and Measured annual Streamflow in the Cache la Poudre River at Greeley

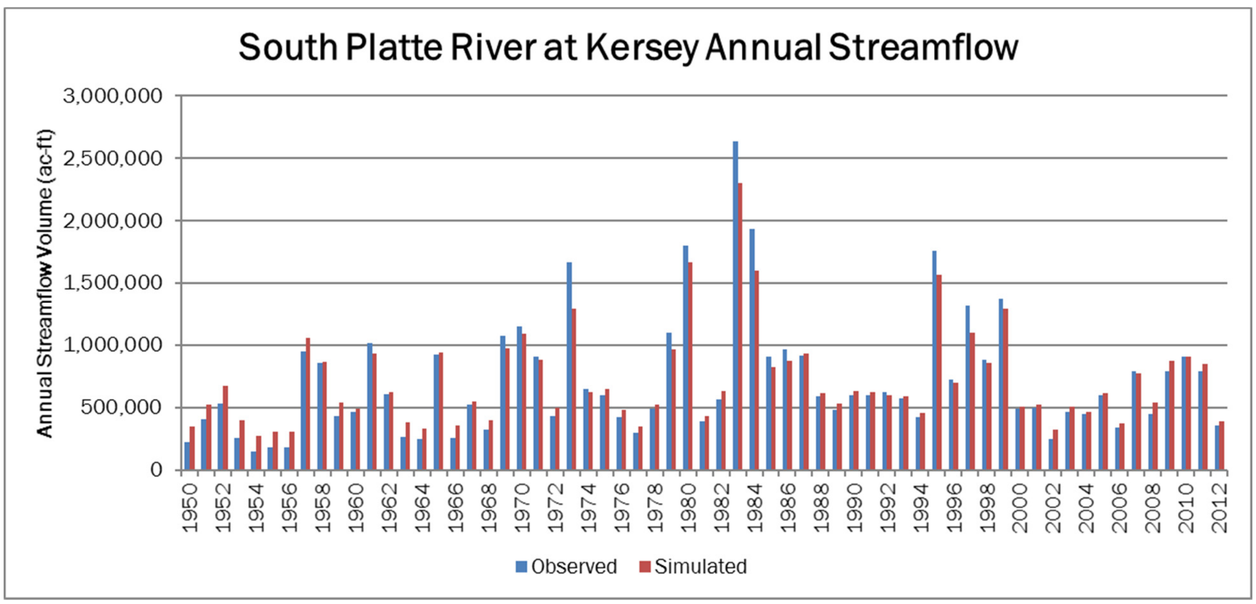


Figure 5-15. Simulated and Measured Annual Streamflow in the South Platte River at Kersey

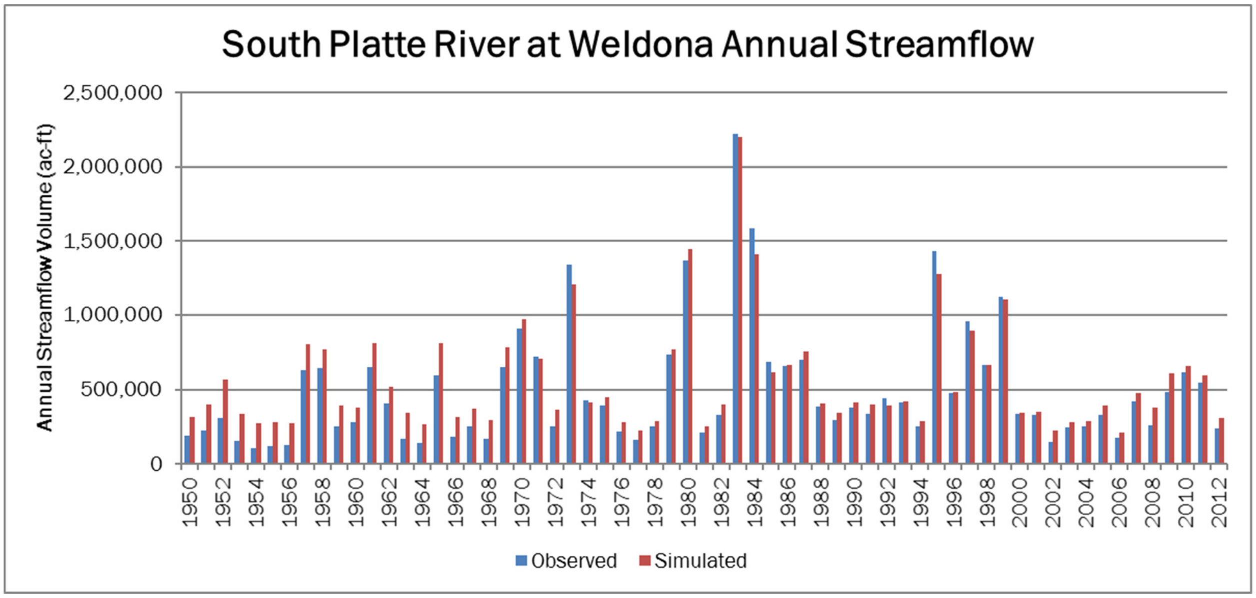


Figure 5-16. Simulated and Measured Annual Streamflow in the South Platte River at Weldona

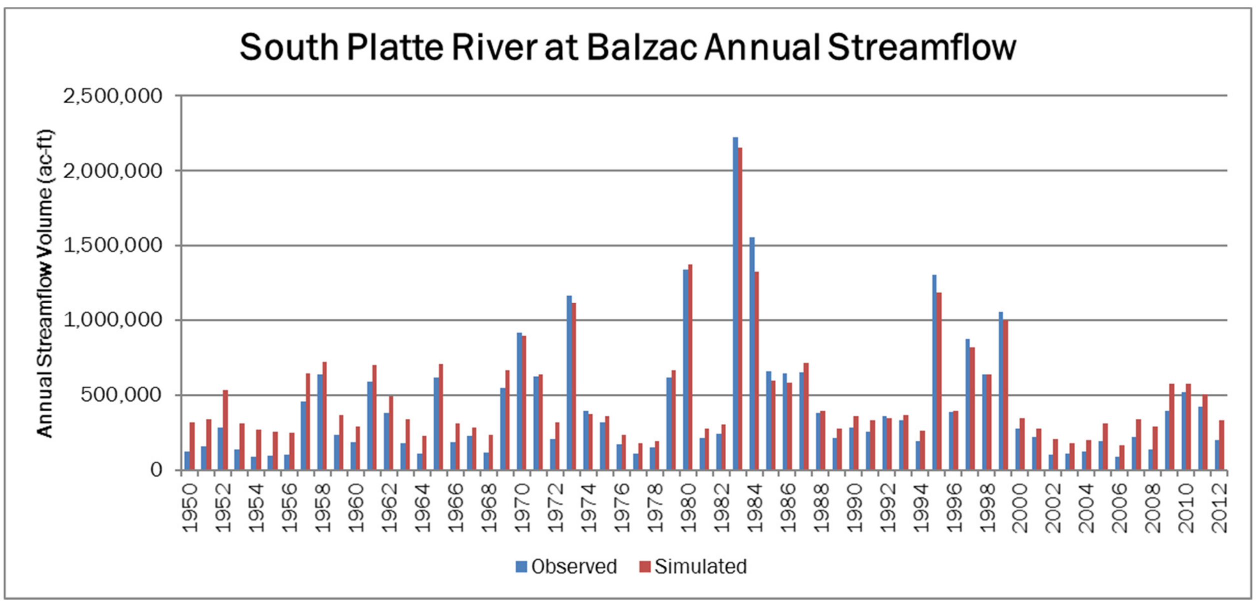


Figure 5-17. Simulated and Measured Annual Streamflow in the South Platte River at Balzac

