A Summary of the Development of the Central Carbonate-Rock Province Groundwater Flow Model

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Pertaining to:
Groundwater Applications 54003 through 54021 in
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and
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ACRONYMS

BLM	Bureau of Land Management
CCRP	Central Carbonate-Rock Province
CSS	composite scaled sensitivities
EIS	environmental impact statement
ET	evapotranspiration
RMU	regional modeling unit
SNWA	Southern Nevada Water Authority
SoSWR	sum of squared-weighted residuals

ABBREVIATIONS

afy	acre-foot per year
bgs	below ground surface
ft	foot
km	kilometer
m	meter
m^3/d	cubic meter per day

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1.0 INTRODUCTION

This expert report summarizes the efforts conducted by the Southern Nevada Water Authority (SNWA) in cooperation with the Bureau of Land Management (BLM) to develop a numerical groundwater flow model of the Central Carbonate-Rock Province (CCRP) of Nevada and Utah in support of the SNWA Clark, Lincoln, and White Pine Counties Groundwater Development Project (hereinafter referred to as the Project). The extent of the Project study area (i.e., the regional model area) is shown in Figure 1-1 of SNWA (2009b; p 1-2). The numerical model is based on a conceptual model primarily described in a separate report (SNWA, 2009a) and was used as part of the environmental analysis for the Project. Specifically, the numerical model was developed to simulate groundwater development scenarios to evaluate the range of potential water-related effects of the Project's groundwater production at the regional scale. Two previous models for this region, the Death Valley Regional Flow System Model (D'Agnese et al., 1997; Belcher and Sweetkind, 2010) and the Great Basin Regional Aquifer-System Analysis model (Prudic et al., 1995) provided the foundation for much of the modeling approach, methodology, and documentation for the CCRP model. These models are summarized in Section 1.3 of SNWA (2009b; p 1-5).

This expert report focuses primarily on explaining the following modeling topics:

1. model purpose, scope, and assumptions,
2. the numerical modeling approach,
3. the collaborative model development process,
4. model design and construction,
5. model calibration,
6. model evaluation,
7. model limitations, and
8. adherence to Methods and Guidelines of Effective Model Calibration (Hill, 1998).

1.1 Model Purpose, Scope, and Assumptions

The CCRP Numerical Model focuses predominantly on the regional groundwater flow system. Intermediate systems may also be addressed if they are in contact with the regional flow system. Perched or local flow systems are not modeled. The model will ultimately be used, along with other analyses, to evaluate the potential effects of groundwater withdrawal on the environment. As pumping, monitoring, and testing data become available in the future, the model will be improved and utilized as a tool in an adaptive management process for groundwater management in the Project Basins. Further insight into the purpose of the CCRP Numerical Model is described in SNWA (2009b) beginning on page 1-7.

The CCRP model is specifically designed to simulate historical, existing, reasonably foreseeable, and future groundwater withdrawals, including the proposed SNWA pumping and environmental impact statement (EIS) alternatives, to evaluate the potential effects on the following:

- Potential drawdowns in the regional and intermediate flow systems within the model area;
- Regional (primarily) and intermediate (secondarily) springs, groundwater evapotranspiration (ET) areas, streams, or wells that are hydraulically connected to regional and intermediate parts of the flow system; and
- Flow system boundaries.

The CCRP model is NOT designed for the following uses:

- Simulation of perched (local) portions of the flow system, including perched springs, perched groundwater ET areas, perched streams, or wells located in perched zones or the effects that pumping from the regional flow system would have on these features.
- Prediction of drawdown at a specific pumping well due to the resolution of the model cells. [The inability of a finite-difference model to accurately represent the drawdown at a well is described rather clearly in the groundwater modeling text by Anderson and Woessner (1992) where they state the following:

  "The diameter of a well is typically much smaller than the dimensions of the (model) cell. To represent the effects of a point sink more accurately, small cells around pumping nodes are preferred. But field problems generally require large grids and can seldom accommodate cells as small as the actual well diameter…A finite difference model does not simulate this gradient accurately because the model extracts or injects water to the entire cell rather than to the nodal point. The head calculated by the model is not a good approximation of the head in the well, but heads at nodes away from the point source or sink are correct." (Anderson and Woessner, 1992; page 147, paragraph 3)]

- Derivation of accurate predevelopment steady-state groundwater budgets for individual basins or flow systems within the study area or estimates of interbasin flow (directions and volumes) across boundaries.
- Derivation of new delineations of groundwater basin or new flow-system boundaries.

The effort focused specifically on the design, construction, calibration, and evaluation of the CCRP Numerical Model, which was conducted predominantly in two major phases of work. The model was developed in cooperation with the BLM, including review and input from a BLM technical team, and was also reviewed by the EIS cooperating agencies.

The first phase consisted of model construction activities and preliminary simulations to derive a numerical representation of the conceptual model that approximately matched the response of the flow systems under predevelopment conditions. In the preliminary versions of the numerical model, predevelopment conditions were interpreted from data spanning the full period of record to supplement the scarce data available from years prior to 1945.

The second phase consisted of the calibration of a numerical representation of the groundwater flow system during steady-state conditions (assumed to be occurring prior to 1945) and transient conditions (simulated from 1945 through 2004). Transient conditions were assumed to exist after 1945 in many parts of the region. This determination was based on a comprehensive evaluation of spring discharge, stream flow, and water level data gathered throughout the entire region. However, the assumption of when transient conditions were initiated was based predominantly on an analysis of water-level measurements. Only 57 wells contained water-level information prior to 1945, and, unfortunately most of these wells only had one averaged yearly measurement during this period. For water-level data existing after 1945, a series of filters were assigned to specific wells or water-levels at a well based on the quality of data at each specific well. The details of this analysis of transient data can be found in SNWA (2009b, Appendix B).

