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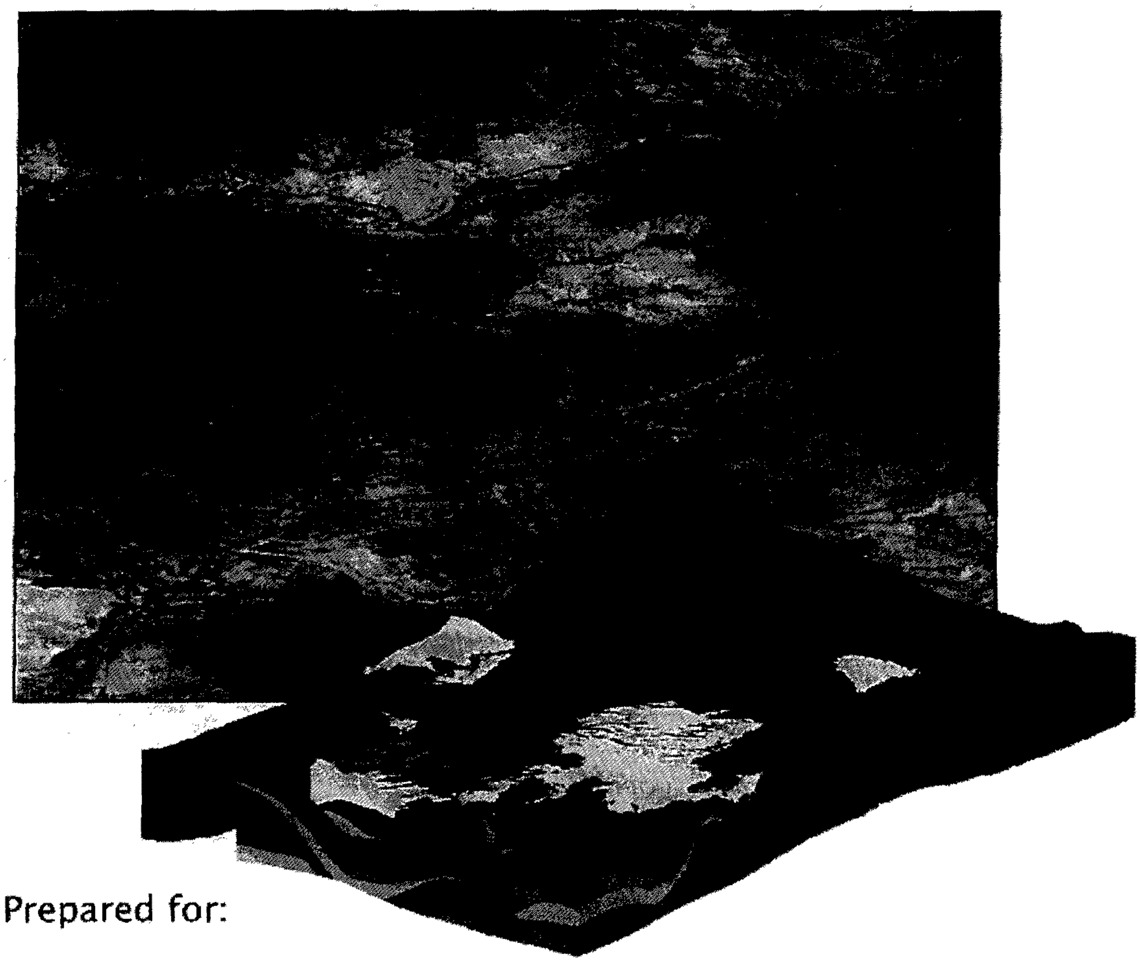
Report on Santa Fe County Model Development and Regional Aquifer Evaluation



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- Andy Core and Jack Frost of the Office of the State Engineer,
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- Doug Sawyer, Tien Grauch, Scott Minor, Brian Rodriguez, Mark Hudson of United States Geological Survey, and
- Gary Smith, University of New Mexico.

It is our sincerest hope that our colleagues will find this report useful and in this way we can in some measure repay them.

In addition, as discussed further in this report, our model was built in collaboration with the City of Santa Fe and their contractor, Camp, Dresser and McKee. We are grateful for their experience and input to the development process.

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ACRONYMS AND ABBREVIATIONS

CDM	Camp, Dresser, and McKee
City	City of Santa Fe
County	Santa Fe County
DBS&A	Daniel B. Stephens & Associates
DSS	decision support system
EBTAG	Española Basin Technical Advisory Group
ET	evapotranspiration
EV	Estancia Valley (aquifer system)
ft/d	foot (feet) per day
ft/yr	foot (feet) per year
GHB	general head boundary
GIS	geographic information system
GMS	Ground water Modeling System
GUI	graphical user interface
H^*	composite simulated head (hydraulic)
HFB	hydrologic flow barrier
hm	measured heads (hydraulic)
hs	simulated heads (hydraulic)
HSU	hydrostratigraphic unit
INTERA	INTERA Incorporated
LANL	Los Alamos National Laboratory
Ma	million years before present
MD	mean difference
ME	mean error
MSFC	Mid Santa Fe County (aquifer system)
NMBGMR	New Mexico Bureau of Geology and Mineral Resources
NSFC	North Santa Fe County (aquifer system)
OSE	Office of the State Engineer
ppm	parts per million
PWWS	public water supply system
RMSE	root mean square error
SFCM	Santa Fe County Model
SNOTEL	snowpack telemetry
URGWOM	Upper Rio Grande Water Operations Model
USGS	U.S. Geological Survey

relevant to this study. However, none of the models provide the coverage required for the County's needs.

Development of the hydrogeologic conceptual model involved compilation of data from numerous sources which are detailed in INTERA 2005. A variety of recent and valuable data sets has become available for use in modeling of both surface and subsurface geology in the study area. As a basis for the parameterization of the numerical flow model, a three-dimensional geologic model was assembled. The representative geologic section developed for the geologic model was based on an evaluation of the detailed regional stratigraphy, and hydraulic properties both measured and inferred. The initial task for development of the geologic model was to correlate the many geologic columns available from quadrangles and cross-sections to a consistent geologic column that was used in model development. Interpretations of geologic contacts (elevations) based on this geologic column were then used to develop model geologic unit structure contours and isopachs. Using these horizontal two-dimensional datasets, vertical cross sections are constructed for incorporation into a three-dimensional solid geologic model for the region. The hydrostratigraphic units (HSUs) incorporated into the geologic model include: Quarternary alluvium and Ancha Formation; Tertiary Cerros del Rio Formation, Rio Grande Axial Deposits, Tesuque Formation, Espinaso Formation, and undifferentiated intrusives; Cretaceous Mesa Verde Group and Mancos Formation; Jurassic Morrison Formation and Entrada Sandstone; Triassic Chinle Formation; Permian undifferentiated sediments, Sandia/Sangre de Cristo Formation; Pennsylvanian Madera; and Precambrian crystalline rocks.