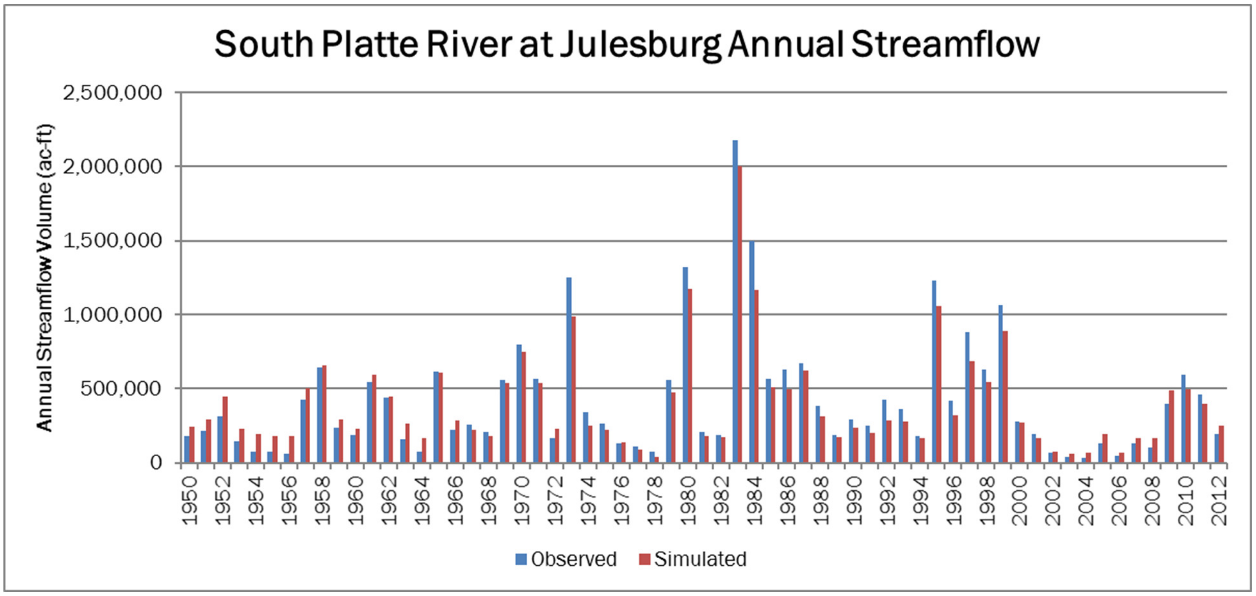


Figure 5-18. Simulated and Measured Annual Streamflow in the South Platte River at Julesburg

5.3.4 Stream Gain/Loss

Simulated stream gains/losses from and to the alluvial aquifer are compared to estimated values between the gages described in Section 5.3.3, above. In the absence of direct measurements of stream gains from groundwater and losses to groundwater, stream gain/loss may be estimated using a variety of mass balance approaches. These mass balance approaches involve subtracting the measured surface inflows to a given stream reach from the outflows from that reach, such that a positive mass balance is assumed to be the result of groundwater discharge to the stream and a negative mass balance is the result of stream loss to the underlying aquifer. As with the initial modeling effort, the “Pilot Point” water balance method was used to estimate stream gains/losses (CDM 2013; Capesius and Arnold 2012). The Pilot Point method as used for the model is based on a daily mass-balance approach in which extreme mass-balance values are subject to constraints on minimum and maximum stream gain/loss. Furthermore, the daily constrained mass-balance values are also smoothed using a moving-average approach with a moving average period of 15 days. Finally, monthly average stream-gain/loss estimates are calculated from the daily Pilot Point stream-gain/loss estimates, in order to compare with the model’s monthly results.

As described in the initial model report, stream gains/losses are used as qualitative rather than quantitiative calibration parameters (CDM 2013). The inherent uncertainties in the estimation of actual stream gains/losses for the South Platte River and its tributaries make these estimates appropriate to be qualitative calibration parameters to be compared to the simulated values in terms of whether stream reaches are gaining or losing, the overall magnitude of stream gains/losses, and the seasonal patterns of stream gains/losses for reaches through time.

Figures 5-19 through 5-34 present hydrographs of the estimated and simulated monthly and cumulative stream gain/loss for the calibration reaches. Many of the simulated stream gain/loss reaches have less monthly and seasonal variation than the estimated values from the Pilot Point method while others (e.g., South Platte River between Fort Lupton and Kersey, Balzac, and Julesburg) show approximately the same magnitude of variations between estimated and simulated stream gain/loss. The updated model simulates Cherry Creek as a losing stream during most of the simulation period. Note that Cherry Creek Reservoir is not explicitly represented in the model, and this may partly explain discrepancies between the estimated and simulated stream gain/loss.

The Cache la Poudre River simulated stream gains are approximately 67% greater than those estimated by the Pilot Point method. The simulated stream gain/loss values along the South Platte River match reasonably well to the estimated values from the Pilot Point method. Of particular note is the excellent match between simulated and estimated streamflow stream gain-loss for the reach from Fort Lupton to Kersey.

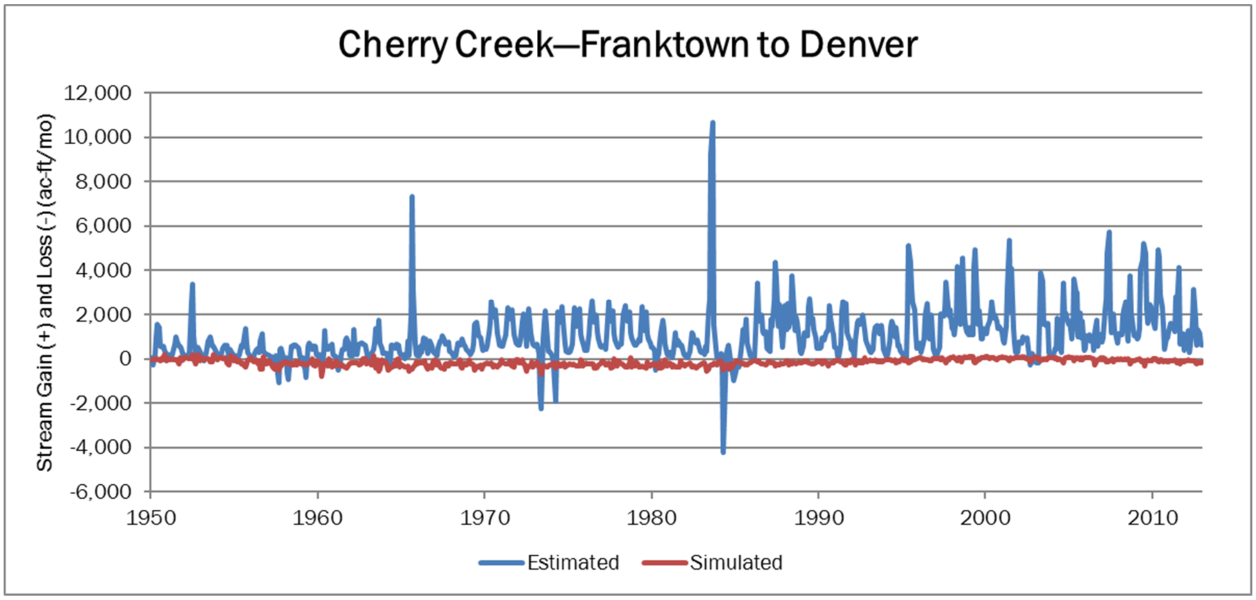


Figure 5-19. Simulated and Estimated Stream Gain/Loss, Cherry Creek Franktown to Denver