The CCRP numerical model is based on three major simplifying assumptions described in SNWA (2009b), Section 1.5 beginning on page 1-10. In general, it is difficult to use computer models to describe groundwater flow in an area as geographically large and geologically complicated as the Carbonate-Rock Province of Nevada and western Utah (Prudic et al., 1995). However, as has been demonstrated by previous investigators who conducted groundwater modeling studies of the Great Basin or portions of it (Prudic et al., 1993; 1995; D'Agnese et al., 1997; 2002; and Faunt et al., 2004), it is possible and useful to develop such models. Inevitably, simplifying assumptions must be used to adapt the complex conceptual model for numerical simulation.

The three major simplifying assumptions used in the development of the CCRP numerical groundwater flow model include:

1. Groundwater in the region flows through fractures and solution openings of consolidated rocks, as well as in porous basin-fill deposits. Fracture-flow simulation is, however, impractical at a regional scale; therefore, a porous medium model is used.

2. The flow system is assumed to have been under predevelopment steady-state conditions before 1945.

3. For the post-1945 time period, the flow systems were assumed to be under transient conditions due to stresses imposed by man through well pumping and diversion of spring and stream flow originating from groundwater. The stresses and effects of natural fluctuations on the flow systems, namely those associated with variations in precipitation, were not simulated.

The validity and reasonableness of these assumptions are described in detail in SNWA (2009b, Section 1.5).

2.0 NUMERICAL MODELING APPROACH

The numerical model was developed by generally following the 14 methods and guidelines for effective model calibration described by Hill (1998) and recently updated by Hill and Tiedeman (2007). The relevant guidelines were applied to all stages of development of the numerical model.

The 14 guidelines by Hill and Tiedeman (2007, Table 1.3) may be organized into explicit steps within the model development process. These include:

Groundwater System Conceptualization, Model Design and Construction:

1. Apply the principle of parsimony (start very simply; build complexity slowly).

Model Calibration:

2. Use a broad range of system information (soft data) to constrain the problem.
3. Maintain a well-posed, comprehensive regression problem.
4. Include many kinds of observations (hard data) in the regression.
5. Use prior information carefully.
6. Assign weights that reflect errors.
7. Encourage convergence by making the model more accurate and evaluating the observations.
8. Consider alternative models.

Model Evaluation:

9. Evaluate model fit.
10. Evaluate optimized parameter values.
11. Identify new data to improve simulated processes, features, and properties.
12. Identify new data to improve predictions.

Uncertainty Analysis:

13. Evaluate prediction uncertainty and accuracy using deterministic methods.
14. Quantify prediction uncertainty using statistical methods.

This general modeling approach is applicable to any process modeling exercise, not just groundwater models. It is consistent with the iterative nature of the development of groundwater flow models as described by Bredehoeft (2003).

The platform selected for construction of the numerical model was the finite-difference modeling code, MODFLOW-2000 (Harbaugh et al., 2000). More specifically, a customized version of MODFLOW-2000, Version 1.18.01, was used to construct the CCRP model. Given that MODFLOW-2000 has several limitations for sensitivity analysis and parameter-estimation capabilities, a customized version of UCODE_2005 (Poeter et al., 2005), a parameter-estimation code, was selected for these purposes. UCODE_2005 adds significant flexibility in parameter definition, allowing application of formulas to create derived parameters that may be dependent on a function or multiplier.

Complete details regarding modeling approach and selected modeling codes are described in SNWA (2009b, Section 2.0).

3.0 COLLABORATIVE MODEL DEVELOPMENT PROCESS

The entire CCRP groundwater model development process was a carefully coordinated collaborative process conducted by the SNWA and their contractors, the BLM and their EIS contractors, and key technical advisors and/or observers. BLM assembled a Hydrology Technical Group in the early stages of the EIS-related groundwater modeling exercise. The primary objective of this group was to provide technical advice and recommendations to BLM, so that BLM could ensure the hydrologic data analysis and numerical model development would meet the scientific integrity standard applicable to National Environmental Policy Act documents and the best available science requirements applicable to the Endangered Species Act.

The BLM Hydrology Technical Group members included:

- Penny Woods, BLM
- Eileen Poeter, Poeter Engineering (for BLM)
- Patrick Plumley, AECOM (for BLM)
- Bob Boyd, BLM
- Dan Netcher, BLM
- Rick Felling, Nevada State Engineer's Office
- Keith Halford, U.S. Geological Survey

The Hydrology Technical Group review process included meetings and conference calls to discuss and resolve technical issues. Model development began in November 2006 with group interactions occurring approximately monthly. For a period of approximately 18 months beginning in May of 2008, internet-based online meetings and conference calls were held monthly and sometimes weekly or twice weekly as needed to resolve technical issues that arose. The interactions were quite collaborative with significant give-and-take between members of the SNWA modeling team and the Hydrology Technical Group. At times, for issues that required additional discussion, analysis, and review, smaller groups of individual members of the Hydrology Technical Group met separately to address or resolve technical issues requiring more detail.

This process of review, interaction, comment, and discussion resulted in the Hydrology Technical Group reviewing data gathering and synthesis, data analysis, model conceptualization, model design, model construction, model calibration, and model evaluation.

The process also involved more traditional formal peer reviews of drafts of preliminary reports and interim model work products (including review and testing of model inputs and outputs).

Input, expertise, and insight was also offered by the Nevada State Engineer's Office which participated in most technical meetings, and in many cases, added valuable insight into the groundwater flow systems, including for example, water-use estimates throughout the model domain.

Major comments provided by the Hydrology Technical Group throughout the development of the CCRP model and their resolution are summarized in SNWA (2009b, Section 3.0).

4.0 MODEL DESIGN AND CONSTRUCTION

The construction of the transient numerical groundwater flow model, including the abstraction process of the flow systems in the model area into MODFLOW-2000 and UCODE_2005 is described in detail in SNWA (2009b; Section 4.0). The process includes the selection of the MODFLOW-2000 packages and the preparation of the necessary input files. The construction steps discussed in this section include (1) numerical model discretization, (2) representation of hydrogeologic framework, (3) definition of external model boundary conditions, (4) representation of natural surface and groundwater discharge, (5) representation of areal recharge from precipitation, (6) estimation of anthropogenic stresses, and (7) derivation of observation data sets. Also, parameters associated with the various components of the numerical model are presented. The reader is directed to SNWA (2009b, Section 4.0) for these details.