A database of measured hydraulic properties in the model region was developed from numerous public and private sources. The largest collection of hydraulic test results was found in Johnson et al. (2004), which provides approximately 200 transmissivity measurements from wells within the region compiled into a consistent database. INTERA performed a review of the available literature for development of properties in portions of the basin not covered by Johnson et al. (2004). Once the geologic model and hydraulic property database was developed, the hydrogeologic model was intersected with the model grid to define which HSUs are resident in each model grid. Hydraulic properties are then defined at the HSU scale. Then, composite properties are developed based on HSU properties and the relative juxtapositions and proportions of each HSU in each model cell.

Historical and present-day water-level data were collected from a variety of sources. In addition, historical water-level data was used to estimate a "pre-development" head surface for the water table. Pre-development water-level data was primarily taken from Spiegel and Baldwin (1963), Mourant (1980), and Johnson et al. (2004). Johnson et al. (2004), the U.S. Geological Survey (USGS) Ground water Site Inventory database for wells not included in the Johnson et al. (2004) database, and the OSE database were used for historical water level data. CDM (2002) provided data for the Buckman well field, and Shomaker (2001) data was used for the El Dorado production wells for pump-off measurement. In the model domain, the database has 702 wells that have at least one head measurement within the collective period of record from April 1945 through November of 2004. The well with the longest period of record runs is the Old Hickox well, with runs from August 1946 through May 2003. The well with the greatest number of time series measurements is the Alto well, with 765 measurements from 1954 through 2001.

To evaluate the SFCM flow balance, estimates of predevelopment inflows and outflows were used to conceptualize the predevelopment ground water flow balance, or the steady state condition, of the model region. To develop the flow balance, studies on recharge and stream and spring discharge were reviewed. Conceptual models for these processes of recharge and discharge were documented along with the available calibration targets. The steady state flow-balance is provided in the following table. This conceptual flow balance was developed to provide guidance as a soft calibration target and to provide an understanding of large-scale basin hydrology.

Steady-State Conceptual Ground water Flow Balance for the Model Region

Flow Component	Flow Estimate (AFY)	Flow Percent
Areal Recharge	7,000	16%
Mountain Front Recharge	30,000	67%
Stream Loss	5,000	11%
Subsurface Boundary Flows	3,000	7%
Net Inflow	45,000	100%
Stream/Spring Gains(ET)	33,000	73%
Rio Grande	24,000	53%
ET	11,000	24%
Subsurface Boundary Flows	1,000	2%
Net Outflow	45,000	100%

After development, natural aquifer discharge is augmented by discharge from pumping. Domestic and municipal pumping were approximately equal in the late 1940s at about 800 ac-ft/yr each. Pumping has increased significantly since that time to greater than 25,000 ac-ft/yr in 2004, by which time domestic pumping had increased to 3,199 ac-ft/yr. Municipal pumping peaked in 2002 at 15,110 ac-ft/yr. Other types of pumping include community water systems and irrigation wells which made up another 5,000 to 6,000 ac-ft/yr by 2004. Pumping was simulated using the Multi-Node Well Package to address the issues related to multi-aquifer completions.

The SFCM was calibrated to steady-state conditions comparing simulated to observed heads for 184 observation wells and comparing stream gain loss. The model compared well to observed heads in the basin. The steady-state model probably over-estimates stream gains although there is significant uncertainty in stream-aquifer interactions in the basin today and certainly in predevelopment times. The steady-state model slightly over-predicts model heads. This high bias in residuals was accepted given the fact that we were using theoretically unaffected post-development head targets to represent predevelopment conditions. The model was also simulated across a historical transient period from 1947 through 2004. The model was not calibrated to transient conditions but was just run in the transient model. A review of model residuals and well hydrographs show that the model performs reasonably well in the transient mode but there are some issues which require revision.

A Decision Support System based on a site suitability analysis was developed to identify promising areas for supply-well sites based on a variety of criteria including the location of existing supply wells, streams, springs, existing infrastructure, and population centers, as well as areas of favorable geology. Once four potential well locations were selected, the model was used to simulate a pumping well at each location. Each hypothetical well was pumped at 100 ac-ft/yr (approximately 60 gpm) for 40 years, and the potential pumping effect was evaluated against three metrics: (1) drawdown at the nearest supply well, (2) spring depletion, and (3) stream depletion.

The transient model was used as one component to provide a relative measure of potential impacts of each potential well site to surrounding environs. While the model provided a useful means for integrating hydrogeologic data collected to date and assessing potential impacts, the model as it stands currently is exploratory in nature and will require further work to be considered a reliable predictive tool. For this reason, our method for determining potential well sites was heavily weighted in geology and other physical constraints.

The limitations of the model are summarized as follows:

- The SFCM attempts to model complex geologic environments where limited hydraulic parameters are available.
- The SFCM, as well as many other models in the area, assumed that areal recharge occurs across the entire model domain. This is an assumption which requires additional consideration.
- The SFCM, as well as all other models in the basin, assume that hydraulic conductivity decreases with depth of burial. The depth decay constant is a very sensitive parameter for steady-state model calibration but cannot be uniquely determined through calibration. The implementation of this parameter requires additional investigation in model revisions.
- The SFCM extends to significant depth throughout the model domain because it was based upon a complete geologic model. The geology and physical properties within the model are poorly understood below a depth of 2000 feet and the accuracy of the model must be considered highly uncertain below these depths.

The SFCM as currently documented in this report, provides a good initial model for the region of interest to the County. The conclusions reached using this model are considered preliminary because of the issues related to data gaps and calibration described above. Recommendations for necessary improvements to this model include:

- Further analysis and refinement of boundary conditions in the southwestern part of the model,
- Further refinement of the geologic model in the Galisteo Basin area of the model as well as the locations optimal for well siting as described in Section 10.0 of this report.
- Refinement of the approach to mountain front and areal recharge implementation.
- Refinement, and perhaps redevelopment, of the MODFLOW stream formulation for stream reaches which are currently out of calibration with known or inferred gain/loss estimates.
- Completion of transient calibration once conceptual issues such as boundary implementation and recharge are satisfied through calibration of the steady-state model. A transient sensitivity analysis should also be performed.

1.0 INTRODUCTION

INTERA Incorporated (INTERA) was retained by Santa Fe County (the County) to perform a Geohydrologic Study and Regional Aquifer Evaluation under contract number 25-104-UT, dated January 25, 2005. The main objective of the study is to determine potential water supply well locations that will have minimal environmental impacts for future water resource development in the County. A key aspect of the study is development of a model of ground water flow in the County which can be used to evaluate potential water supply well locations for future exploration boreholes and ground water resource development.

