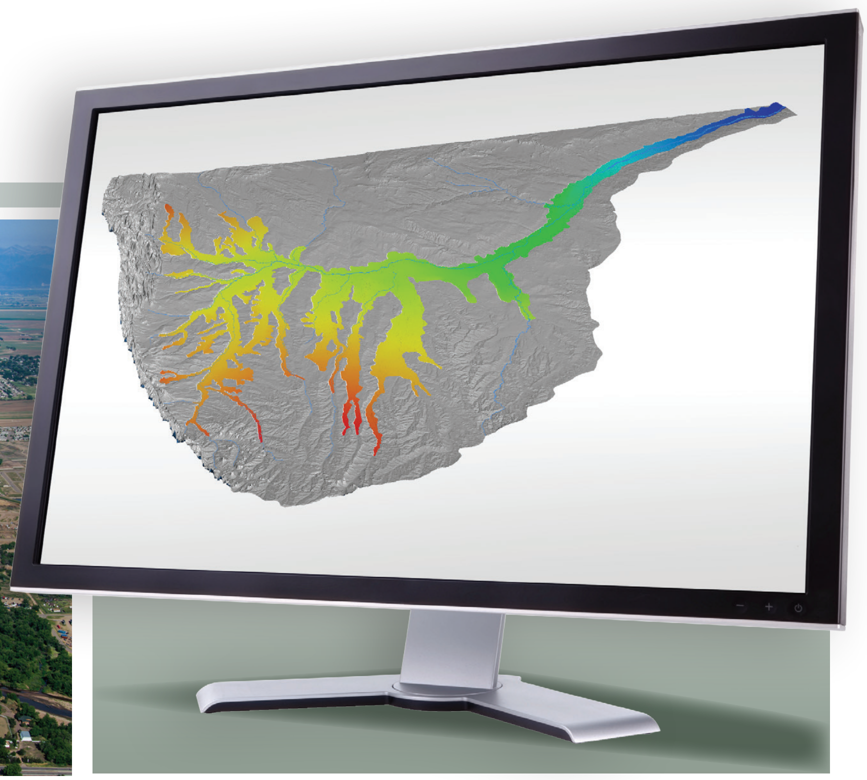
Brown AND Caldwell

EXECUTIVE SUMMARY | 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.