5.0 MODEL CALIBRATION

The process followed to calibrate the numerical model is described in SNWA (2009b) Section 5.0 followed by a presentation of calibration activities designed to test and adjust the conceptual model represented in the numerical model. These calibration activities consisted of reweighting the observations and testing and adjusting the various components of the conceptual model. Model parameters were also refined during these calibration activities. The final parameter-estimation simulations are discussed in SNWA (2009b, Section 6.0) along with the evaluation of the calibrated numerical model.

Although automated-regression techniques may constitute more efficient and accurate tools for model calibration, manual trial-and-error calibration to improve model fit to actual observations is often necessary to develop a reasonable representation of a complex hydrogeologic system with sparse data and significant uncertainties. In fact, combining the two methods provided greater flexibility in testing the representation of various features of the flow system in the numerical model. This approach is quite common in utilizing automated-regression techniques for calibration of groundwater flow models in the geologically complex Great Basin region. Numerous models developed by the USGS and the DOE in southern Nevada found it necessary to utilize this approach (D'Agnese et al., 1997; Belcher and Sweetkind, 2010).

5.1 Model Calibration Guides

The parameter-estimation and testing-analysis capabilities of UCODE_2005 provided valuable insights, which were used to guide the calibration of the numerical model. Useful model-calibration guides consisted of indicators of data quality, the relative importance of each parameter in the parameter-estimation process, and indicators of calibration improvement. Particularly useful were the dimensionless sensitivities, the composite scaled sensitivities (CSS), the Sum of Squared-Weighted Residuals (SoSWR), and the weighted residuals.

- The dimensionless sensitivities quantify the influence of a single observation on a single parameter estimate. They are not only used internally by UCODE_2005 to seek a solution, but they were also used externally by the modelers to evaluate the importance of observations to the parameter estimation.

  For example, an uncharacteristically large or small hydraulic conductivity for a tectonic block of Lower Carbonate Aquifer in the model may be significantly influenced by an erroneous spring flow measurement that was indicated by a large dimensionless sensitivity of the spring flow observation in the model during calibration.

- CSS were used during calibration to decide which parameters to include and exclude from the parameter-optimization process. In general, parameters with relatively high CSS values were included in the estimation process, while parameters with relatively low CSS values were not. Parameters with high CSS values typically indicate that there are numerous model observations (constraints) to help define a corresponding parameter values.

  For example, there were many water-level observations in the Upper Valley Fill (UVF) in some hydrographic areas. In this case, hydraulic conductivity parameters for UVF in these hydrographic areas typically had high CSS values. Another example would include the high quality of numerous spring flow measurements at Muddy Springs in the southern part of the model domain. These very large and fairly accurate spring flows provided significant constraint on model parameters defining the nature of the carbonate aquifer units from which the springs emanate.

- As the SoSWR is a reflection of the fit of the simulated values to the observed values, it represents an indicator of overall model fit. A decrease in the SoSWR was used as a general measure of improvement in model fit.

  In the CCRP model, the dominant type of model observations (model constraints) included hydraulic head observations and hydraulic-drawdown observations. Therefore, as the model was calibrated through changes to various parameters that represent the aquifer system and a better match to heads and drawdowns was achieved, the global SoSWR was reduced indicating an overall improvement to model calibration. Being dimensionless, the SoSWR is also useful for comparing observation errors of different types, such as flows and hydraulic heads. This is best illustrated by reviewing the summary of observation types and SoSWR found in SNWA (2009b, Table 6-1).

- Weighted residuals, while indicative of model fit, are dimensionless and can be less intuitive compared to unweighted residuals. Consideration of unweighted residuals is intuitively appealing because the values have the dimensions of the observations and indicate, for example, that a hydraulic head is matched to within 10 m. Unweighted residuals can, however be misleading because observations are measured with different accuracy. For the CCRP model, unweighted hydraulic-head residuals tend to be larger in areas with (1) moderate to large hydraulic gradients than in areas with flat gradients (for example, at the mountain-front and alluvial-fan interface), and (2) where surface topography varies dramatically (for example, along mountain ranges). These areas though are not always coincident. Weighted residuals demonstrate model fit relative to what is expected in the calibration based on the precision, or noise, of the data. They are less intuitively appealing because they are dimensionless quantities. A weighted residual is the product of the residual and the square root of its weight. A discussion of the weighted and unweighted residuals and their use in evaluating model fit is described in SNWA (2009b, p. 6-3 through 6-11.)

5.2 Conceptual Model Testing and Adjustment Process

The representation of the conceptual model in the numerical model was iteratively refined using a combination of trial and error and the parameter-estimation methods of UCODE_2005.

An iteration generally consisted of (1) modifying a given component of the conceptual model representation (observation weight or model construction element), (2) adjusting the component by trial and error (UCODE_2005 run with single MODFLOW-2000 simulation), and (3) performing a UCODE_2005 optimization run (UCODE_2005 run with multiple MODFLOW-2000 simulations), when the results of the trial-and-error simulations were judged reasonable.

The results of the UCODE_2005 testing analyses were used throughout the process to evaluate the state of the calibration and to make decisions about subsequent adjustments. Interactions with the Hydrology Technical Group occurred regularly during this part of the model development so that all participants could evaluate the potential changes to the model and the resulting effect of these changes on model fit. These results were used to reevaluate observation weights and to make changes to the model construction, both regionally and locally, by adjusting defined parameters or modifying aspects of model construction.