This study focuses the search for potential ground water resources within the County in areas east of the Rio Grande, west of the Sangre de Cristo Mountains, and north of the Estancia Basin. These areas include a geologically and hydrogeologically complex region south of the Santa Fe River and north of Galisteo Creek. Figure 1-1 illustrates the project area. Development of the Santa Fe County Model (SFCM) provided the framework for this water resources evaluation and a tool for future use by the County as it endeavors to develop its conjunctive water resource management strategy.

INTERA and the County collaborated with the City of Santa Fe (the City) and their consultants, Camp, Dresser, and McKee (CDM) in the model-development phase of this study. In early 2005, the City began a new model development effort aimed at updating the CDM (2002) model. It was decided in early 2005 that the City and the County would join forces and collaborate on the development of a new regional model. The model development phase of this project is documented in Sections 2.0 through 7.0 of this report. Due to differences in City and County objectives and schedules, INTERA completed the first version of the model described in this report (hereafter referred to as the Santa Fe County Model (SFCM)) in order to evaluate specific well locations in a time frame important to the County. The SFCM model completion and application are described in Sections 9.0 through 11.0 of this report. The SFCM has been provided to the City and CDM and it is anticipated that additional improvements will be made and provided to the County; however, the time frame for this phase of the project is unknown.

There have been two earlier reports produced for the County which provide important background information. The *Final Report on Data and Model Evaluation for the Santa Fe County Regional Aquifer Evaluation* was completed in June 2005 (INTERA, 2005). A summary of this Report is provided in Section 1.1. The *Final Report on Model Construction for the Santa Fe County Regional Aquifer Evaluation* was completed in December 2005 (INTERA, 2005a). A summary of this report is provided in Section 1.2

1.1 Data and Model Evaluation Report – June 2005

The Data and Model Evaluation Report (INTERA, 2005) was completed on June 10, 2005, as a first requirement under INTERA's scope of services with the County. There were two main objectives for completion of this report (1) Evaluate existing data and provide a summary of reliable data and data sources to be used in development of the conceptual hydrogeologic framework to be incorporated into the construction of SFCM and (2) Evaluate existing models for the area and recommend a model for the County. Pertinent information from this report, as well as new information obtained since its completion, is provided in Sections 2.0, 4.0, and 5.0.

1.2 Model Construction Report – December 2005

The Model Construction report (INTERA, 2005a) was completed on December 30, 2005 as a second requirement under INTERA's scope of services with the County. The main objective of this report was to describe in detail the outcome of the SFCM model construction. This report provides the initial documentation of the following model attributes:

- Domain
- Layering
- Hydraulic Properties
- Lateral Boundary Conditions
- Areal Recharge, and
- Pumping.

In addition this report provides a snapshot of model construction and implementation at the beginning of calibration. Many of the parameters, such as properties, boundaries, and recharge have been modified in the calibration phase of the model development. This updated information is provided in Section 6.0 of this report.

The material presented in the Model Construction Report was developed through technical discussions and, in some cases, compromise between the County and the City and their respective consultants.

1.3 Model Limitations

The County's first objective for use of the model described in this report was to evaluate potential well locations for future water resource development. The County's schedule to complete this initial study was initially September 2005. After the initiation of this project the County and City agreed to collaborate on the development and calibration of this model and also agreed to extend the schedule to December 2005.

The development and calibration of a three-dimensional regional-scale model is a significant task best executed by a dedicated project team able to identify and quickly respond to challenges that arise during the project. The collaboration between INTERA staff, County staff, City staff and CDM staff during this project, while useful for providing a mutually agreeable technical basis for the data, model configuration and calibration goals, did not enable the County and INTERA to achieve all the calibration goals identified early in the project. This was principally due to differences in City and County objectives and schedules as well as the inherent inefficiency in collaborating during model development and calibration with participants located in different states. For example, significant time was spent simply developing an approach for collaborative model development which pushed the actual model development and calibration closer toward the February 2006 deadline. Therefore, the first version of the model described in this report (hereafter referred to as the Santa Fe County Model (SFCM)) is an interim model which can and should be improved upon. Recommendations for necessary improvements to the SFCM are provided in Section 11.0. The SFCM has been provided to the City and CDM and it is anticipated that additional improvements will be made and provided to the County; however, the time frame for this phase of the project is unknown.

2.0 STUDY AND MODEL DOMAIN

The County seeks to expand its water supply through the sustainable development of County water resources. It is in the County's best interest to develop new ground water resources in regions of the County that will cost-effectively provide resources and minimize potential conflicts. Implicit in the County's water-resource development goals is minimal impact to regions currently impacted by, experiencing conflict as a result of, or sensitive to ground water discharge.

The full SFCM domain is illustrated on Figure 2-1. On the western, northern, and eastern boundaries, the active SFCM domain is similar in extent to the CDM (2002) model. The extent of the SFCM active domain on the southern boundary, however, is significantly greater than the extent in previous models, including the Shomaker et al. (2001) model, which limited the southern extent of the active model domain to the boundary of the Española Basin. Because INTERA identified several small public water supply systems (PWSSs) located south of Galisteo Creek in the Galisteo Basin, INTERA extended the domain boundary to include these PWSSs.

As extended by INTERA, the southern boundary of the SFCM model domain approximately follows the southern boundary of the Middle Santa Fe County (MSFC) aquifer system, a boundary drawn roughly between the quaternary alluvium of the Galisteo Formation and the Tertiary Chinle Group intrusives of the Mancos Formation (Lewis and West, 1995). At its southeastern corner, the SFCM active domain boundary follows an outcrop of Precambrian rocks associated with the Sangre de Cristo uplift. Extension of the model domain to include the Chinle Group was rejected for two reasons: 1) the group is behind a source of mountain-front recharge and 2) inclusion would have added tens of hydrostratigraphic columns to the model, resulting in a significant increase in model overhead.

The northern extent of the SFCM active domain excludes the northern Estancia Basin, a region INTERA assumed the County would not require to be hydrogeologically assessed by the SFCM. The eastern extent of the model domain also excludes an area that extends north into Cañoncito/Apache Canyon. INTERA determined this area to be characterized by poor hydrologic potential (it is located east of one of the major mountain-front recharge boundaries in the SFCM active domain; yield from an exploratory well drilled within the area in 1997 was 8 gallons per minute [gpm]) (GGI, 1997) and by geologic and structural complexity that would have been very difficult to capture within the scale of the SFCM. Among the structural and geological complexities INTERA identified for this area are its geologic age (Precambrian, Pennsylvanian/Permian, Triassic, and Quaternary) and its unpredictable and apparently structurally-controlled well yields (possibly affected secondary porosity from faulting). Should future County evaluation of ground water resources require assessment of the northern region excluded from the SFCM model, INTERA recommends use of the New Mexico Office of the State Engineer (OSE) model for the Estancia Basin.

The geologic features of the SFCM active domain are discussed further in Section 4.0.

