RGDSS Memorandum

Phase 6 Groundwater Model Enhancement Summary

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TO: File

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SUBJECT: Phase 6 Groundwater Model Enhancement Summary

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1. Introduction

This memorandum summarizes Phase 6 enhancements to the Rio Grande Decision Support System (**RGDSS**) Groundwater Model (**Model**). The objective of this task is as follows:

1. Provide key highlights of the Phase 6 enhancements to the Model.
2. Guide readers to project memorandums that detail these enhancements.

Thirty-six project memorandums were prepared to document the Phase 6 Model enhancements. A listing and brief description of the project memorandums is presented in **Table 1**. Phase 6 project memorandums were divided into nine categories:

1. Geology/Hydrogeology
2. Geographic Information Systems
3. Groundwater Evapotranspiration
4. Non-Irrigation Wells (M&I)
5. Rim Recharge
6. Crop Consumptive Use (StateCU)
7. StateFate
8. MODFLOW Model
9. Response Functions

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In several project memorandums the term "pumping" is used to describe groundwater withdrawals whether the withdrawal is by a mechanical pump or if the well flows under artesian pressure. Some of the wells in the San Luis Valley ("SLV" or "Valley) flow under artesian pressures and do not have a pump installed in the casing even though the term "pumping" is used to describe their withdrawal of groundwater. In any project or task memorandum where the term "pumping" is used the reader should interpret the term as describing groundwater withdrawals whether the withdrawal is by a mechanical pump or if the well flows under artesian pressure.

Previous investigations are discussed in **Section 2**, a brief summary of each of the nine categories is provided in **Section 3** and a directory listing all the Phase 6 memorandums is provided in **Section 4** .

2. Previous Efforts

A 1998 feasibility study by Colorado Water Conservation Board (CWCB) and CDWR provided the framework for the Model (Riverside Technology et.al, 1998). The first formal documentation of the Model was provided for the *San Luis Valley Groundwater Model* (HRS Water Consultants, Inc., 1999). This was a steady-state model that simulated average groundwater flow conditions in the SLV between 1970 and 1982.

The next major documentation was the Phase 4 Ground Water Model Documentation prepared in 2004 (CDWR and CWCB, 2004). In Phase 4 calibration was performed for three study periods; 1) steady-state (1990 to 1998), 2) average monthly (1990-1998 and 3) monthly (1970-2002). The Phase 4 version of the Model called 4P13 was litigated in Case No. 04CW24 as part of the Confined Aquifer New Use Rules for Division 3 which was upheld by the Colorado Supreme Court in Case No. 07SA42.

The Phase 5 version of the Model called 5P12 was litigated in the context of challenges to Subdistrict No.1's Amended Plan of Water Management ("Plan") in Case No. 07CW52. The court's ruling approving the Plan, which included a finding that the Phase 5 version of the Model was the appropriate tool for use in determining stream depletions from the operation of Subdistrict No. 1 wells, was upheld by Colorado Supreme Court in Case No. 2010SA224. Phase 5 was documented by exhibits entered into evidence in 07CW52. In Phase 5 the model time period was extended through the end of 2005. A summary of the Phase 5 enhancements was documented in Trial Exhibit 84 (Bennett, 2009).

3. Phase 6 Enhancement Summary

In Phase 6, as in other phases, the RGDSS Peer Review Team (PRT) provided significant guidance and review during the modeling process. The PRT meetings were open to all interested parties and were attended by CDWR staff, water users, engineers, geologists, modelers and occasional observers. The PRT met 47 times from 2011 through 2015 to review and enhance the Model. The enhancement process was iterative with new approaches and enhancements being proposed, critiqued, reviewed and discussed at a PRT meeting(s), and modified or refined before initial trial implementation. Once implemented the Model results were then analyzed and reviewed by the PRT where additional modifications were then be suggested and the enhancement process continued.

Two major model releases were part of Phase 6:

1. Model Version 6P35, which was the model provided in the water court case associated with the State Engineer's Approval of the 2012 Annual Replacement for Sub District No. 1 of the Rio Grande Water Conservation District pursuant to the Plan of Water Management the

court approved in its Findings of Fact, Conclusions of Law, Judgment and Decree, Case Nos. 06CV64 & 07CW52.