5.3 Final Parameter Estimation

During the model simulations described in SNWA (2009b, Section 5.0), the conceptual model representation in the numerical model was refined to yield a better fit of the model to the observations. At the same time, parameter estimates were improved but were not considered to all be final calibrated values. At the end of the calibration process, attempts were made to refine these estimates using the optimization capabilities of UCODE_2005. The details of these activities are provided in SNWA (2009b, Section 6.1).

6.0 MODEL EVALUATION

Section 6.0 of SNWA (2009b) presents the evaluation of the transient numerical model calibration and describes the final parameter-estimation simulations. The model evaluation approach utilized in SNWA (2009b) provides a means for assessing the relative sensitivity of estimated parameter values and other measures of parameter and prediction uncertainty.

The evaluation of the numerical model calibration includes (1) reviewing the model fit and simulated hydraulic heads and flows, (2) evaluating parameter sensitivities and parameter-estimation results, and (3) evaluating the modeling parameter values. Finally, an evaluation of the flow systems as simulated by the model is provided. This evaluation includes detailed descriptions of interbasin flow, groundwater-flow regions, and groundwater budgets. The details are based on the optimized solution obtained through model calibration using sparse data. The details of this model evaluation are described in SNWA (2009b, Section 6.0) and directly correlates to the Guidelines for effective model calibration described in by Hill (1998) and recently updated by Hill and Tiedeman (2007).

7.0 MODEL LIMITATIONS

The numerical model contains the most up-to-date representation of hydrogeologic data for the CCRP of the Great Basin region. However, it is still a model covering vast and remote regions of Nevada and Utah where data required for numerical model calibration (most importantly hydraulic-head observations, hydraulic-drawdown observations, spring-flow observations, and stream-flow observations) are limited. This lack of data inevitably leads to limitations and uncertainties in values simulated by the numerical model.

As described in other modeling studies in this region (D'Agnese et al., 1997; Belcher and Sweetkind, 2010), these limitations and uncertainties are very common for regional-scale models developed for very large expanses of the geologically and tectonically complex Great Basin. Inevitably, uncertainties are unavoidable but can be reduced through time with continued data collection and iterative model updates as development and monitoring occurs in the Project Basins.

Inherent model limitations result from uncertainty in five basic aspects of the model, including inadequacies in (1) the hydrogeologic framework, (2) the precipitation recharge, (3) the historical anthropogenic data, (4) the observations, and (5) the representation of hydrologic conditions. These limitations are described below.

7.1 Hydrogeologic Framework

Accurate simulation of many of the important flow-system characteristics depends on an accurate understanding and representation of the hydrogeologic framework. Limitations exist in the numerical model because of the difficulties inherent in the interpretation and representation of the complex geometry and spatial variability of hydrogeologic materials and structures in a hydrogeologic framework and numerical model. The hydrogeologic framework is further complicated by the lack of data within the model area.

7.1.1 Complex Geometry

Geometric complexity of hydrogeologic materials and structures is apparent throughout the model domain. Notable large-scale examples that have a significant effect on regional groundwater flow are (1) the fault system at the Muddy River Springs Area, (2) the lateral faults of the Pahranagat Shear Zone, and (3) the calderas of the Caliente Caldera complex.

A system of apparent regional-scale large transmissivity features likely provides the mechanisms for groundwater discharge at the Muddy River Springs Area. The complexity of these features is not fully known and the hydrogeologic framework represented in the model is grossly simplified because of the coarse numerical model resolution.

Regional-scale small transmissivity features associated with the Pahranagat Shear Zone contribute to a generally southward stair stepping of the regional water table. The lack of available geologic knowledge in this area adds uncertainty to the simulation of directions and quantities of groundwater flow out of Pahranagat Valley. East and northeast of the Pahranagat Valley, a series of interpreted calderas and intra-caldera intrusions cause regional discontinuities in the flow system. The complex geometries associated with these features are not fully known and cause uncertainties in simulating the regional, large-hydraulic gradient coincident with these features. Given the large size of the study area and the significant number of hydrogeologic features, it is neither practical nor possible to collect more precise geologic data to resolve these uncertainties. However, the modeling approach chosen is appropriate to evaluate regional groundwater flow and behavior for the purposes of the model.

7.1.2 Complex Spatial Variability

As with complex hydrogeologic geometries, spatial variability of material properties of the hydrogeologic units and structures is also a limitation in the CCRP model. The assumption of homogeneity within a given regional modeling unit (RMU) in the hydrogeologic framework model, or hydraulic-conductivity parameter zone in the numerical model, limits the simulation by removing the potential effects of variability in grain-size distribution, degree of welding, and fracture density and orientation. This limitation is the unavoidable result of data limitations and simplifications due to lack of understanding of the hydrogeologic framework and flow model construction and discretization techniques required to model such a large region.

The Lower Valley Fill RMU is a good example of a hydrogeologic unit that has significant spatial variability. This highly heterogeneous unit consists of (1) older Tertiary sediments, which possess varying grain-size distributions and degrees of lithification and (2) Tertiary volcanic rocks, which possess units of varying composition, degrees of welding, and hydrothermal alterations (SNWA, 2009a). These heterogeneities, which can affect hydraulic properties and consequently groundwater flow, cannot be represented accurately in the hydrogeologic framework and numerical models. In fact, many of the limitations of the simulation within the Caliente area are in part due to the underrepresentation of local-scale hydrogeologic complexities in the regional-scale hydrogeologic framework and numerical models. Those limitations notwithstanding, the modeling approach chosen is appropriate to evaluate regional groundwater flow and behavior.

7.1.3 Hydrogeologic Model Representation

Discretization and abstraction of the physical hydrogeologic framework impose limitations on all components of the hydrogeologic framework and numerical models. While the 3,281 ft (1,000 m) resolution is appropriate to represent regional-scale conditions, it presents difficulty in accurately simulating areas of geologic complexity. The grid cells tend to generalize complexities that have an impact on regional hydrologic conditions. This situation is particularly prevalent in large-hydraulic-gradient areas where sharp geologic contacts or fault characteristics can influence regional hydraulic heads and groundwater discharges. The current level of understanding of the geology throughout the model area, while state-of-the-art, is not detailed enough to warrant a higher-resolution regional flow model at this time.