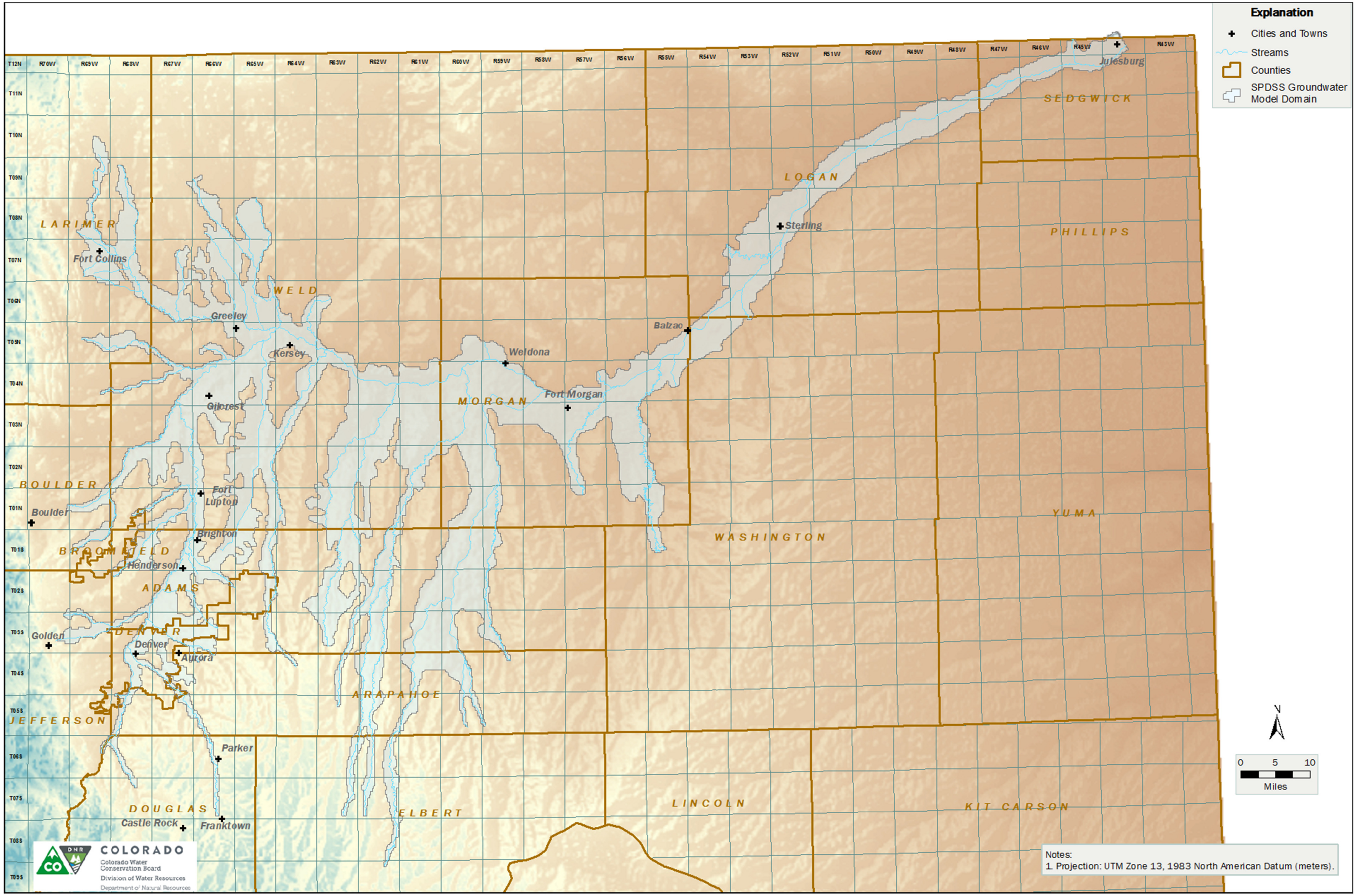

Figure ES-1. Model Study Area

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).

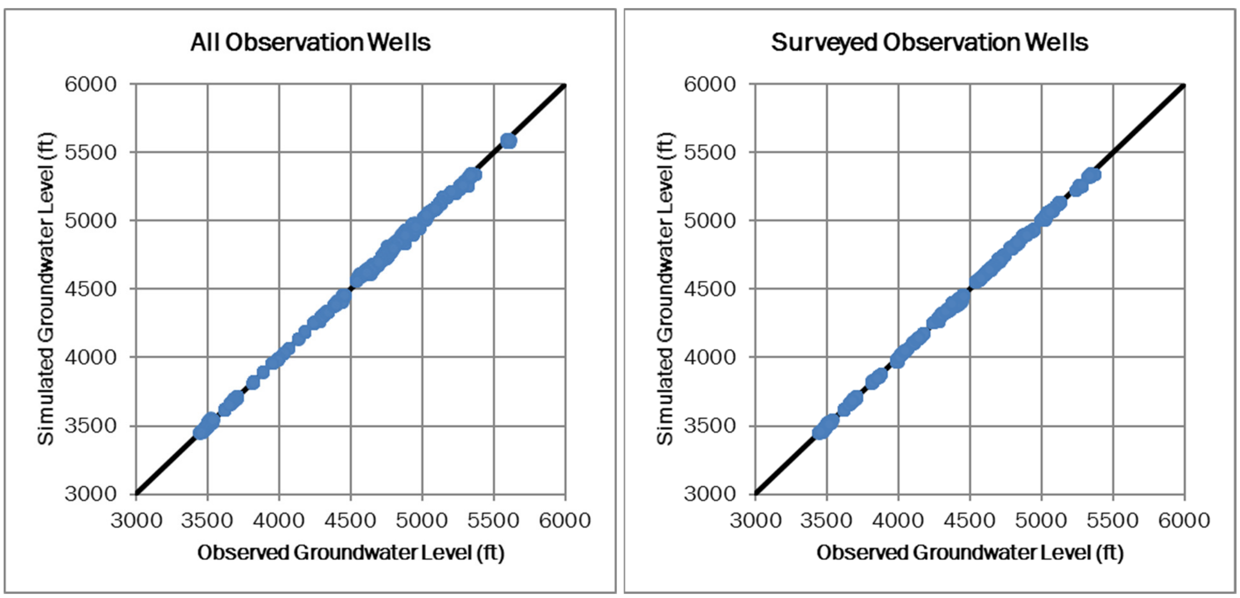

Figure ES-2. Observed vs. Simulated Groundwater-Elevation Scatterplots

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.