2. Model Version 6P98 which was the model provided in the Rules Governing the Withdrawal of Groundwater in Water Division No. 3 and Establishing Criteria for the Beginning and End of the Irrigation Season in Water Division No. 3 for all Irrigation Water Rights filed by the State Engineer in the Water Division No. 3 Water Court on September 23, 2015.

Model Version 6P98 is the release described herein and in associated documents, however, enhancements which were made in 6P35 and included in 6P98 are also documented. Key enhancements under Phase 6 included:

- Extended study period through 2009 (6P35) and 2010 (6P98)
- Incorporated metered groundwater withdrawal data for 2009 (6P35) and 2010 (6P98)
- Enhanced the understanding of the complex geology with targeted hydrogeologic studies conducted in several of the major river sub-basins within the SLV
- Added Irrigated Parcel Datasets for 2002, 2005, 2009 (6P35) and 2010 (6P98)
- Enhanced the understanding of the irrigated acreage, crop irrigation water requirements, and water supplies
- Generated Response Functions for seven Response Areas: Alamosa-La Jara, Conejos, Response Area No.1, Rio Grande Alluvium, Saguache, San Luis Creek and Trinchera Creek

A detailed listing of all enhancements is presented in the RGDSS Phase 6 memorandum under the file name *RGDSS_P6_MOD_Enhancements.pdf.* A brief summary of each of the nine general categories is provided in the following sections.

3.1. Geology/ Hydrogeology

The technical reports in this topical category summarize the work done on enhancements to definition of the hydrogeology of the SLV in Colorado, as part of Phase 6 of the RGDSS (2012 – 2015), along with recommendations for corresponding refinements to the RGDSS groundwater model.

The hydrogeologic interpretations and refinements presented in this set of reports were developed by HRS Water Consultants, Inc. ("HRS") as part of the RGDSS on behalf of the Colorado Water Conservation Board and the Colorado Division of Water Resources during Phase 6 of the RGDSS project. All of the work was done with the authorization of the Colorado Division of Water Resources. As a contractor to the State on the RGDSS, HRS was responsible for responding to questions involving hydrogeology for this phase of the RGDSS. HRS also participated in the RGDSS PRT during this phase (as well as previous phases) of the project. Eric J. Harmon, P.E. was the principal author of all of the Phase 6 hydrogeology reports.

Hydrogeology-related inquiries to which HRS responded were from three sources: the State (CDWR staff), the principal RGDSS modeling contractor (Principia Mathematica) and the PRT.

The objectives of these reports were to respond to questions and provide recommendations for refinements to the RGDSS in various geographic areas and topics in the SLV, including:

- Improved definition of boundary inflows and aquifer layer definition in some areas of the SLV, including the southeast boundary region (Costilla County) and the northwest boundary region (Saguache Creek valley)
- Improved well layering assignments in various areas of the SLV

- Improved definition of geologic structure as it affects the hydrogeology and water levels or confined aquifer heads, including in the San Luis Creek region, the Costilla Plain region, and the lower Conejos River region
- Improved definition of aquifer layering and perched water table areas in the Conejos / San Antonio region and the Rio Grande alluvial valley region between Del Norte and Monte Vista.
- Evaluated and implemented improvements to the calibration match to wells with high residuals
- Evaluated and implemented improvements to the water level assignment protocol in confined layers

3.2. Geographic Information System (GIS)

GIS enhancements were divided into three components and are summarized below.

RGDSS Irrigated Dataset Enhancements: The RGDSS Irrigated Parcel Datasets spatially represent parcels that were irrigated during a particular year. In previous phases of the RGDSS, irrigated parcel datasets were developed for years 1936 and 1998. In Phase 6, the existing irrigated parcel datasets were refined based on higher resolution imagery and additional datasets were created representing years 2002, 2005, 2009, and 2010 such that irrigated areas are more completely and accurately represented through time. Details of the enhancement of the irrigated parcel datasets are provided in the RGDSS Phase 6 memorandum under the file name *RGDSS_P6_GIS_Parcels.pdf.*