3.0 REVIEW OF EXISTING MODELS

To develop the SFCM, INTERA reviewed several hydrologic models developed for the Española Basin. This section presents the major attributes of each model INTERA reviewed and INTERA's assessment of the relevance of the model to the SFCM and the evaluation of County ground water resources. With three exceptions, McAda and Wasiolek (1988), Core (1996), and Shomaker et al. (2001), the basis for INTERA model review was written model documentation rather than model input.

3.1 Summary of Available Models

The following hydrologic models of the Española Basin were available for INTERA review during development of the SFCM and assessment of County ground water resources:

- Hearne (1985)
- McAda and Wasiolek (1988)
- Frenzel (1995)
- Core (1996)
- Barroll and Logan (1998)
- Keating et al., (2002)
- Shomaker et al. (2001)
- CDM (2002)

Of these models, the boundaries employed by Frenzel (1995), Core (1996), and CDM (2002) are coincident with McAda and Wasiolek (1988). Figure 3-1 depicts these coincident domains, the domains of the other models, and the boundary for the SFCM domain. Table 3-1 provides a summary of the principal attributes used by the models reviewed. As discussed further in Section 5.0, the assessment of capture, based on historical data for recharge, surface and ground water interaction, and horizontal to vertical anisotropy, or cross-flow, was important to development of the SFCM. For this reason, Table 3-1 additionally includes brief descriptions of how these attributes were simulated by those models for which they were available or employed.

3.1.1 Hearne (1985)

The Hearne (1985) model was developed to assess the impact of an irrigation plan on the Pojoaque River basin. The model was developed with 22 layers to account for the structural dip of the formations while keeping aspect ratios of the grid cells similar. The model was calibrated to predevelopment conditions, defined as conditions before 1946, and against historical conditions for the years from 1947 through 1980. The model was then used to assess impacts of the irrigation plan over a 100-year planning horizon.

This model is poorly suited for the County's purposes for many reasons. First, it was developed using an early precursor to MODFLOW, which had little of the functionality of the modern versions of the code. Second, the model has a very coarse grid-scale coupled with a layering strategy that was based not on lithology but on structural and anisotropic considerations. This amount of layering is excessive for the County's purposes. Third, because the model authors constrained the model to the area of interest, the model has no applicability to areas of interest for the SFCM outside and south of the Pojoaque River basin. Finally, model development

Although the Frenzel model represents recharge in a manner largely similar to the McAda and Wasiolek model, i.e., as a mixture of constant-head, constant-flux, and head-dependent boundaries, some modifications made to McAda and Wasiolek by Frenzel were adopted by CDM (2002) and were therefore of significance to development of the SFCM. Among these changes are the reduction of the areal recharge rate from 0.5 inches per year (in/yr) to 0.02 in/yr for most of the Tesuque aquifer system and the Pajarito Plateau west of the Rio Grande; an increase in hydraulic conductivity around La Cienega Springs; and the elevational drop, effected to maintain saturated conditions in the springs region, of 30 to 50 feet for the bottom of some grid-cells in layer 1. In considering the significance of both the Frenzel and McAda and Wasiolek models, however, INTERA noted that the implementation of springs as specified flow boundaries limited use of the model for assessment of impacts from ground water pumping on spring flows. Because of this and other limitations similar to those identified for the McAda and Wasiolek (1988) model, INTERA determined that the Frenzel model was not sufficient to the County's assessment of ground water resources.

3.1.4 Core (1996)

The OSE uses a version of the McAda and Wasiolek (1988) model modified for general water-right administration purposes. As modified, the OSE model (Core, 1996) is a simple superposition model that the OSE uses to estimate changes to head and flow conditions relative to those specified by the McAda and Wasiolek model, which the OSE uses as its base model. The only significant alteration made by the OSE to the McAda and Wasiolek model is to five flux cells specified for use in modeling La Cienega Springs. To allow pumping to impact spring flows to the point of eclipsing flow altogether, the OSE replaced these cells with drain boundary conditions.

In considering the usefulness of the Core model, INTERA paid particular attention to limitations and caveats specified by the OSE and Core for the model use. The OSE recommended that water rights applicants contact the OSE when evaluating wells deeper than 800 feet and stipulates that the model is best used (i.e., most accurate) for areas in the interior of the model grid and should not be used for Eldorado, Seton Village, Hyde Park, or any other area where production is expected to be from fractured rocks stratigraphically underlying the Tesuque aquifer system. Core's recommendations include not using the model for evaluating pumping effects from the Buckman well field, west of the Rio Grande, the Pojoaque Basin, any region north of the Rio Pojoaque, or for a well situated within 2 miles of La Cienega Springs.

Given that neither Core nor the OSE recommend application of the superposition model to the Buckman well field or the SFCM area of interest, INTERA determined that the Core model was of limited significance to the County's needs and development of the SFCM.

3.1.5 Barroll and Logan (1998)

The OSE found both the Hearne (1985) and McAda and Wasiolek (1988) models to have insufficient detail and potential boundary and discretization problems relative to OSE requirements for reviewing well permits in the northern Española Basin in and around the City of Española. To address these issues, the OSE instructed Barroll and Logan to develop a new superposition MODFLOW model for the Española region and to calibrate the model to well-field drawdown in the city. Barroll and Logan used three model layers to model the Tesuque aquifer system, varied layer thicknesses from 200 to 600 feet, and implemented streams as general head boundaries so that stream depletions could be estimated and streams would not be disconnected from the aquifer. INTERA found the Barroll and Logan model not applicable to the County's needs for many reasons, principal among them being the fact that the model does not consider the County area of interest.

3.1.6 Keating et al. (2002)

The Keating et al. (2002) model is regional model prepared to encompass Los Alamos National Laboratory (LANL). A revision to an earlier model that Keating and others had started to develop in 1998, the model was undertaken to provide reasonable boundary conditions for LANL. LANL had not been included in the western extent of many of the models that had been developed for the Española Basin. In 1998, the stated goals of the LANL regional modeling effort were synthesis of available hydrogeologic and geochemical regional data, facilitation of conceptual model understanding, and prediction of flow velocities within the region; the model presented by Keating et al. in 2002 was developed to provide modeling support to well-siting decisions, to integrate new data, and to perform geochemical modeling by ground water transport..

The model domain is shown on Figure 3-1 and extends as far south as the Santa Fe River. Developed using FEHM, a finite-element code that employs very fine mesh rather than traditional model layers, the model is geologically fully three-dimensional and sub-divides several hydrostratigraphic units (HSUs) within the Santa Fe Group into eight units corresponding roughly to facies defined by Kelley (1978). Among these are the Paleozoic-Mesozoic, which the model divides into a shallow, potentially fractured, HSU, and a deeper HSU, conceptualized to be less permeable, and the Precambrian, which is divided into three HSUs according to geographic location.