7.2 Precipitation Recharge

Modeling limitations for precipitation recharge stem from the approximation methods used to estimate recharge and the assumption that the effects of both year-to-year and season-to-season precipitation variability on recharge are negligible.

Groundwater recharge cannot be measured directly in the field for areas as large as the model area. Furthermore, groundwater recharge is spatially and temporally variable. The yearly rates and spatial distribution of the mean recharge were estimated through model calibration. Although a solution was obtained in this manner, the actual annual rates and particularly the spatial distribution of recharge remain very uncertain. Another source of uncertainty is the assumption that recharge does not vary with time. This assumption constitutes an important limitation, particularly in the simulations of the groundwater development scenarios. Under this assumption, potential variations in recharge due to precipitation variability cannot be simulated. Data does not exist to aid in forecasting spatial and temporal variability in precipitation, and therefore the use of the assumption that recharge does not vary over time is necessary and appropriate for this exercise. Despite this limitation, the modeling approach chosen is appropriate to evaluate regional groundwater flow and behavior.

Precipitation variability over the course of the simulation affects groundwater recharge. However, the numerical model simulates a constant average recharge from precipitation rates averaged over 30 years (Parameter-elevation Regressions on Independent Slopes Model [PRISM] normal precipitation grid) and does not account for precipitation and recharge variability over the simulation period.

7.3 Historical Anthropogenic Data

Historical groundwater-pumping and surface-water diversion records are insufficient to develop very useful historical stress data sets for the model. In particular, there are very few continuous records of ground water pumping for any given hydrographic area in the model domain. In addition, there are no records of groundwater withdrawals of the magnitude expected to occur during the Project. Therefore, the historical anthropogenic data sets were estimated from the available information. The estimation process has important limitations leading to uncertainties in the data set.

As historical records of actual groundwater use are sparse, the consumptive water-use estimates were derived using estimates based on water-rights information obtained from the Nevada Division of Water Resources and the Utah Division of Water Rights. Reported groundwater- production or surface-water diversion data were used where available to support the estimation process.

In many of the croplands, irrigation with groundwater could not be clearly identified because irrigation water is supplied by both surface water and groundwater. In these areas, groundwater is commonly pumped to supplement surface-water sources used to irrigate crops. This adds another layer of complexity to estimating groundwater use in that supplemental groundwater pumping generally only occurs when conditions warrant it, such as in low runoff years.

7.4 Observations

Hydraulic-head and groundwater-discharge observations constrain model calibration through the parameter-estimation process; therefore, uncertainty in these observations results in uncertainty in the numerical model. Uncertainty exists in (1) the quality of the observation data, (2) the appropriateness of the hydrogeologic interpretations, and (3) the way in which the observation was represented in the numerical model. This uncertainty was minimized via thorough analysis of all available hydraulic-head observation data prior to and throughout the calibration process.

7.4.1 Quality of Observations

The sparse distribution and high concentration, or clustering, of hydraulic-head observations are numerical model limitations. Because available data in the overall region are scarce and available multiple observations in isolated areas are overemphasized, biasing occurs in those parts of the model. Water-level-data scarcity is particularly noticeable in Long, Jakes, Coal, Garden, Dry Lake, and Delamar valleys and Lower Meadow Valley Wash because of the lack of wells in those valleys. High clustering of observations occurs along riparian areas of Pahranagat Wash, Meadow Valley Wash, and the Muddy River. Given the vast area of the model, it is not practical or possible to obtain more precise water-level data to resolve this issue, nor is it necessary to do so for the purposes of this modeling effort. A declustering method was used to address this situation; however, this declustering only applies to situations where multiple water levels occur in a given model cell (SNWA, 2009b, Section 4.7.3, p. 4-82).

7.4.2 Interpretation of Observations

It is difficult to determine whether hydraulic-head observations represent regional versus perched or localized conditions. Field testing is often not sufficient to distinguish conclusively between regional or localized conditions. The data necessary to determine unequivocally the presence of perched or local groundwater are rarely, if ever, available. Because large simulated hydraulic-head residuals in recharge areas often suggest the possibility of perched water, either the hydraulic-head observations in this category were removed or the observation weight was decreased. Fewer observations, or observations with lower weights, result in higher uncertainty in the numerical model.

Large-hydraulic-gradient areas also are difficult to interpret. Limited water-level data in these areas exacerbate the situation. Hydraulic-head observations defining large hydraulic gradients are also typically associated with perched or localized water.

The model also does not account for precipitation variability over the course of the simulation. The majority of wells that show possible water level changes due to precipitation variability (85 out of 112) occur in isolated geographic locations within Steptoe Valley and occur within a 10-year time period of an extremely wet cycle in the region. This limited precipitation variability data could not be reasonably extrapolated to the remaining wells (1,751) due to differences in location and precipitation. As a result, the weight (or the relevance) of these observations as model constraints was reduced (SNWA, 2009b, p. 7-4).

Accurate groundwater-discharge estimates for many of the springs and ET areas do not exist and are thus numerical model limitations. Collection of higher quality, spatially distributed, groundwater-discharge observations began only as recently as 2002 (SNWA, 2008; 2009a; Welch et al., 2007). The lack of long-term, high quality estimates of ET rates (and the variability of these rates) significantly limits the ability of the model to simulate these groundwater-discharge areas accurately. In addition, using estimates of present day groundwater discharge to approximate predevelopment groundwater discharge also is a model limitation. The lack of historical groundwater-discharge estimates is an unrecoverable data gap that adds uncertainty to any groundwater flow simulation of this region.

7.4.3 Representation of Observations

Although the volumetric discharge from ET per basin is reasonably matched, the model does not accurately simulate the specific areas where ET occurs. This is due to the limitations associated with the representation of groundwater ET areas in the model, including the coarse resolution of the model and the representation of ET areas using hydraulic-head dependent boundaries known as drains.