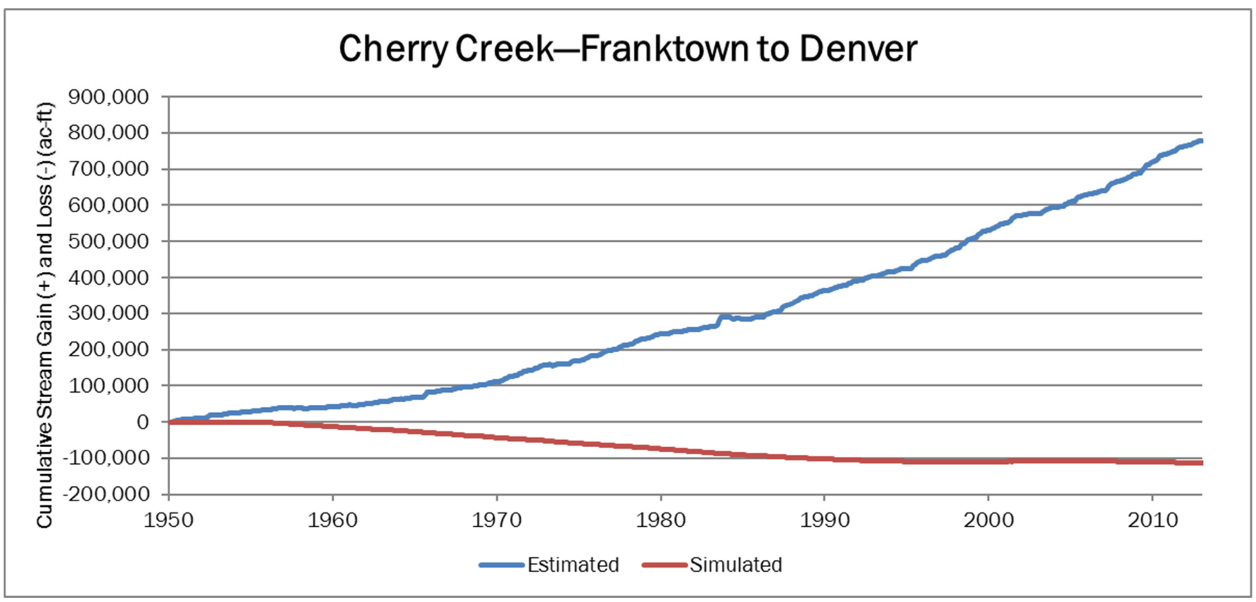


Figure 5-20. Simulated and Estimated Cumulative Stream Gain/Loss, Cherry Creek Franktown to Denver

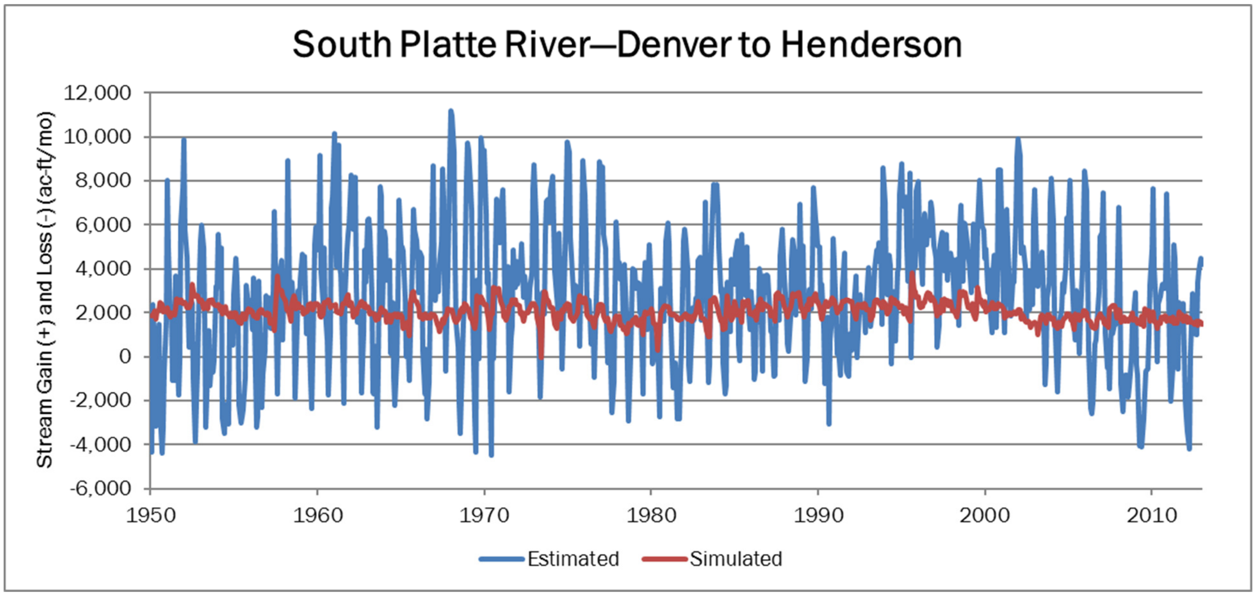


Figure 5-21. Simulated and Estimated Stream Gain/Loss, South Platte River Denver to Henderson

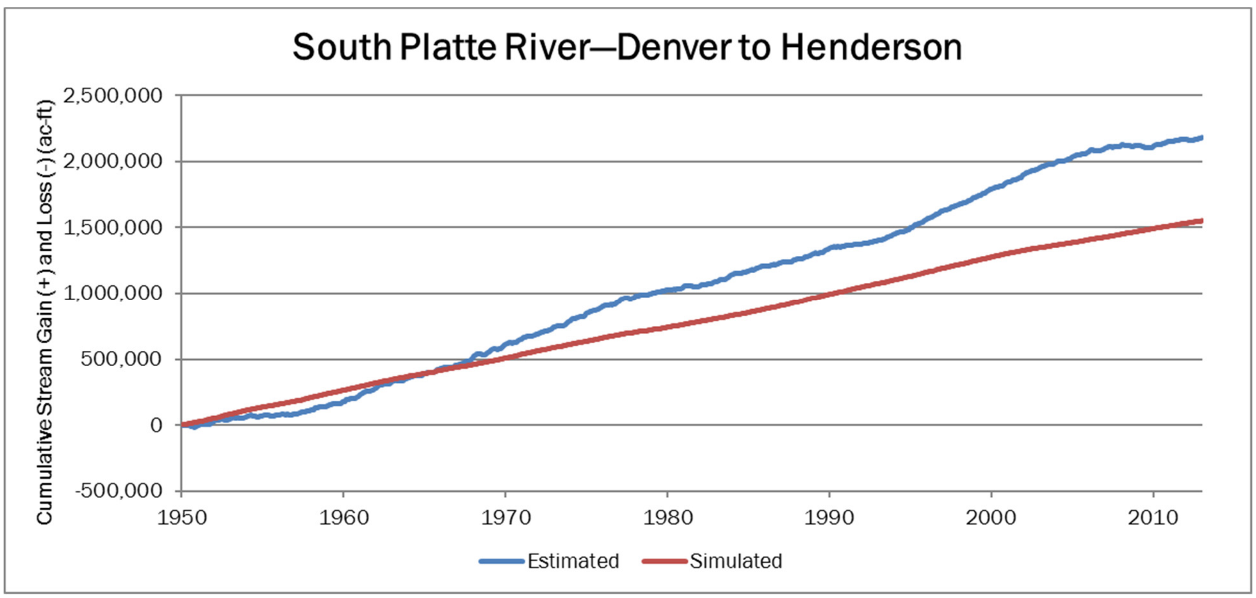


Figure 5-22. Simulated and Estimated Cumulative Stream Gain/Loss, South Platte River Denver to Henderson