Sprinkler Acreage Timeline Enhancements: A Sprinkler Acreage Timeline was developed in RGDSS Phase 5 to track the progression of sprinkler acreage through time. In Phase 6, the sprinkler acreage timeline was enhanced by incorporating refinements and additions to the irrigated parcel datasets, utilizing satellite imagery to confirm years that systems were installed, and implementing a dynamic methodology that tracked access to groundwater and changes to a sprinkler's irrigated acreage through time. Details of the enhancement of the sprinkler acreage timeline are provided in a RGDSS Phase 6 memorandum under the file name *RGDSS_P6_GIS_Sprinkler.pdf.*

GIS Processing Enhancements: In Phase 6, the GIS processor programs **agg, Mksub3** and **mkprf** were enhanced. The **agg** program is used to combine the individual parcel and well mappings produced by the CDSS Toolbox and output mappings for multi structures. Multi structures are used in areas where complex water management by several ditches are best represented as a single unit. The **mksub3** program is used to compute the potential subirrigation coverage for the "other" category that is subirrigation that occurs on lands not mapped as alfalfa or meadow (a.k.a. grass pasture). The **mkprf** program calculates the fraction of irrigated land for determining precipitation recharge. Documentation for these processors is provided in a RGDSS Phase6 memorandum under the file name *RGDSS_P6_GIS_Processing.pdf.*

3.3. Groundwater Evapotranspiration

Groundwater can contribute to evapotranspiration from native vegetation, irrigated crops, and even bare soil when groundwater levels are near to or within rooting zones or near the ground surface. The RGDSS groundwater flow model simulates evapotranspiration from groundwater (**ETg**) as a function of depth to groundwater within groundwater model cells. These **ETg** functions are represented as segmented lines from the ground surface to a depth where the **ETg** rate becomes zero for the following generalized land cover and crop types.

- **Non-irrigated land cover types:**
  - water hydrophytes (wetland/riparian)
  - heavy vegetation (coniferous/deciduous trees)
  - medium vegetation (non-irrigated meadow)
  - bare ground
- **Irrigated crop types:**
  - meadow
  - alfalfa
  - other crops

In Phase 6, the **ETg** functions in the RGDSS groundwater flow model were updated based on recommendations from consulting experts. The revised **ETg** functions and enhancements to the **ETg** process are detailed in a RGDSS Phase 6 memorandum under the file name *RGDSS_P6_GWET_ETfromGW.pdf.* The development of the maximum monthly **ETg** limits is described in the RGDSS Phase 6 memorandum under the file name *RGDSS_P6_GWET_Subirr.pdf*.

3.4. Non-Irrigation Wells (M&I)

In Phase 6, a significant amount of work was conducted by the CDWR modeling group, by HydroBase development personnel, and by Division 3 staff to update the model well list and enable the evaluation of groundwater withdrawals and return flows from the non-irrigation wells in Division 3 and updating of the groundwater modeling input data through 2010.

Details on the M&I enhancements are provided in a RGDSS Phase 6 memorandum under the file name *RGDSS_P6_M&I_NonirrWells.pdf.* Wildlife specific enhancements are detailed in a RGDSS Phase 6 memorandum under the file name *RGDSS_P6_M&I_WildlifeWells.pdf*

3.5. Rim Recharge

The Model explicitly represents 30 streams and simulates their flows and interactions with the groundwater system. The stream inflow into the Model domain from the major streams is well understood because of the numerous streamflow gages that measure the flow in these streams. Inflows from 35 minor stream drainage basins around the perimeter, or "rim" of the Valley, are incorporated into the Model as "rim inflow." The amount and timing of water entering the Valley as rim inflow is not gaged and therefore must be estimated. The rim inflow that enters the Model domain may be diverted for use and the remaining flow then recharges the groundwater aquifer system as "rim recharge." Rim recharge is defined as infiltration to the groundwater system from those streams not explicitly simulated in the Model.