The model is calibrated to pre-development conditions, defined as conditions before 1945, and to transient conditions for 1945 through 1995. Major rivers are modeled as constant head boundaries. The model's lateral boundaries are handled as a combination of no-flow or specified head. Recharge applied in this model is based on the work of Wasiolek (1995), for basins originating from the Sangre de Cristo, and Gray (1997), for the Los Alamos Canyon area. In the model, recharge was applied diffusely and conceptualized to be occurring in canyons and streams beds. The recharge was also reported to have been specified based on a direct correlation with elevation.

This model is not applicable to the County's immediate requirements for ground water resource development because of it regional focus and because it does not cover the areas of interest south of the Santa Fe River . However, the County could use the LANL model in future revisions of the SFCM to constrain boundary flows and geologic properties to the northwest.

3.1.7 Shomaker et al. (2001)

A detailed hydrogeologic study performed by Shomaker et al. (2001) for the Eldorado Area Water and Sanitation District included the development of a ground water hydrologic model. The study is useful for its high level of data assimilation and its incorporation of an understanding of fundamental constraints on further development in the area. The model, developed using a modified version of MODFLOW96, centers on the development of Eldorado in the southern portion of the Northern Santa Fe County (NSFC) hydrologic system.

The model has four layers and constant horizontal grid-spacing at 800 feet. The model domain extends to the north as far as the Santa Fe River and to the south and southwest along the

Galisteo Creek (Figure 3-1). The layers vary in thickness from 100 to 1,350 feet, with the top-most layer handling the relatively higher permeability of the Tesuque and Ancha Formations and alluvial sediments in the area. Following Wasiolek (1995), the model estimates mountain-front recharge and arroyo recharge by a precipitation redistribution method and applies the estimates as specified flow boundary conditions. No areal recharge is applied. Streams and rivers are modeled using the RIV2 Package, which uses a head-dependent boundary with flow dependent upon stream flow (stage) and water table elevation relative to the stream bed. The model assumes a horizontal to vertical anisotropy dependent upon geologic units and varying from 1 to 100. For years prior to 1947, the model is calibrated to steady-state conditions; model calibration for years from 1947 to 1998 is to transient conditions. Predictive simulations were made for years through 2100.

The model cannot support the County's study without modification and recalibration. The model domain does not adequately incorporate the Municipal well field and does not have the constraint of flow system discharge at the Rio Grande. It also does not consider the capture associated with the Buckman well field. Drawdowns predicted by the Shomaker model are affected by boundary conditions in the Santa Fe area, an effect acknowledged by the authors. The model also has potential boundary condition effects on predicted drawdown along the southern boundary. This model is a good initial ground water model of the very complex flow system comprising the southern portion of the NSFC aquifer system in and around El Dorado.

3.1.8 CDM (2002)

In 2002, CDM developed a MODFLOW96 ground water flow model to support the City's evaluation of near-term water-supply alternatives. The model was specifically developed to assess drawdown and depletions in the vicinity of the Buckman well field. The model is based largely upon the Frenzel (1995) model, and the model domain is identical to that of both McAda and Wasiolek (1988) and Frenzel models (Figure 3-1). To represent alluvial sediments in the Rio Grande Valley and in tributaries within the region, the CDM model modified the Frenzel model by adding an additional model layer to the vertical discretization scheme. The CDM model layers vary in thickness from 100 to as much as 1,400 feet. The lateral model boundary conditions are based on Frenzel and are a combination of constant head and constant flux. Recharge is applied similarly to the Frenzel model, also including areal recharge and mountain-front recharge as flux boundaries.

CDM models the Rio Grande and the Pojoaque and Tesuque Rivers with the MODFLOW stream package (Prudic, 1989) and, like Frenzel and McAda and Wasiolek, models the Santa Fe River as specified flux boundaries. CDM's simulations of La Cienega Springs, as a specified flux boundary only impacted by pumping if the user specifies the depletion rate, is also consistent with the Frenzel model. In its model documentation, CDM states that it increased vertical conductance within the model relative to Frenzel and reports a horizontal-to-vertical anisotropy ratio varying from 10 to 1,000. But review of vertical conductance documented by Frenzel indicates that the vertical conductance used by CDM is actually a reduction of that used by Frenzel. The CDM model is calibrated to steady-state conditions for years prior to 1947 and to transient conditions for years from 1947 to 2000. Predictive simulations were made for years through 2060.

3.2 Model Review Conclusions

The ground water models developed for the County regions and described in this section are useful for the study of a number of ground water-related issues, and each provides information which is relevant to this study. However, none of the models provide the coverage required for the County's needs. The SFCM extends farther south than the southern extent of the Shomaker et al. (2001) model. The McAda and Wasiolek (1988) model provides a good SFCM footprint for the northern portion of the County. The Keating et al. (2002) model provides some potential constraints for setting or constraining fluxes at the northern and western model boundaries. The Shomaker et al. (2001) model has provided some insight into the geologic controls in the Galisteo Creek region, especially in the Eldorado area. The Shomaker et al. (2001) model report also provides some valuable information with regard to watershed water balances in the southeastern model region.

4.0 HYDROGEOLOGIC SETTING

This section of the report provides a review of the hydrogeologic setting of the study region. The review covers the hydrostratigraphy and structure of the aquifers and aquitards in the region, the hydraulic properties, hydraulic heads and ground water flow patterns, recharge, and natural aquifer discharge.

4.1 Hydrostratigraphy and Structure

4.1.1 Data Sources

A variety of data are necessary to develop a geologic model, which is the foundation of any ground water flow model. These include data for lithology and structure, as well as the location and nature of faulting. A variety of recent and valuable data sets has become available for use in modeling both surface and subsurface geology in the study area. Examples of key resources include data from Grauch and Bankey (2003), Sweeney et al. (2002), and Johnson et al. (2004). Many of the data from Grauch and Bankey (2003), including Tesuque thickness data within the northern portion of the Española Basin and the eastern limit of the Cerros del Rio volcanic field, have been converted to electronic format and included in Johnson et al. (2004).