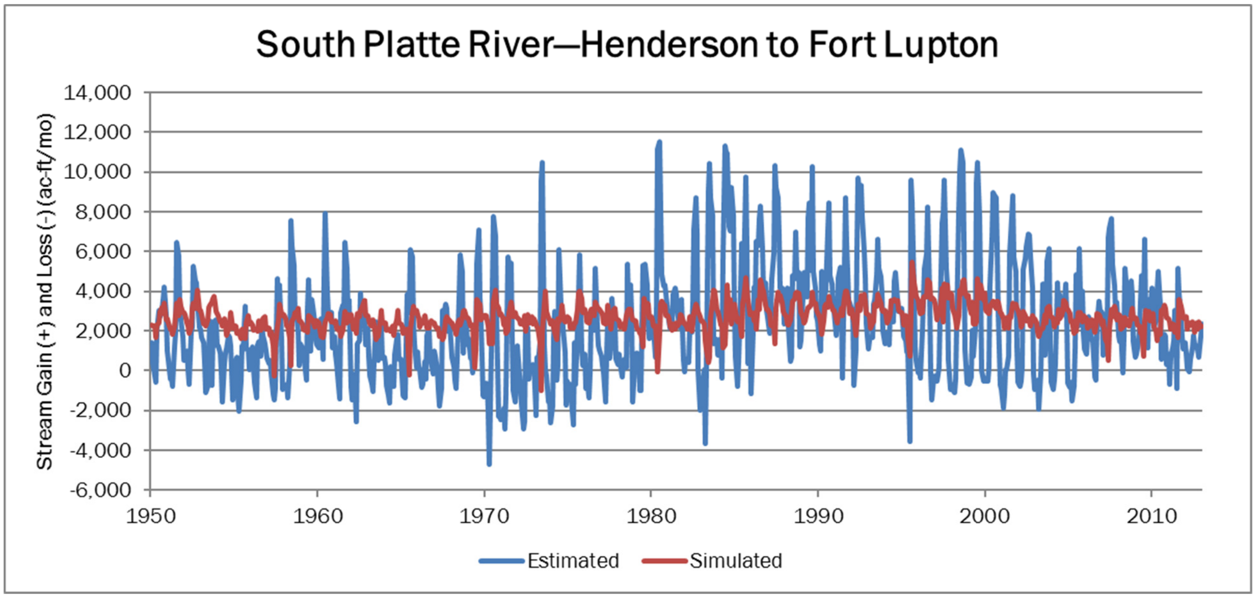


Figure 5-23. Simulated and Estimated Stream Gain/Loss, South Platte River Henderson to Fort Lupton

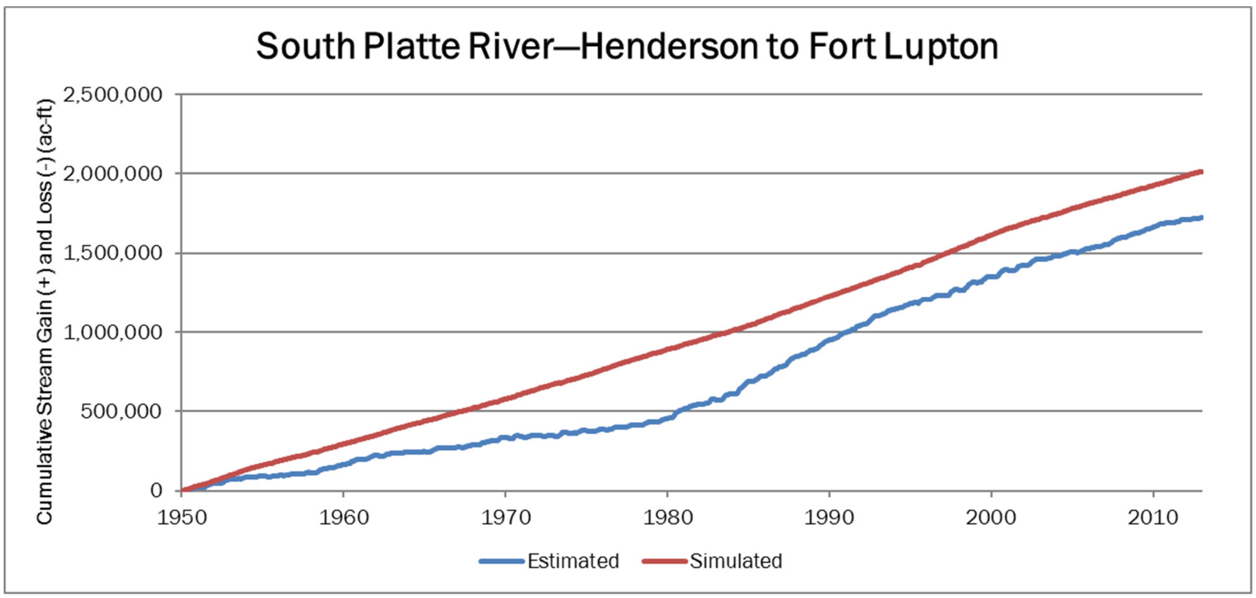


Figure 5-24. Simulated and Estimated Cumulative Stream Gain/Loss, South Platte River Henderson to Fort Lupton

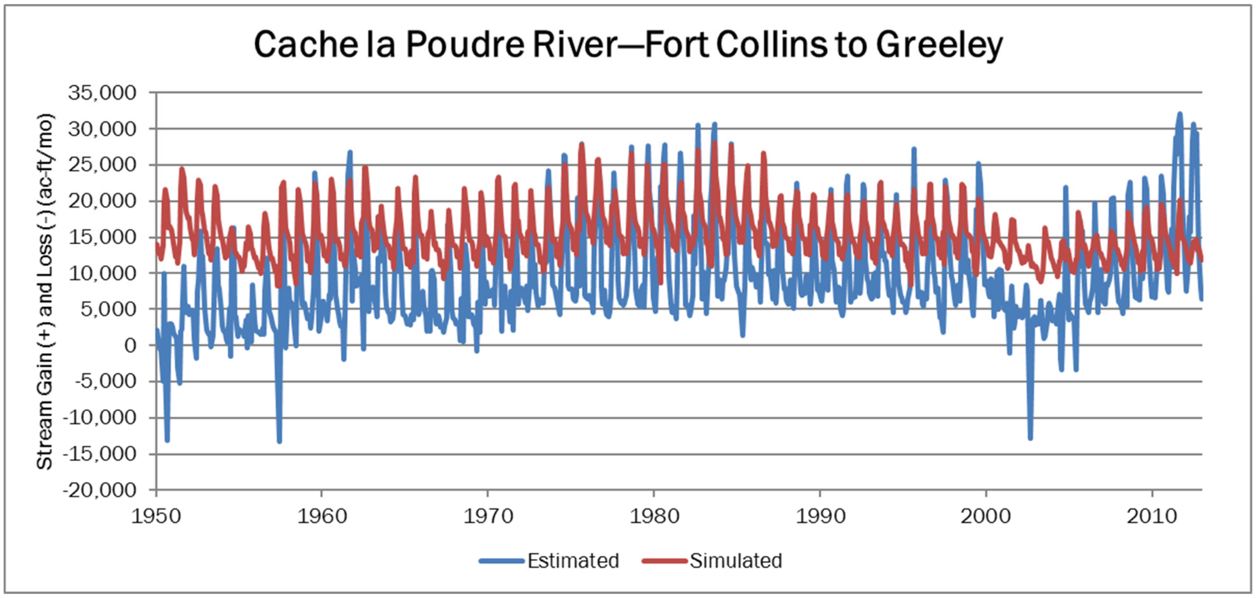


Figure 5-25. Simulated and Estimated Stream Gain/Loss, Cache la Poudre River Fort Collins to Greeley