Simulating small discharge volumes less than 296 afy (less than 1,000 m^3/d) was difficult in the CCRP numerical model. For instance, incised drainages and other focused discharge areas are difficult to simulate accurately. This difficulty is particularly noticeable along Meadow Valley Wash and Pahranagat Wash. In many cases, the hydraulic conductivity of the hydrogeologic units present at the land surface and the geometry of these topographic features control the simulated discharge.

The elevations assigned to numerical model cells that contain ET also affect the ability to simulate groundwater conditions more accurately. The elevations in ET cells were set to values of land-surface elevation reduced by one of two values of extinction depth depending on location. The values of land-surface elevation were based on a 1:24,000-scale digital elevation model, and the extinction depth values were set to either 16.4 ft (5 m bgs) or 32.8 ft (10 m bgs). This simplified method of representing ET cell elevations does not accurately approximate extinction depth for all discharge areas, particularly in areas with highly variable rooting depths and discontinuous areas of capillary fringe. Snake Valley is an example of a discharge area that may have a zone of extensive capillary fringe. In areas of the model where these conditions exist, observed hydraulic heads may be lower than the ET cell elevations. The consequence is that the numerical model has difficulty simulating groundwater discharge within the delineated ET areas.

In summary, in several cases, the distribution of ET is not simulated accurately; however, the total ET from a given ET area matches estimates well. This limitation will cause simulated drawdowns to propagate faster between the basin edge and simulated ET areas until ET is captured due to decline in the water table. Errors in ET simulation minimally affect drawdown propagation after ET capture starts because simulated discharge volumes are approximately correct.

7.5 Hydrologic Conditions Representation

The hydrologic conditions that, perhaps, most influence the CCRP numerical model are the representation of external and internal boundary conditions. Limitations in external-boundary condition definition are the result of both incomplete understanding of natural conditions and associated poor representation of the natural conditions in the numerical model. Because very little data exist in the areas defined as lateral flow-system boundaries, the boundaries are highly uncertain. Also, defining these boundaries in the numerical model is effectively limited to either a no-flow or a constant-head boundary. Both types of boundary definitions impose significant constraints on model results. Given the vast area of the model, it is neither practicable nor possible to obtain information allowing precise definition of boundary conditions. However, the modeling approach chosen is appropriate to evaluate regional groundwater flow.

In summary, the described model limitations are predominantly inherent and unavoidable.

8.0 ADHERENCE TO GUIDELINES FOR EFFECTIVE MODEL DEVELOPMENT AND CALIBRATION (HILL, 1998)

Ideally, a groundwater model is constructed and the data for that model are collected with the purpose of the model in mind, with the evolving model used to guide additional data collection efforts. However, in three-dimensional, transient groundwater models like the CCRP model, the evolution of the conceptual model over time can be significant with numerous changes and refinements as a model is calibrated and a better understanding about the groundwater system's potential behavior is reached. In addition, new data may challenge the previous conceptual model, as well as change the parameter values optimized during the original calibration.

To ensure that a reasonably accurate groundwater model is developed and subsequently used to make predictions about groundwater system behavior and to guide new data collection, Hill (1998) and Hill and Tiedeman (2007) developed methods and guidelines in the form of steps by which available data can be used to develop a model that is as accurate as possible. Once a reasonable model is developed, its quality may be assessed by again utilizing previously considered guidelines. Thus, the guidelines are not intended to be sequential and may be repeated many times during model calibration.

As stated above (Section 2.0), the CCRP model was developed by generally following these 14 guidelines. The relevant guidelines were applied to all stages of development of the CCRP model. In the discussion below, descriptions of the Guidelines are largely cited from Hill (1998) in an effort to clearly describe each guideline and illustrate how it was applied in the CCRP model calibration.

8.1 Guideline 1: Apply the Principle of Parsimony

Using the principle of parsimony, a groundwater model is kept as simple as possible while still accounting for the system processes and characteristics evident in the observations and while respecting other information about the system. In many fields, including groundwater hydrology, the known complexities of the systems being simulated often seem overwhelming, and being parsimonious in model development can require substantial restraint.

It was important to apply the principle of parsimony to various aspects of the CCRP model construction and calibration. In the development of the CCRP model, it was important to investigate the processes and characteristics that were likely to be most dominant first and add processes or complexity gradually, always testing the importance of the added complexity to the model observations. For example, in the CCRP model, significantly fewer regional modeling units were represented in the initial model runs, with additional RMUs added through out the calibration. Likewise, initial model runs utilized very simplified representations of groundwater recharge with more complexity added to represent recharge processes as the calibration proceeded and model fit improved.

Strict adherence to this guideline occurred throughout the CCRP model calibration.

8.2 Guideline 2: Use a Broad Range of Information to Constrain the Problem

Effective groundwater models must utilize a broad range of hydrogeologic information to accurately represent the system they simulate.

For example, if a groundwater model is to have any credibility, it must respect what is known about the hydrology and hydrogeology of a groundwater system. In the case of the CCRP model, a very complex conceptual model was developed and described in SNWA (2009a). Representing as many of the hydrogeologic characteristics described in the conceptual model report as possible was a key objective of the CCRP modeling exercise. Also utilizing the many groundwater flow system observations described in the conceptual model report to constrain the CCRP model calibration was critical. Observations used to constrain the CCRP model included hydraulic-head, hydraulic-drawdown, spring-head, groundwater ET, spring-flow, spring-flow change, and stream-flow observations.

Strict adherence to this guideline occurred throughout the CCRP model calibration. The details of how conceptual model features were incorporated into the model are described in Section 4.0 of SNWA (2009b).

8.3 Guideline 3: Maintain a Well-Posed, Comprehensive Regression problem

A well-posed regression problem is one that will converge to an optimal set of parameter values given reasonable starting parameter values. Given commonly available data, the requirement of maintaining a well-posed regression produces rather simple models with relatively few estimated parameters. However, the best regression results are typically derived when very simple models are created. In a hydrogeologically complex region like the Great Basin there is a challenge to determine the greatest possible level of model complexity while still maintaining a well-posed regression.