The primary digital data used for development of the geologic conceptual model include:

- Base of the Ancha – digital data from Johnson et al. (2004)
- Base of the Tesuque – digital data from Johnson et al. (2004) and Grant (1998)
- Tesuque thickness – digital data from Phillips and Grauch (2004)
- 1:500,000 digital geologic map of New Mexico (Anderson et al., 1997)
- 1:50,000 digital geologic map – digital data from Johnson et al. (2004)
- Digital geologic map derived from Grant (1998) by the New Mexico Office of the State Engineer
- Digital geologic map of the Tetilla Peak quadrangle – digital data from Sawyer et al. (2002)
- Fault locations:
  - 1:500,000 digital geologic map of New Mexico (Anderson et al., 1997)
  - Johnson et al. (2004) digital line data

The following draft 7.5-minute geologic quadrangles from the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) were also used:

Captain Davis Mountain (Lisenbee and Maynard, 2002)

- Chimayo (Konig, 2003)
- Cundiyo (Konig et al., 2002)
- Espanola (Konig, 2003)
- Frijoles (Goff et al., 2002)
- Galisteo (Lisenbee, 1999)

- Guaje Mountain (Kempter and Kelley, 2002)
- Glorieta (Ilg et al., 1997)
- Golden (Maynard, 2002)
- Madrid (Maynard et al., 2002b)
- Picture Rock (Maynard et al., 2002a)
- San Felipe Pueblo NE (Black et al., 2000)
- Santa Fe (Read et al., 2000)
- Santo Domingo Pueblo and Santo Domingo Pueblo SW (Smith and Kuhle, 2000)
- Seton Village (Read et al. 1999)
- Turquoise Hill (Koning and Hallett, 2001)

Specific cross-section data used to build the hydrogeologic conceptual model consisted of data from A-A' and B-B' cross sections for the Captain Davis Mountain, Madrid, Picture Rock, and Seton Village quadrangles and the Balleau (2000) study area; A-A', B-B', and C-C' cross sections for the Galisteo quadrangle, and the E-E' and A-A' cross-sections from Johnson et al. (2004) and Glorieta Geoscience (2000), respectively.

Interpretations of the geology with depth provided by the cross-sections from the geologic quadrangles were also incorporated into the hydrogeologic conceptual model as well as surface geology from the maps. Many of these cross-sections were based on deep oil-exploration wells and water supply wells drilled in the vicinity of the study area. The specific cross sections and state quadrangle maps used in the development of the geologic model are shown on Figure 4-1. This figure also shows the locations of known borings and "virtual" boring locations used in the development of the geologic model. Known boring locations consisted of the oil-exploration wells and deep-water wells located mostly in the southeastern portion of the study area. Where data was not available or limited, virtual boreholes were made at point locations based on the interpretations provided by the many cross sections provided with the quadrangle maps listed above. Table 4-1 list the oil exploration wells used to develop the hydrogeologic conceptual model. Appendix A includes a listing of all boreholes and includes the borehole location within the model domain, the boreholes that were used to pick formation contact elevations for the geologic model, and references for the borehole information.

4.1.2 Geologic Framework

The County is located dominantly within the Española Basin, a tectonic basin filled with several thousand feet of alluvial fan deposits and some interbedded basalt and ash beds. Most sediment within the basin is referred to as the Santa Fe Group, which is Tertiary in age. The basin is bounded on the east and west by the Sangre de Cristo uplift and the Jemez Mountain volcanics, respectively. The northern boundary of the basin nearly coincides with the northern boundary of the County, with a narrow connection to the northern San Louis Basin through the Embudo Channel. To the south the Tertiary basin-fill sediments thin, and the basin is bounded by the Cerrillos Intrusion (Grauch and Bankey, 2003). Also in the southern part of the basin, a series of faults, including the La Bajada fault, have uplifted this area relative to the Santo Domingo Basin to the south.

The Santa Fe Group sediments are considered to be in hydraulic communication with the underlying sedimentary units and volcanic units in the northern part of the basin. The Tertiary to Quaternary Santa Fe Group, the principal aquifer in the County area, is composed primarily of the Tesuque and overlying Ancha and Puye Formations. In the Rio Grande Valley of the

Albuquerque Basin, the Tesuque Formation has a thickness of more than 9,000 feet (Kelley, 1978).

The nature of the rocks below the Santa Fe Group is not well understood, as few wells have penetrated the entire thickness. The Tesuque Formation and the overlying Ancha and Puye Formations of the Santa Fe Group are a series of coalescing alluvial fan deposits that are discontinuous and locally very heterogeneous. The Ancha Formation is situated mostly above the water table throughout the Española Basin, but where it is not, it is in hydraulic communication with the Tesuque. The Ancha is more homogeneous and permeable than the Tesuque, so in areas where these units are in hydraulic communication, ground water flows preferentially through the Ancha. The Puye Formation is even more permeable, composed predominantly of sands and gravels, and it overlies the Tesuque west of the Rio Grande and therefore is outside the study area. Transmissivity for these units in the Española Basin ranges from 0.05 to 11,000 square feet per day (ft^2/d) (Lewis and West, 1995).

The Tesuque Formation of the Santa Fe Group is the principal aquifer for the area and was first proposed by Spiegel and Baldwin for the Miocene basin fill sediment, a primarily pinkish tan, silty arkosic sandstone deposited in the Rio Grande Rift near Santa Fe (Spiegel and Baldwin, 1963). The Tesuque Formation is the largest aquifer in the Española Basin. The complex nature of the Tesuque depositional environment, coupled with the discontinuities created by faulting, has resulted in a very heterogeneous and anisotropic formation which consists of interbedded layers of gravel, sand, silt, and clay, with some intercalated volcanic ash deposits derived largely from the Sangre de Cristo Mountains (Spiegel and Baldwin, 1963; Lewis and West, 1995; Johnson et al., 2004). The alternating sequences of sandstones and siltstones dip to the west at angles ranging from 0 to 30° (Golobek et al., 1983).

Dan Koning of the New Mexico Bureau of Geology has recently completed detailed maps and cross sections of the County area (Johnson et al., 2004). These basin-fill sediments are mapped by Koning as the Tesuque Formation; however, he has recently subdivided these units into several "lithostratigraphic" units based on provenance (origin of the sediments), texture, and other general sedimentologic characteristics. The units of interest to development of the County's model are

Lithosome A – a granite-rich gravel and arkosic sand, silt, and mud deposited on an alluvial slope, which Koning has further subdivided on the basis of gross texture;

Lithosomes B and C – floodplain mud, silt, and very fine to fine sand plus sandy to gravelly channels deposited on a basin floor (these units are distinguished only by the petrology of the gravel and therefore distinguishing these layers within the County's model does not appear to be important at this time); and

Lithosome S – pebbly sand channel deposits together with fine sand, silt, and mud floodplain deposits associated with a large drainage that exited the Sangre de Cristo Mountains near Santa Fe.

The sediments for Lithosome A were derived from various streams draining the Sangre de Cristo Mountains. The unit is characterized by a predominance of small, coarse, channel deposits with various amounts of calcium carbonate cement and clay that reduce its permeability. This unit is unsaturated in most of the study area.

Lithosomes B and C were deposited on a basin floor by an axial fluvial system from a mixed provenance. These units comprise the main aquifer supplying the Buckman well field. Because the units are comprised mainly of siltstone and mudstone, most of the ground water flow will be in the coarser channel deposits which have varying degrees of connectivity.

Lithosome S contains fluvial deposits associated with the ancestral Santa Fe River. The overall coarse texture of this unit, particularly in its eastern extent near Santa Fe where it lacks the finer-grained, overbank mud deposits, makes Lithosome S relatively more permeable than other units in the area except for some coarser units of Lithosome A in the upper Tesuque.