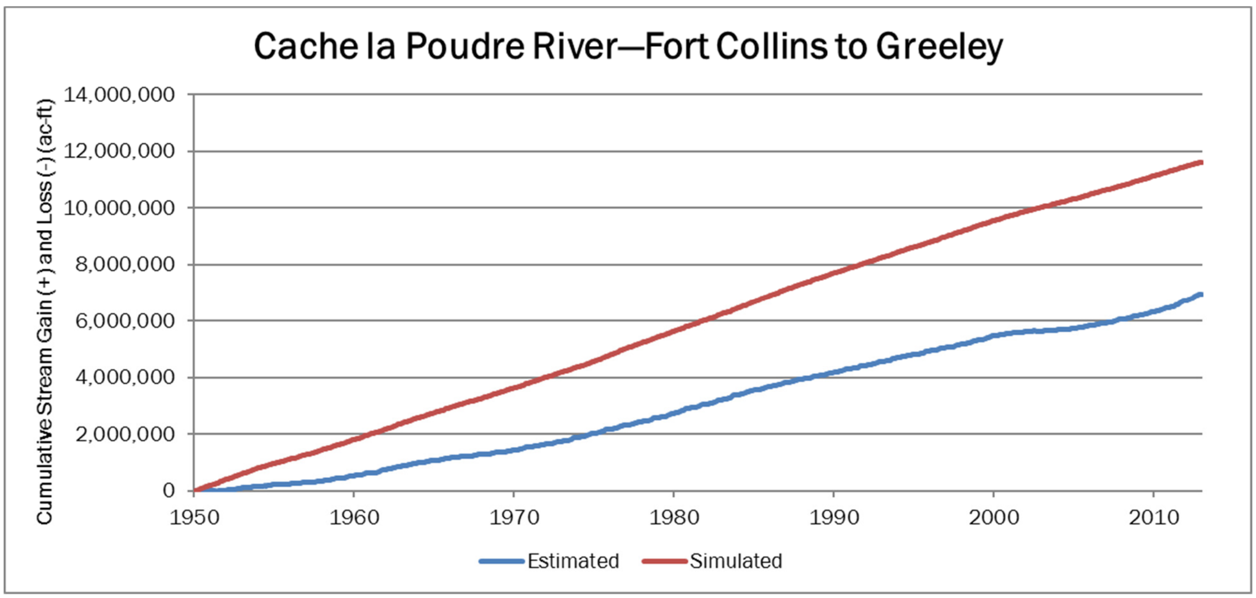


Figure 5-26. Simulated and Estimated Cumulative Stream Gain/Loss, Cache la Poudre River Fort Collins to Greeley

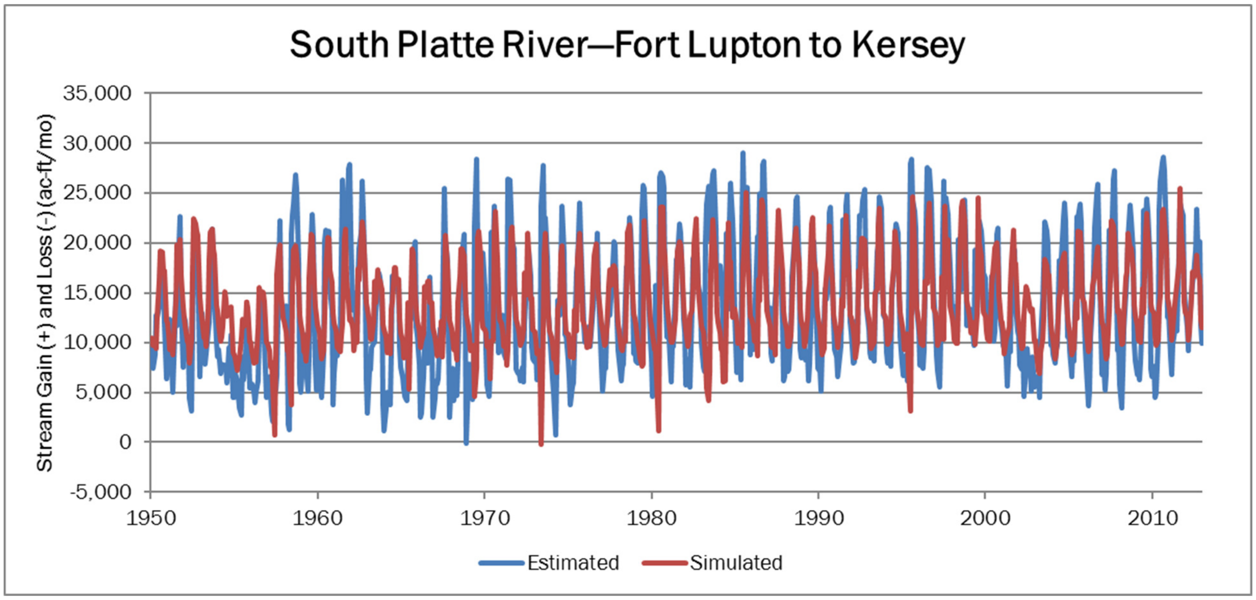


Figure 5-27. Simulated and Estimated Stream Gain/Loss, South Platte River Fort Lupton to Kersey

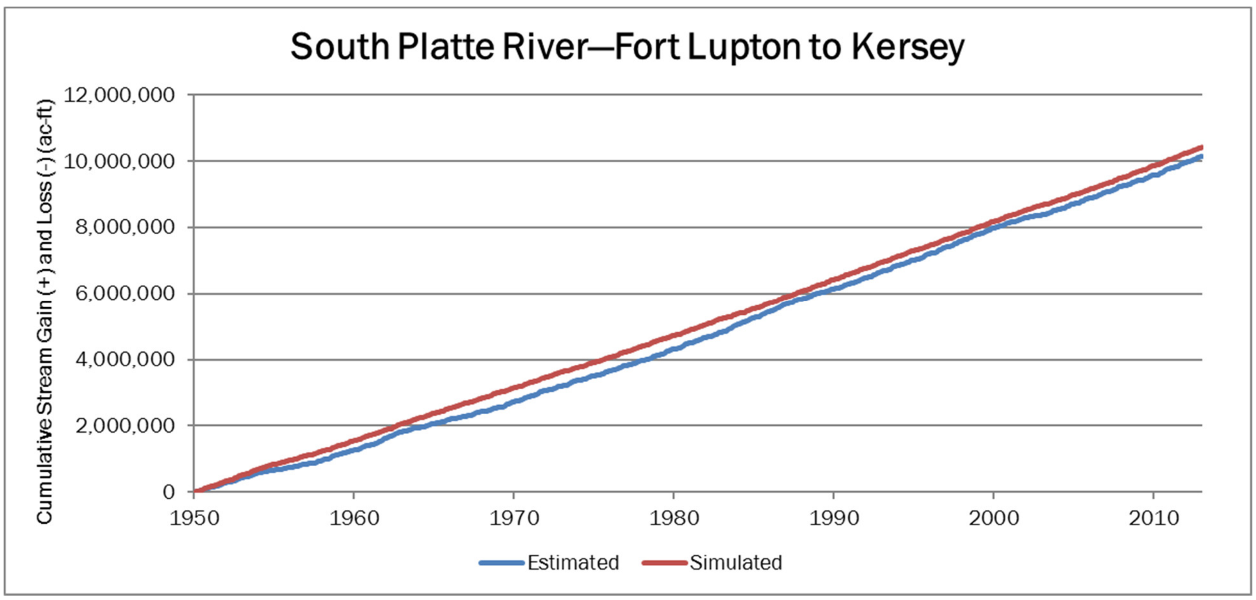


Figure 5-28. Simulated and Estimated Cumulative Stream Gain/Loss, South Platte River Fort Lupton to Kersey