During the calibration of the CCRP model, hydrologic and hydrogeologic information, and CSS and parameter correlation coefficients were continually reviewed to assist in parameter definition and to determine if additional model features were justified given the model observation data. For example, many hydraulic barriers (representing faults) were added to better represent large hydraulic gradients and spring flows in areas where hydraulic observations and hydrogeologic understanding supported the addition of this detail.

CSS and parameter correlation coefficients were well suited for this purpose in the CCRP model calibration because they depend only on the sensitivities and are independent of the actual values observed. For example, in the CCRP model, if some parameters had CSS that were less than about 0.01 times the largest composite scaled sensitivity, the regression had difficulty converging on an optimal parameter value. In addition, if pairs of parameters had a large correlation coefficient this was typically an indication that each of these parameters influenced the other, and that only one could be estimated at a time. In these cases, one of the parameters was removed from the estimation process. This often occurred in groundwater recharge areas where the net recharge is correlated to the hydraulic conductivity of the rock unit into which it recharges.

This guideline was used throughout calibration to evaluate continually which parameters had sufficient sensitivity to be estimated through auto-calibration methods. It was also used to determine if model parameters needed to be combined. Ultimately, the parameters that had sufficient observations to constrain their estimation were utilized in the final model runs to derive optimal parameter values. A detailed discussion of this exercise is presented in SNWA (2009b) in Section 6.2.

8.4 Guideline 4: Include Many Kinds of Data as Observations in the Regression

Guideline 4 stresses the importance of using as many kinds of observations as possible. For example, in the CCRP groundwater model, it was very important to augment the available hydraulic-head observations with numerous flow observations. The latter served to constrain the model solution much more than the relatively easy to fit hydraulic heads and, therefore, using observations that reflected the rate of groundwater flow out of the model at a specific location promoted the development of a more accurate model.

In the CCRP model, 2,707 hydraulic-head observations, 4,301 hydraulic-drawdown observations, 126 groundwater ET discharge observations, 44 steady-state spring flow observations, 27 transient spring flow change observations, 16 model flow boundary observations, and 144 spring or stream flow observations were utilized to constrain the model calibration. In addition, the hydraulic head at selected spring locations and estimated interbasin flows were tracked during calibration as an additional check on the validity of model results.

8.5 Guideline 5: Use of Prior Information

In groundwater models, “prior information” is a term that typically refers to direct measurements that can be made in the field that are directly transferable to the numerical model as input values. An example of this would be a field measurement of hydraulic conductivity that could be directly transferred to the numerical model. There were no appropriately-scaled direct measurements of this kind available for the CCRP model. As a result, “prior information” was not utilized.

8.6 Guideline 6: Assign Observation Weights that Reflect Measurement Errors

Assigning appropriate observation weights is an important component of auto-calibration by non-linear regression. Model observation weights ultimately constrain the model calibration. In general, relatively accurate water levels or spring flows that are used as observations are weighted more heavily than relatively inaccurate measurements. A comprehensive analysis was conducted as part of the CCRP model exercise to calculate appropriate observation weights that reflect measurement error. This analysis can be found in SNWA (2009b, Appendix B).

8.7 Guideline 7: Encourage Convergence by Making the Model More Accurate

Nonlinear regression models of complex systems often have difficulty converging on an optimal solution. In general, convergence is improved as the model becomes a better representation of the system that produced the observations being matched by the regression, so that the goal of achieving convergence and a valid regression and the goal of model calibration generally are identical. Substantial insight about the model can be obtained by using the information available from unconverged regressions, such as dimensionless and scaled sensitivities, CSS, parameter correlation coefficients, weighted and unweighted residuals, and parameter updates calculated by the regression. This information can be used to evaluate the parameters, observations, and fit of the existing model, and to detect inaccuracies in model construction.

During calibration of the CCRP model, modifications were continually made based on these types of results analysis including estimating fewer parameters, modifying the defined parameters, modifying other aspects of model construction, and/or including additional data as observations in the regression. A detailed description of these activities are described in Sections 5.0 and 6.0 of SNWA (2009b).

8.8 Guideline 8: Evaluate Model Fit

The most basic attribute of nonlinear regression methods is that, given a well-posed problem, parameter values are calculated that produce the best fit between simulated and observed values. The model can then be evaluated without wondering whether a different set of parameter values would be better.

Two common problems are strong indicators of model error: (1) the model does a poor job of matching observations, and (2) the optimized parameter values are unrealistic and confidence intervals on the optimized values do not include reasonable values. The first is discussed here under Guideline 8; the second indicator is discussed under Guideline 9.

Weighted residuals are good indicators of model fit but, being dimensionless, can be confusing to interpret. To present model fit more clearly, it is useful to review maps of unweighted residuals. Both of these methods are utilized in the CCRP model evaluation and described in Section 6.0 of SNWA (2009b).

8.9 Guideline 9: Evaluate Optimized Parameter Values

An evaluation of optimized parameter values may be conducted by comparing the optimized values and their confidence intervals with independent information about the parameter values. The independent information may include ranges of expected values, and (or) a relative ordering of values. For the CCRP model, this is described in Section 6.3 (SNWA, 2009b). Parameter values that are evaluated include hydraulic conductivities, storage, and recharge. Each of these appear to have estimated or optimized values that fit reasonably with independent information for the region.

8.10 Guideline 10: Test Alternative Models

In most groundwater models, there is more than one possible representation of the system involved, and this guideline encourages testing as many alternative models as feasible. Such testing is a viable alternative when inverse modeling is used. Models that are more likely to be accurate tend to have three attributes: better fit, weighted residuals that are more randomly distributed, and more realistic optimal parameter values. For the CCRP model, alternative final parameter optimization runs were conducted to determine if different configurations of parameters would yield a better fit or more realistic optimized parameter values. These model runs, are described in Section 6.2 in SNWA (2009b). In addition, the Hydrology Technical Group provided several alternative models to evaluate related to (1) the role of faults as conduits and barriers to groundwater flow, and (2) the possibility of variations in specific yield.