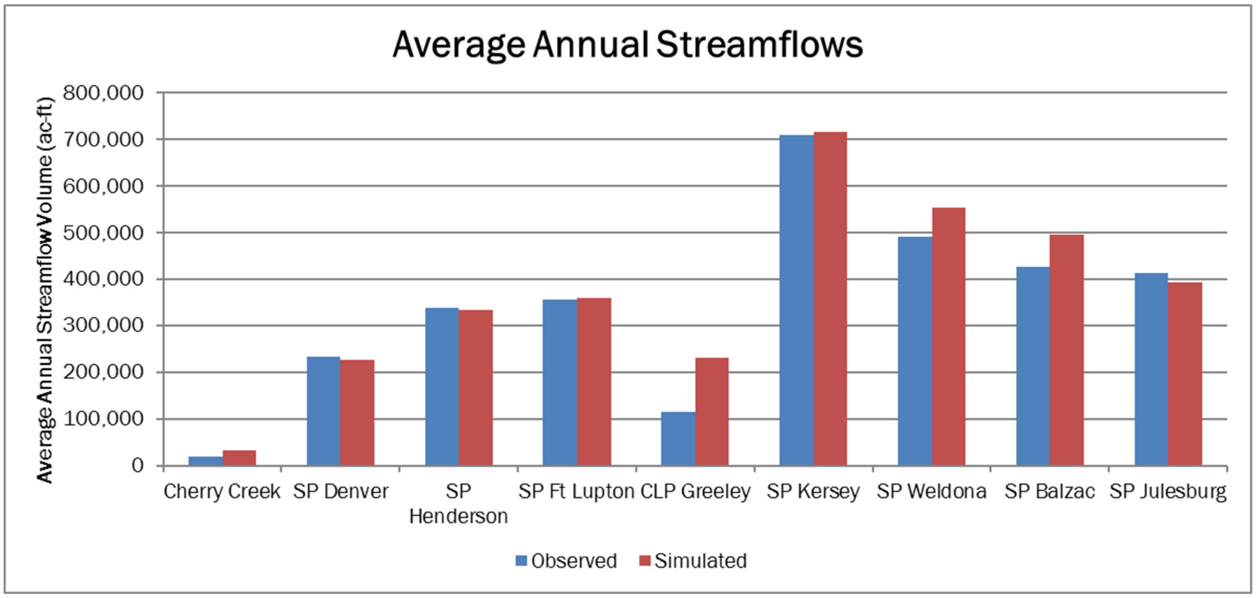

Figure ES-3. Comparison of Simulated and Measured Average Annual Streamflows

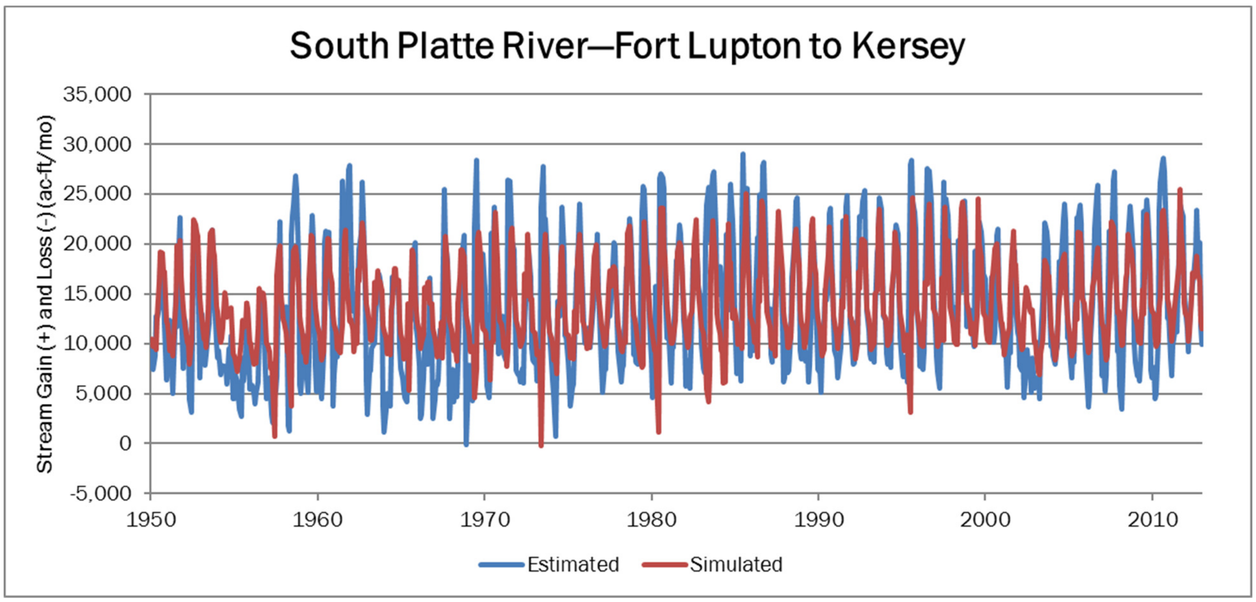

Figure ES-4. Simulated and Estimated Stream Gain/Loss, South Platte River Fort Lupton to Kersey

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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