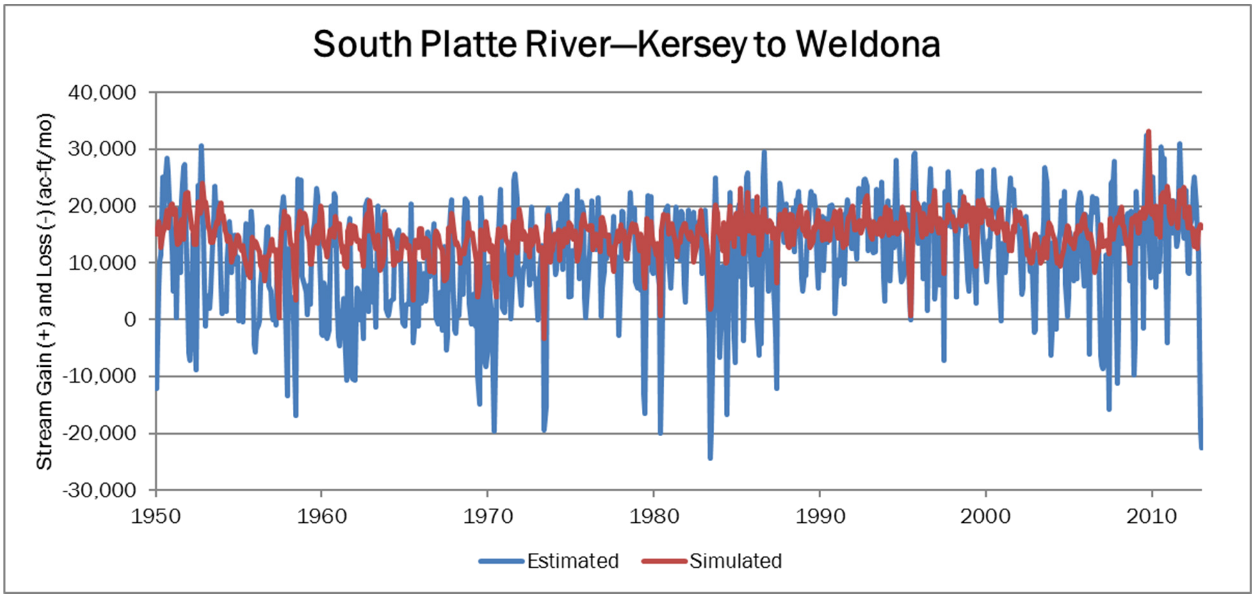


Figure 5-29. Simulated and Estimated Stream Gain/Loss, South Platte River Kersey to Weldona

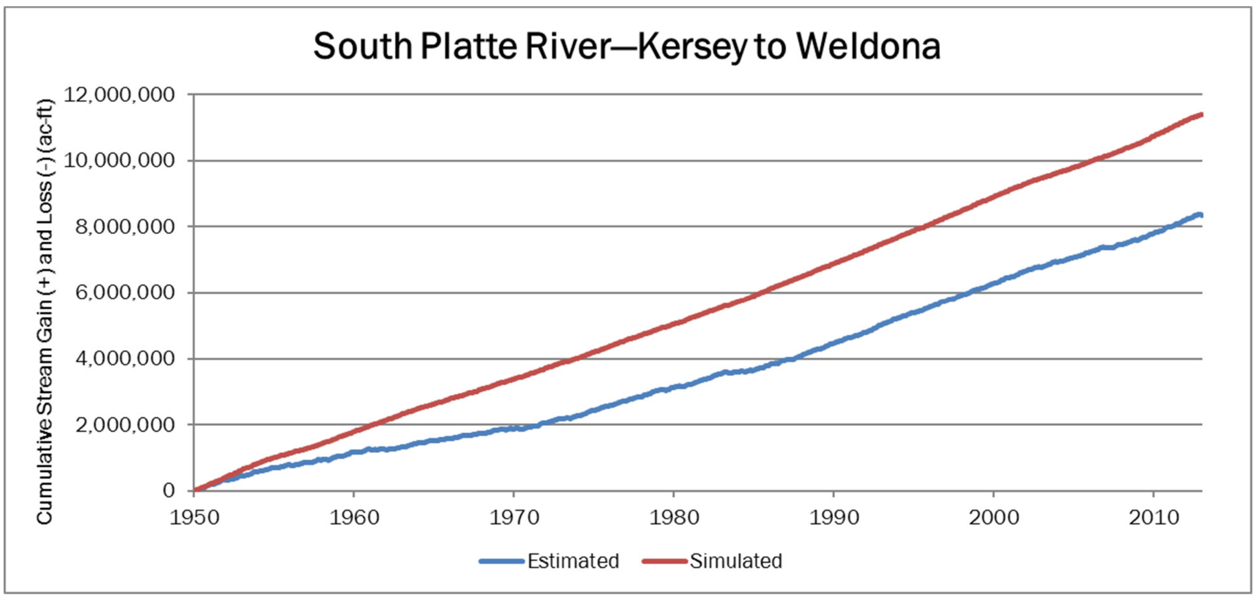


Figure 5-30. Simulated and Estimated Cumulative Stream Gain/Loss, South Platte River Kersey to Weldona

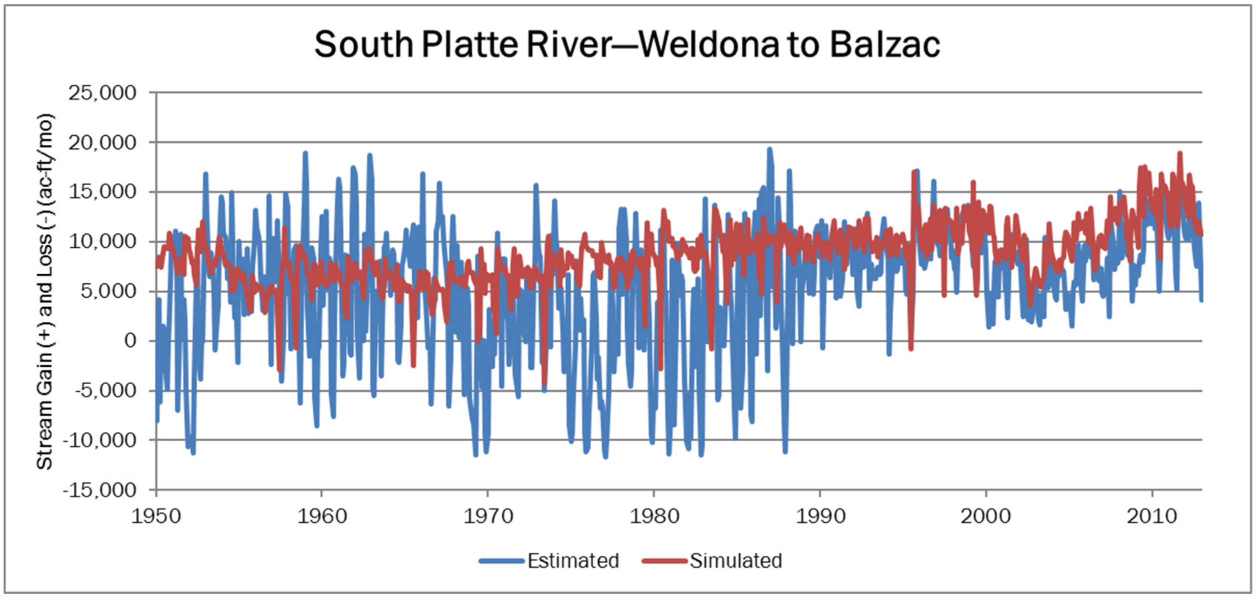


Figure 5-31. Simulated and Estimated Stream Gain/Loss, South Platte River Weldona to Balzac