Llithosomes A, B, C, and S have been divided into subunits based on lithology. Given the more highly permeable nature of Lithosome S, the geologic model incorporates this subunit as a separate layer (see section 0).

The Ancha Formation is the uppermost basin fill unit in the Santa Fe embayment (Johnson et al., 2004). The Santa Fe embayment is bounded by the Sangre de Cristo Mountains to the east, Galisteo Creek to the south, the Cerrillos Hills to the southwest, and the Santa Fe uplands which are underlain by the Tesuque Formation north of the Santa Fe River. The Ancha Formation extends under the Cerros del Rio basalts westward toward the Santa Fe River, but is not as thick in this area. It is comprised of gravel, sand, and silt derived from the southwestern flank of the Sangre de Cristo Mountains. The formation is Plio-Pleistocene in age and is mostly non-cemented and weakly consolidated. The Ancha Formation ranges in thickness from 33 to 270 ft in the Santa Fe embayment. Because if its high permeability and lack of cementation, where saturated it can be a prolific aquifer. This unit may be important to INTERA's geologic model, particularly in the southern part of the model domain.

Shallow alluvial deposits, which are younger than the Santa Fe Group, lie beneath and adjacent to the Rio Grande and the Santa Fe River and their main tributaries throughout the County area. These deposits are better sorted and have larger average grain size than the Tesuque Formation. These deposits vary in thickness from a few to less than 100 feet depending on the distance from major drainage areas. Many domestic wells completed in these shallow alluvial deposits produce excellent water.

4.1.3 Conceptual Geologic Model and Geologic Column

As a basis for the parameterization of the numerical flow model, a three-dimensional geologic model was assembled. One of the first steps in the geologic model construction is the development of a representative geologic section that combines the detailed regional stratigraphy based on hydraulic properties, both measured and inferred. All of the available cross -sections for the region and the geologic quadrangles were reviewed. In many cases, the geology as mapped in a geologic quadrangle is at a local scale with many members and informal classifications. The initial task for development of the geologic model was to correlate the many geologic columns available from quadrangles and cross-sections to a consistent geologic column that could be used in model development. Interpretations of geologic contacts (elevations) based on this geologic column can then be used to develop model geologic unit structure contours and isopachs. Using these horizontal two-dimensional datasets, vertical cross-sections are constructed for incorporation into a three-dimensional solid geologic model for the region.

Table 4-2 provides the geologic column used for the development of the model hydrostratigraphy and as the basic framework for hydraulic parameterization. This stratigraphic column is the basis for the three-dimensional geologic model and will hereinafter be referred to as HSUs.

Depositional environments and volcanic events provided the basis for selecting the units included on the stratigraphic column. Important deformational events created different depositional settings for the development of the geology observed today in the Galisteo and Española Basins. These various geologic settings resulted in units of variable composition that are important to the regional hydrogeology. During the Paleozoic, before the uplifts and volcanism that characterize much of the landscape in the Santa Fe area today, New Mexico was covered by the Western Interior Seaway where the Pennsylvanian Madera limestone was deposited over a granitic Precambrian basement. During various cycles of this shallow sea, non-marine sands, silts, and muds were intermittently deposited with limestone beginning with the fine-grained mudstones of the Permian Sangre de Cristo Formation. Overlying these sediments is a coarsening upward sequence of Permian sediments that includes, from youngest to oldest, the sands, muds, and limestones of the Yeso Formation; the Glorieta sandstone; the San Andres limestone; and the sands and limestone conglomerate of the Bernal Formation (Ilg, et al; 1997).

The Chinle Formation, a thick sequence of mudstones interbedded with sandstones and limestone, was deposited during the Triassic. From the Jurassic until the end of the Cretaceous, sequences of muddy shales and sands were deposited. These sequences are comprised of the Morrison Formation, including the Entrada Sandstone, the Mancos Formation, and the Mesa Verde Group.

At the end of the Cretaceous and the beginning of the Tertiary, the mountain-building Laramide Orogeny occurred. Stretching and thinning of the earth's crust during this period, combined with depositional overburden from the erosion of the newly formed mountains, created the Galisteo Basin, which filled with the mud, sand, and gravel of the Galisteo Formation deposited from the north.

During the Oligocene, approximately 30 million years before the present (Ma), widespread tectonic disturbances characterized by the eruption of volcanoes and the intrusion of magma bodies into existing sediments formed the Tertiary intrusives in the southwestern part of the study area. These intrusive magmas created a series of sills, dykes, and laccoliths as they pressed upward through the Precambrian basement causing deformation of and intrusions into the overlying sediments. These volcanic and intrusive units and the overlying sediments were subsequently eroded away to form the present-day Cerrillos Hills. Sediments from this erosional process were deposited within the Galisteo Basin creating the Espinaso Formation.

About 20 Ma, regional-crustal extension formed a series of north-south offset faults and depressions known as the Rio Grande Rift. Offsets along the rift zone formed steep mountains where the crust buoyed up and formed escarpments on the down-thrown sides. In the study area, this rifting is responsible for the creation of the Pajarito Uplift and the La Bajada fault. At this time, the Rio Grande formed within the basins created by the rift-zone depressions. These basins, including the Española Basin, were filled with the thick gravel, sand, and silt deposits of the Santa Fe Group, which includes the Tesuque Formation.

Around 10 Ma additional uplifting forming the Sangre de Cristo Range caused isolation of the Española and Galisteo Basin. The Santa Fe Embayment was formed where asymmetrical deposition occurred. The Tijeras-Cañoncito fault forms the edge of a north-trending synclinal basin where sediments of the Santa Fe Group thicken to the north. From this fault, eroded thicknesses of the Santa Fe Group gradually decrease forming a U-shaped hinge line where sediments increase in thickness to the north. The USGS collected aeromagnetic data in this area south of the City in order to define the thicknesses of the Santa Fe Group in this area. Interpretations of the thicknesses of the Santa Fe Group and the Tesuque Formation can be made in the area because of the magnetic properties of the underlying volcanic and volcaniclastic sediments. The USGS study suggests that localized areas of increased thickness (as much as a few hundred feet) occur within the general synclinal form of the southern portion of the embayment on an erosional relief of the underlying Espinaso Formation (Phillips and Grauch, 2004). Data from this study were used in conjunction with well log information in the three-dimensional geologic model to define the bottom of the Tesuque Formation.

4.2 Hydraulic Properties

A database of measured hydraulic properties in the model region was developed from numerous public and private sources. The largest collection of hydraulic test results was found in Johnson et al. (2004), which provides approximately 200 transmissivity measurements from wells within the region (Figure 4-2) compiled into a consistent database. Many of the other reports reviewed were found to be considered and collected within the Johnson (2004) database. INTERA performed a review of the available literature for development of properties in portions of the basin not covered by Johnson et al. (2004). Additional hydraulic property data are included in Shomaker et al. (2001) and Daniel B. Stephens & Associates (DBS&A) (1994). Hydraulic properties for the model were distributed based on the geologic column developed for the conceptual model (see section 0).