8.11 Guideline 11: Evaluate Potential New Data

Potentially new data may be evaluated to test specific aspects of the model. In the case of the CCRP model, observation data on hydraulic heads and spring flows collected after 2004, which marks the end of the transient calibration period, were evaluated on an ad hoc basis to test if the model results were consistent with these data. In regard to additional hydraulic head and spring flow data, model results were consistent with these additional available data.

8.12 Guideline 12: Evaluate the Potential For Additional Estimated Parameters

At any stage of model calibration, CSS can be analyzed as described in Guideline 3 to determine if the available data are likely to support additional detail in representing the system characteristics associated with the defined parameters. Parameters with large composite-scaled sensitivities can be subdivided in ways that are consistent with other data, such as geologic and hydrogeologic data in groundwater problems. The new set of defined parameters can then be evaluated using the methods of Guideline 3, and regression pursued if warranted. As described above under Guideline 3, this was conducted throughout the model calibration effort.

8.13 Guideline 13: Use Confidence and Prediction Intervals to Indicate Parameter and Prediction Uncertainty

Confidence intervals can be calculated and presented in graph form to illustrate the uncertainty of estimated parameter values or prediction results. In the CCRP model, 95 percent linear confidence intervals were calculated for optimized parameters and shown in Table 6-8 on page 6-49 of SNWA (2009b). In addition, a series of graphs are illustrated in Figures 6-43 through 6-49 that show the ranges of unestimated hydraulic conductivity parameter values resulting from model calibration. In most cases, the hydraulic conductivity values fall predominantly within the measured data for hydraulic properties described in the Conceptual Model Report (SNWA, 2009a).

8.14 Guideline 14: Formally Reconsider the Model Calibration from the Perspective of Predictions

It is important to evaluate the model relative to predictions throughout model calibration. For reasonably accurate models, it also is useful to consider the predictions more formally. In the CCRP modeling process, the Hydrology Technical Group provided a series of model sensitivity and uncertainty analyses to assess the change in model predictions resulting from a change in the hydraulic diffusivity of key regional modeling units within the model.

9.0 OVERALL QUALITY OF THE MODEL

The model is suitable for the purpose of environmental analysis in the region. The model uses the best available science and contains the most up-to-date representation of hydrogeologic data for this part of the Great Basin. The model fits actual field observations well. Inevitably, model uncertainties are unavoidable but can be reduced through time with continued data collection and iterative model updates as development and monitoring occurs in the Project Basins (Prieur, 2011; Watrus and Drici, 2011). The model was, and will continue to be, calibrated and evaluated using state-of-the-art methods. This, and the strict adherence to the methods and guidelines provided by Hill (1998), illustrates that ultimately, the CCRP model is a very good representation of the flow system at the regional scale. Therefore, this numerical model achieves the primary objective of the CCRP modeling exercise, which is to simulate potential drawdowns from groundwater withdrawals from the Project Basins.

10.0 DEFINITIONS OF TERMS

Regional, Intermediate, and Local Groundwater Flow Systems – Most groundwater flow systems develop into catchments of varying scales and inter-relationships. There are combinations of groundwater flow systems that are local, intermediate or regional in scale in the Great Basin. Local flow systems are the shallowest and most dynamic, involving short flow paths (mostly <5 km) with groundwater discharging to the nearest lowland feature. In contrast, regional flow systems have the deepest and longest flow paths (typically exceeding 50 km), with intermediate systems operating between these two end-members. Local flow systems tend to be dominant in areas of high topographic relief, while intermediate-regional systems are more evident in flat-lying areas. Groundwater exchange with surface water features are primarily governed by their location with respect to groundwater flow systems, the geological characteristics of their beds and climatic factors. River reaches, ET areas, and springs can receive contributions of groundwater from flow systems of all scales. All three systems are typically connected and may have coincident recharge and discharge areas.

Perched Groundwater Flow System – A relatively small catchment flow system relative to local groundwater flow systems that is completely disconnected from the larger regional, intermediate, or local flow systems.

Parameter Estimation – A formal method of groundwater model calibration that calculates a model parameter value given some mathematically described process and a set of relevant observations.

Optimized Parameter Values – Groundwater model parameters are said to be “optimal” or “optimized” when the parameter values estimated using auto-calibration through non-linear regression result in an objective function that has a minimal solution.

Deterministic Models – Deterministic models are groundwater models that are process based. These models try to represent the physical processes observed in the real world. Typically, such models contain representations of surface runoff, subsurface flow, ET, and channel flow, but they can be far more complicated.

Stochastic Models – Stochastic Models are typically referred to as “black-box” models that are based on data and using mathematical and statistical concepts to link a certain input (for instance rainfall) to the model output (for instance runoff). Stochastic models do not typically attempt to represent cause-effect relationships in natural processes.

Dimensionless Scaled Sensitivities – Are calculated during auto-calibration using a nonlinear regression and can be used to compare the importance of different observations to the estimation of a single parameter. Observations with large dimensionless scaled sensitivities are likely to produce more information about a given parameter compared to observations associated with small dimensionless scaled sensitivities.

Composite Scaled Sensitivities (CSS) – Reflect the total amount of information provided by the observations for the estimation of one parameter. They are calculated for each parameter using dimensionless scaled sensitivities and can be calculated for some or all observations.

Sum of Squared Weighted Residuals (SoSWR) – The sum of all squared weighted residuals calculated during a model parameter-estimation run. This number generally decreases as the global model fit is improved during calibration.

Weighted Residuals – Represent the fit of the regression in the context of the expected accuracy of the observation. Observations that are believed to be less accurate are de-emphasized when weighted residuals are considered.

Unweighted Residual – Represents the difference of the simulated and the observed observation value.

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