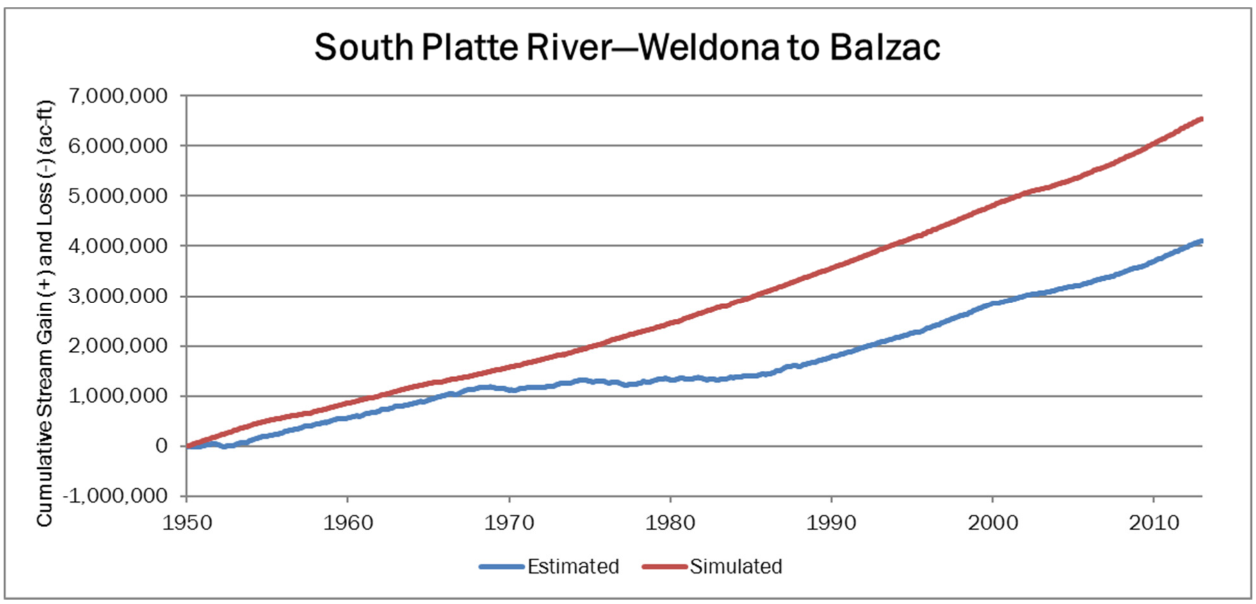


Figure 5-32. Simulated and Estimated Cumulative Stream Gain/Loss, South Platte River Weldona to Balzac

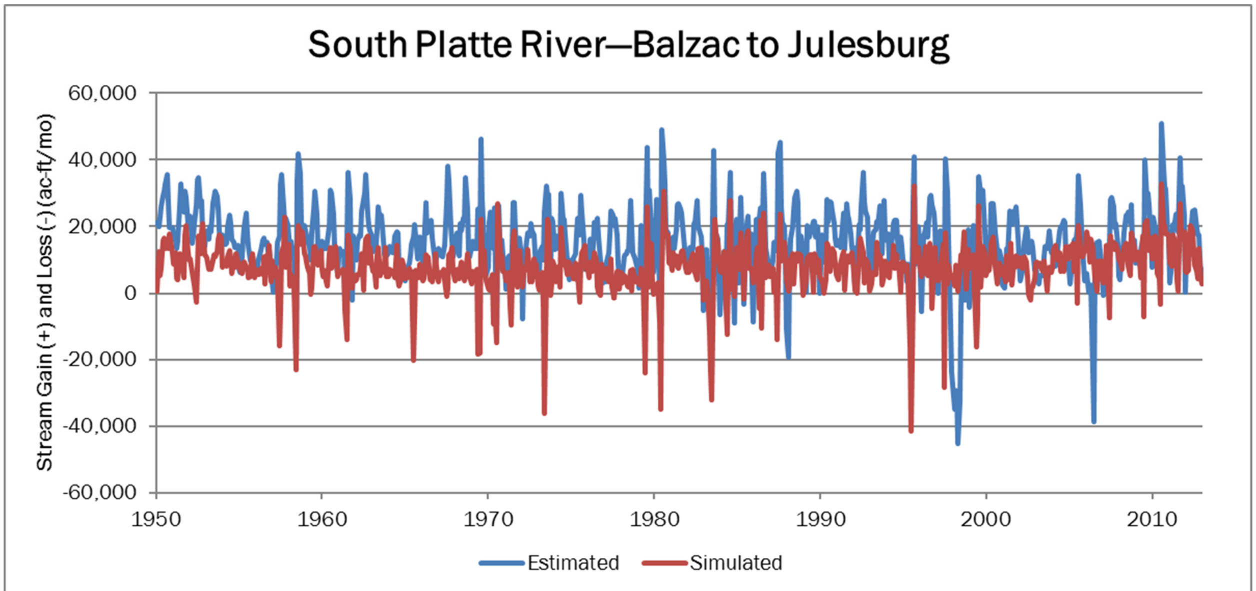


Figure 5-33. Simulated and Estimated Stream Gain/Loss, South Platte River Balzac to Julesburg

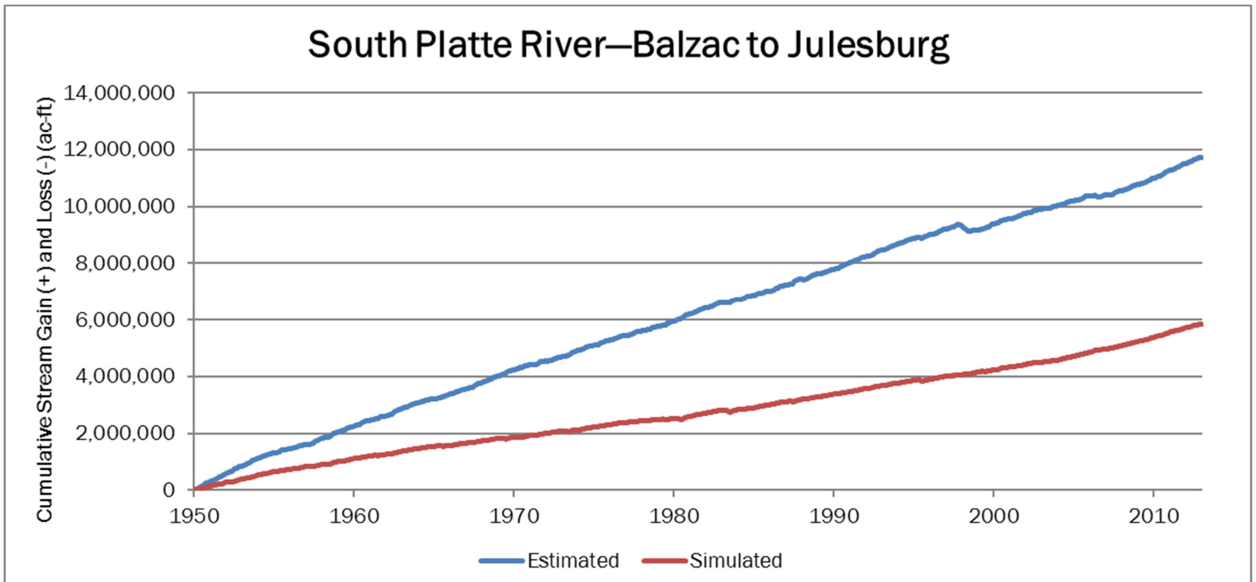


Figure 5-34. Simulated and Estimated Cumulative Stream Gain/Loss, South Platte River Balzac to Julesburg