Details on Rim Recharge are presented in a RGDSS Phase 6 memorandum under the file name *RGDSS_P6_RimRecharge.pdf.*

3.6. Crop Consumptive Use (StateCU)

The Phase 6 Rio Grande Basin historical crop consumptive use was performed on a monthly basis for the period from 1950 through 2010. Key enhancements conducted in coordination with the PRT include:

1. Metered groundwater withdrawal data was provided for 2009 and 2010.
2. The approach to estimate historical irrigated acreage was revised. The Phase 4 approach relied on 1998 irrigated acreage mapping and historical agricultural statistics. The Phase 5 approach estimated 1950 through 1997 irrigated acreage data by interpolating between the 1998 and 1936 data. It estimated 1999-2005 data using the 1998 data. In Phase 6, irrigated acreage data for 1999 through 2001 is estimated using 1998 data, 2003 and 2004 data are estimated using 2005

data, 2006 through 2008 data are estimated by interpolating between 2005 and 2009 data, and data for years 2002, 2005, 2009, and 2010 utilize the new irrigated parcel datasets for those years.

3. Treatment of water supply and irrigation methodology was enhanced. The Phase 4 approach recognized three combinations of water supply and irrigation methods: 1) Surface Water Flood, 2) Groundwater Flood and 3) Groundwater Sprinkler. The Phase 6 approach includes a fourth category for Surface Water Sprinkler.
4. Treatment of water use on the Rio Grande Canal, Farmers Union Canal, Prairie Ditch, and San Luis Valley Canal Company (ditches with recharge decrees) was enhanced.

Details on the StateCU enhancements are provided in a RGDSS Phase 6 memorandum under the file name *RGDSS_P6_StateCU_Process.pdf*. In addition, the following memorandums are related to Phase 6 StateCU enhancements:

- *RGDSS_P6_StateCU_WellMeters.pdf*: Provides analysis and evaluation of the Division 3 well measurement program
- *RGDSS_P6_StateCU_MeterPumpCommands*.pdf: Provides documentation for the TSTool commands used to include and distribute metered groundwater withdrawals in the StateCU analysis
- *RGDSS_P6_StateCU_RevCropCharacteristics.*pdf; Provides recommendations for revised crop characteristics that were incorporated into the StateCU analysis
- *RGDSS_P6_StateCU_ClimateStationWeighting.pdf*: Provides enhancements for climate station weighting
- *RGDSS_P6_StateCU_AdditionalCrops.pdf*: Provides information on additional Phase 6 crop types
- *RGDSS_P6_StateCU_Precipitation.pdf:* Details effective precipitation methodology
- *RGDSS_P6_StateCU_Code.pdf* : Details StateCU code enhancements

In addition, the following GIS project memorandums include information related to Phase 6 StateCU enhancements*:*

- *RGDSS_P6_GIS_Sprinkler.pdf*: Documents enhancements to the methodology used to compute the sprinkler acreage timeline used for structures within the RGDSS StateCU model
- *RGDSS_P6_GIS_Parcels.pdf*: Documents enhancements to the irrigated parcel datasets and related datasets used for the RGDSS

3.7. StateFate

StateFate (Fate of Surface Water Returns and Drain Flows) is a preprocessor program which routes water between StateCU and StatePP. It handles the complex task of routing drain flows and tail water that are potential surface water sources for some ditches. It also provides the interface between the StateCU program which performs the consumptive use calculations and the **S**tatePP preprocessor that distributes the StateCU data to model cells in the MODFLOW model. StateFate was documented in a RGDSS Phase 6 memorandum under the file name *RGDSS_P6_Statefate.pdf*.

3.8. MODFLOW Model

Documentation for the MODFLOW model enhancements was divided into five major groups:

Model Enhancements: The current version of the Model is 6P98. The Model continues to be updated and refined to more accurately represent the complex groundwater flow system. Detailed listing of all enhancements to Model Version 6P98 are detailed in a RGDSS Phase 6 memorandum under the file name *RGDSS_P6_MOD_Enhancements.pdf*:

StatePP: StatePP is the program used to create all the groundwater withdrawal, recharge and evapotranspiration MODFLOW input files. Documentation of this program is provided in a RGDSS Phase 6 memorandum under the file name *RGDSS_P6_MOD_StatePP.pdf*:

Model Setup: The general steps involved in the model setup process include: 1) building the model input files, 2) building the Parameter Estimation (PEST) control files, 3) estimating new best aquifer parameters using PEST , 4) performing a suite of model runs, 5) performing impact runs, 6) performing response function runs, and 7) post-processing the results. Details of this process are provided in a RGDSS Phase 6 memorandum under the file name *RGDSS_P6_MOD_ModelSet.pdf:*

Stream Package: The stream package in MODFLOW is used to represent natural streams, drains, canals modeled as streams, and McIntire Springs in the groundwater model. The process for building the stream package file is detailed in a RGDSS Phase 6 memorandum under the file name *RGDSS_P6_MOD_Streeam.pdf.*

Calibration: For the calibration process, the Phase 6 model water level and stream flux results were compared to the observed data. Documentation and numerous graphs of this calibration are provided in a in a zip file entitled *RGDSS_P6_MOD_Calibration.zip.*

3.9. Response Functions

A Response Function is a simplified representation of the cause and effect relationship between groundwater withdrawal and net depletions to one or more surface streams within Water Division No. 3. The current Response Functions are based on results from the Rio Grande Decision Support System (RGDSS) Groundwater Model Version 6P98. The procedure used to run the Model and calculate the response functions for Subdistrict No. 1 is described in *Using the RGDSS Groundwater Model to Compute Response Functions* from Case No. 07CW52. The same procedure was used for the new Response Areas, with refinements to deal with the unique features of different areas and streams. The updates and enhancements to the Response Functions incorporate additional field data, and cover the additional Response Areas. The following bullets summarizes the key enhancements to the Response Functions;

- In addition to Response Area No. 1, Response Functions were developed for the following Response Areas: Rio Grande Alluvium, Conejos, Alamosa/La Jara, San Luis Creek, Saguache, and Trinchera.
- The Response Functions generated for the seven Response Areas comprise twenty-seven stream reaches/systems (twenty-three stream reaches and four stream systems).
- The Response Function method called the "Ratio" method was added to appropriately address the non-linear relationships between stream depletions and net groundwater consumptive use (NetGWCU) to calculate net stream depletions under hydrological conditions (intermittent streamflows) that occur in the additional response areas.

- A grouping method using streamflow was implemented to aggregate dry, wet, and average year hydrological conditions to all Response Areas except Response Area No. 1 which uses the NetGWCU groupings.
- The Response Functions were developed in a manner to accommodate subset/group of wells to determine their annual replacement obligations (proportionality).

Details of all response function enhancements are provided in a RGDSS Phase 6 memorandum under the file name *RGDSS_P6_ResponseFunction.pdf*.

4. Phase 6 Memorandum Directory

Table 1 is a directory of the enhancement memorandums generated for Phase 6.

5. References

Bennett, Ray, R., June 22, 2009, RGDSS Phase 5 Ground Water Model Enhancements.

Colorado Division of Water Resources (CDWR) and Colorado Water Conservation Board (CWCB), 2004, Preliminary Draft, Rio Grande Decision Support System, Phase 4 Ground Water Model Documentation;, for Colorado Water Conservation Board and Colorado Division of Water Resources.

HRS Water Consultants, Inc, December, 1999, RGDSS Ground Water Component, Final Report – Task 2, Documentation of the San Luis Valley Ground Water Model.

Riverside Technology, Inc., HRS Water consultants, Inc, and Boyle Consulting Engineers, April 1998, Rio Grande Decision Support system Feasibility Study.

Schreüder, W.A. (2009) Using the RGDSS Groundwater Model to Compute Response Functions. Expert Report, Case No. 07CW52.