5.3.5 Calibration Summary and Model Uncertainty/Limitations

The process for additional calibration of the updated model has involved the update of model input flows and adjustment of model parameters to improve the matches between simulated and measured historical groundwater levels and streamflows, along with simulated and estimated historical stream gain/loss values. The simulated results match the measured and estimated data to an acceptable degree or better for the stated objectives and intended uses of the updated model. The updated model is sufficiently calibrated to perform evaluations of potential future conditions and simulate other “what-if” types of scenarios.

The overall construction of the model and methodologies used to generate model inputs have not significantly changed from the initial version of the model. As such, the updated model, as well as any other groundwater flow model, is subject to the same types of uncertainties described in Section 5.2 of the CDM 2013 Report documenting the initial model construction (CDM 2013). These uncertainties include both model input geologic parameters (hydraulic conductivity values, aquifer storage parameter values, elevations of the base of alluvial materials, streambed conductance values) and flow rates (groundwater well pumping rates, recharge rates, ungaged surface water inflows, tributary surface water flows, diversion flows, return flows, reservoir seepage rates, bedrock-alluvium underflows, and lateral boundary flows).

The 1,000-foot model grid cell size is relatively highly refined for a regional-scale model and is appropriate for performing watershed-scale and mid-range scale analyses. If the model is used on a more localized scale, it may require refinement of the model grid discretization and the geologic model input parameters to appropriately simulate groundwater flow at a local scale. The updated model is best suited to answer regional-scale groundwater and surface-water management questions and other basin-scale analyses.

Section 6

Summary and Recommendations

6.1 Summary

The completed update of the model and the model input construction processes represents a significant upgrade to the SPDSS that will help to provide a better understanding of basin-scale groundwater flow and groundwater/surface water interactions in the Basin. The model was updated from the initial version of the model in a number of key ways:

- The simulation period was extended from the end of 2006 through the end of 2012
- Model inputs have been updated through the data-centered approach with improved underlying data from HydroBase and DWR Irrigation Snapshot GIS data sets
- Several data-centered approach DMIs have been modernized and improved, including the CDSS Toolbox, StateDGI, StatePP, and SFR2 Generator
- Model executable code was upgraded to the robust and fully supported USGS MODFLOW-NWT
- PSB was incorporated, which allows for improved and simplified analysis of model inputs and outputs related to the numerous water budget components of the model
- Model calibration was improved overall, improving the reliability of the model for performing future predictive simulations and other scenarios

The model provides a platform for performing predictive future-casting simulations and other scenarios to help guide potential water management strategies and activities. The model can be used for analyzing and finding potential solutions to groundwater challenges in the Basin, such as high water-table problems, and it can be utilized as a basis for refined local-scale models.

6.2 Recommendations

Through the model update effort, some additional items were identified that may further improve the model's ability to inform understanding of the groundwater flow and groundwater/surface water interactions in the Basin. While significant improvements have been made to the modeling process through the data-centered approach, additional potential future improvements have been identified for consideration as described below:

- For M&I pumping wells without available historical pumping data, review additional records (e.g., well permits and water-rights documentation) and refine the assumptions for estimating historical pumping rates, as well as the periods that wells are active.
- Combine the functionality of StatePP with CDSS Toolbox and StateDGI, potentially converting the StatePP code from Fortran to ArcPy-enabled Python scripts and classes.
- Add functionality to StatePP to read input information from StateDGI for multiple irrigation snapshot periods to allow StatePP to produce MODFLOW input files for entire simulation periods to negate the need to later combine MODFLOW input files from each irrigation snapshot period.
- Add functionality to StatePP to allow the code to read binary StateCU output.
- Add functionality to the Lateral Boundary Flow Processor to read separate MODFLOW WEL and RCH files when using PSB to avoid the additional step of needing to combine the separate files to a single file solely for the purpose of the Lateral Boundary Flow Processor.

- Store estimated ungaged surface flows from the “proc_rainfall” DMI in the SPDSS geodatabase for the SFR2 Generator to write directly to the SFR2 input file to avoid the additional steps of using the “proc_runoff” DMI, as well as maintaining an additional DMI.
- Review the SFR2 segments and routing to identify diversion segments that have no diversion flow and could be removed to simplify the SFR2 input files.
- Further review the SFR2 segment-assigned upstream and downstream streambed elevation values based on the 1/3 arc-second USGS National Elevation Dataset, and consider implementing specification of streambed elevations at individual SFR2 reaches through the SFR2 input “REACHINPUT” keyword.
- Review the current approach to developing model initial heads through a warm-up simulation that repeats 1950 monthly stresses for a number of years, especially in the areas of designated basins. Also consider other methods to develop initial heads, such as reducing model stresses during the warm-up period or contouring groundwater levels based on available data and hydrogeologic interpretation.
- Review the Glover-based approach for estimating lateral boundary flows and consider using a smaller period for the Lateral Boundary Flow Processor’s warm-up period given the hydrologic and administrative changes that have occurred in the Basin.
- Review the representation of reservoirs and other surface water storage structures in the model:
  - Represent Cherry Creek Reservoir as a head-dependent boundary condition instead of a specified flux boundary condition. This reservoir has likely increased the volume of groundwater stored in the Cherry Creek alluvium upstream from the reservoir, and using a head-dependent boundary condition would better represent these conditions. This improved representation will likely improve the MODFLOW-NWT code reductions of pumping at the Aurora alluvial wellfield, the match of simulated groundwater levels to measured water levels at the calibration observation well location between the reservoir and the Aurora wellfield, and the stream gain/loss comparison for Cherry Creek.
  - Represent Chatfield Reservoir and the various irrigation supply reservoirs in the model domain using head-dependent boundary conditions, which may improve model calibration and performance.
- Perform additional model calibration with specific yield values.
- Investigate whether the stream gain/loss estimates may be improved by incorporating estimates of ungaged surface flows into the Pilot Point method.

During the continued development and extension of the SPDSS by CWCB and DWR, it is recommended that groundwater and surface water data continue to be collected and uploaded into HydroBase, which is maintained by DWR. These recommended activities include:

- Continue DWR monitoring of groundwater levels in existing alluvial wells and consider adding transducers and data-logging equipment to select wells where possible.
- Continue DWR efforts to identify, collect, and incorporate into HydroBase available groundwater levels and other data from the USGS and other federal agencies, other state agencies, local agencies, and private entities.
- Continue DWR’s collection of well pumping data from agricultural, M&I, and augmentation wells on a monthly basis at a minimum for incorporation in HydroBase and, where possible, identify and incorporate historical well pumping data.

- During DWR's and CWCB's ongoing development and enhancement of SPDSS, continue to refine the surface water inputs to the model based on the results of the StateMod surface water modeling effort, and use the results of the model to inform the surface water model.
- Continue DWR's and CWCB's periodic updates (e.g., at approximately 5-year intervals) of the model with updated data from HydroBase to account for changes in basin operations since the previous model update and to include any improvements in data quality for historical data.

Section 7

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