Table 1
Phase 6 Memorandum Directory

Category	Document Name	Brief Description
Geology/ Hydrogeology	RGDSS_P6_GEO_7MilePlaza.pdf	2009 Hydrogeologic evaluation of Del Norte - Sevenmile Plaza Area
	RGDSS_P6_GEO_Conejos-SanAntonio.pdf	Hydrogeologic mapping review of Conejos/San Antonio region
	RGDSS_P6_GEO_GridExtent.pdf	RGDSS extent of model grid source documentation
	RGDSS_P6_GEO_LayerProtocol.pdf	Review of water level layer assignment protocol for confined layers
	RGDSS_P6_GEO_Manassa.pdf	Hydrogeologic review of Manassa Fault and McIntyre Spring, Conejos County, CO
	RGDSS_P6_GEO_Mesita.pdf	Hydrogeologic review of the Mesita Fault, Costillo County CO
	RGDSS_P6_GEO_RioGrande.pdf	Hydrogeologic review and data collection, Rio Grande, Del Norte to Rio Grande - Alamosa County line
	RGDSS_P6_GEO_SaguacheCrk.pdf	Hydrogeologic review of Saguache Creek upstream of the town of Saguache
	RGDSS_P6_GEO_Saguache-Gunbarrel.pdf	Hydrogeologic review of confined aquifer - Saguache/Gunbarrel Area
	RGDSS_P6_GEO_SanAntonio-Ortiz.pdf	Hydrogeolgoic mapping review of San Antonio - Ortiz Region
	RGDSS_P6_GEO_SE-Gridetc.pdf	Hydrogeologic review of the southeast model boundary grid, layering and groundwater inflow
	RGDSS_P6_GEO_UpperSanLuisCrk.pdf	Hydrogeologic investigation of Upper San Luis Creek, Saguache County CO
	RGDSS_P6_GEO_WellReview.pdf	Review of wells and areas of high model residuals
Geographic Information System	RGDSS_P6_GIS_Parcels.pdf	Enhancements to irrigated parcel datasets
	RGDSS_P6_GIS_Processing.pdf	Documentation of agg, mksub3 and mkprf pre-processing programs used to develop input data for StatePP
	RGDSS_P6_GIS_Sprinkler.pdf	Enhancements to sprinkler acreage timeline
Groundwater Evapo-transpiration	RGDSS_P6_GWET_ETfromGW.pdf	Summary of evapotranspiration (ET) from groundwater process
	RGDSS_P6_GWET_SubIrr.pdf	Re-evaluation of subirrigation maximum monthly ET

Table 1 (Continued)
Phase 6 Memorandum Directory

Category	Document Name	Brief Description
Non-Irrigation Wells (M&I)	RGDSS_P6_M&I_NonIrrWells.pdf	Summary of non-irrigation groundwater withdrawals and return flows
	RGDSS_P6_M&I_WildlifeWells.pdf	Details on State and Federal wildlife operations
Rim Recharge	RGDSS_P6_RimRecharge.pdf	Stream inflow, rim inflow and rim recharge estimates
Crop Consumptive Use (StateCU)	RGDSS_P6_StateCU_AdditionalCrops.pdf	Documentation for additional Phase 6 crop types
	RGDSS_P6_StateCU_ClimateStationsWeighting.pdf	Review and enhancements of climate station weighting
	RGDSS_P6_StateCU_Code.pdf	Enhancements to StateCU code
	RGDSS_P6_StateCU_MeterPumpCommands.pdf	Commands to include and distribute metered groundwater withdrawals in the StateCU analysis
	RGDSS_P6_StateCU_Precipitation.pdf	Documentation for effective precipitation methodology
	RGDSS_P6_StateCU_Process.pdf	Documentation for crop consumptive use analysis
	RGDSS_P6_StateCU_RevCropCharacteristics.pdf	Provides recommendations for revised crop characteristics that were incorporated into the StateCU analysis.
	RGDSS_P6_StateCU_WellMeters.pdf	Statistical analysis and programmatic evaluation of the Division 3 well measurement program
StateFate	RGDSS_P6_StateFate.pdf	Documentation of StateFate, a pre processing program used to develop Surface Water Return and Drain use data for StateCU and summarize deep percolation for StatePP
MODFLOW Model	RGDSS_P6_MOD_Calibration.zip	Provides the calibration graphs and statistics
	RGDSS_P6_MOD_Enhancements.pdf	Detailed listing of model enhancements
	RGDSS_P6_MOD_ModelSet.pdf	Steps used to perform a complete set of groundwater model simulations for a particular version of the RGDSS Groundwater Model
	RGDSS_P6_MOD_StatePP.pdf	Documentation of StatePP
	RGDSS_P6_MOD_Stream.pdf	Details for building the stream package
Response Function	RGDSS_P6_ResponseFunction.pdf	Summary of response function development