Table 4-3 summarizes the hydraulic conductivity estimates from aquifer tests for each of the hydrogeologic units defined in the geologic column. The Tesuque has the additional delineation of four lithosomes and the data are divided accordingly. The conductivity data for the Permian and Precambrian hydrogeologic units are considered likely to be biased by anomalous local fractured zones that are not widely applicable to the hydrogeologic unit as a whole. Conversely, the data for Tesuque Lithosome A appear to be biased low based on well locations occurring only at the extreme edges of the formation. The Axial Gravels and Cerros Del Rio geologic units had no aquifer test data and maximum and minimum conductivity values were taken from previous modeling reports.

Only Tesuque Lithosome S had sufficient conductivity and depth data with which to reasonably determine a relationship between hydraulic conductivity (K_h) and depth. Figure 4-3 depicts log K_h versus depth for Tesuque Lithosome S. A trend of decreasing K_h with depth is apparent in the figure and the results of a linear regression to the data are displayed on the plot. The K_h values can range up to approximately two orders of magnitude at any given depth which is apparent in the low coefficient of determination (R^2) of only 0.22. Other HSUs lacked sufficient depth data to fit a depth decay coefficient.

Very little data exist for storage parameters for the HSUs in the model area. Initial estimates were based primarily on values from previous modeling reports. The Shomaker (1999) model provides the best source for storage estimates because they also modeled formations other than the Tesuque in the Santa Fe Embayment. Table 4-4 provides the storage values used in the Shomaker (1999) model. Specific yield ranges from a low of 0.01 to 0.2. The low specific yield numbers are generally used for consolidated formations which are expected to have low primary porosities and or secondary porosity. The confined storage numbers range from a low of 0.0001 to a high of 0.0027 for many of the formations at shallow burial. Shomaker (1999) assigned storage properties based on the lithologic nature of the formation, the age and previous depth of burial, and the present-day depth of burial. Decreases in storage with depth for a given media result from a decrease in porosity and higher degree of compaction with depth. A decrease in porosity with depth will also result in a decrease in hydraulic conductivity which provides further conceptual support for the decreasing hydraulic conductivity with depth seen in the Tesuque Lithosome S data (Figure 4-3).

4.3 Hydraulic Heads and Ground water Flow

Hydraulic heads provide the primary calibration target for the ground water flow model. Ground water flows from regions of high hydraulic head to regions of lower hydraulic head. Therefore, contour maps of hydraulic head provide a general description of ground water flow patterns within the region. In this section of the report the data sources for the hydraulic head database will be summarized in addition to both spatial and temporal trends in the regional hydraulic heads.

4.3.1 Hydraulic Head Data Sources

Historical and present-day water-level data were collected from a variety of sources. In addition, historical water-level data was used to estimate a "pre-development" head surface for the water table. Pre-development water-level data was primarily taken from Spiegel and Baldwin (1963), Mourant (1980), and Johnson et al. (2004). Johnson et al. (2004), the U.S. Geological Survey (USGS) Ground water Site Inventory database for wells not included in the Johnson et al. (2004) database, and the OSE database were used for historical water level data. CDM (2002) provided data for the Buckman well field, and Shomaker (2001) data was used for the El Dorado production wells for pump-off measurement.

In the model domain, the database has 702 wells that have at least one head measurement within the collective period of record from April 1945 through November of 2004. The well with the longest period of record runs is the Old Hickox well, with runs from August 1946 through May 2003. The well with the greatest number of time series measurements is the Alto well, with 765 measurements from 1954 through 2001.

Figure 4-4 illustrates a cumulative-distribution function (CDF) of the number of head measurements per well in the database. From Figure 4-4 one can see that more than 65% of the wells have no more than two head measurements. Only 13% of the wells have 10 or more measurements. Figure 4-5 illustrates a CDF of the date of the available head measurements and shows that less than 10% pre-date 1970 and that a significant increase in the rate of measurement occurred in the late 1990s. The great majority of the wells (approximately 70%) have periods of record of less than two years with only approximately 10% of the wells having periods of record greater than 20 years.

An important aspect of the head control database is the fact that most well completions are relatively shallow in the unconfined or semi-confined portions of the basin sediments. McAda and Wasiolek (1988) found that the majority of the wells in the basin were completed within 800 feet of ground surface and they used this fact to develop their model layering. Figure 4-6 illustrates a CDF of the midpoint of the well screens in the database. This figure supports the conclusion that a very small percentage (5% or less) have screen midpoints greater than 1,000 feet. From this analysis, the conclusion can be made that aquifer conditions at depths greater than

1,000 feet below ground surface are poorly characterized in the basin and thus are very uncertain. A model of these aquifers at depths below 1,000 feet is exploratory in nature. Secondly, head surfaces of the aquifers are generally representative of the shallow unconfined portions of the aquifer and vertical gradients at the basin scale are poorly characterized.

4.3.2 Spatial and Temporal Trends of Hydraulic Properties

The hydraulic flow systems of the basin have been described by many investigators (Spiegel and Baldwin, 1963; Hearne, 1980; McAda and Wasiolek, 1988; Lewis and West, 1995, Johnson et al., 2004). The ground water head surface in the basin fill sediments and in the bedrock formations is characterized as being controlled by elevation with higher heads in the higher elevation regions and lower heads in the lower elevation regions. As discussed in the preceding section, because data for the available heads are generally from shallow wells, they are indicative of unconfined head elevations and accentuate the topographic controls.

Figure 4-7 illustrates the predevelopment head surface for the water table in the model area. One can see the potential for flow from the higher elevations. This flow pattern is indicative of the fact that the basin aquifers generally receive recharge from the eastern Precambrian uplift and, to a lesser degree, from the western Jemez volcanic uplift through mountain front recharge. Additional recharge may occur in higher elevation streams and arroyos and in areas of stream capture. Inflow to the basin also occurs from the Embudo constriction and Chama Basin to the north. Some discharge occurs as underflow to the Santo Domingo Basin to the south with the dominant discharge occurring to the Rio Grande and to ephemeral streams within the basin. McAda and Wasiolek (1988) simulated aquifer-stream interaction in the basin and demonstrated the importance of the hydraulic communication between these systems and the importance of baseflow as a component of basin discharge. Estimates of subsurface flow from the Española Basin to the Santa Domingo are uncertain. Recent geological interpretations by the USGS (Minor, in press) indicate that the connection between areas north and south of the La Bajada is very constricted and flow from the Española Basin to the Santa Domingo Basin is expected to be limited. Consistent with this interpretation, Sanford et al. (2004) re-calibrated the McAda and Barroll (2002) model for the Middle Rio Grande and adjusted recharge from the Española/Hagan Basin to the Middle Rio Grande to approximately 770 acre-feet per year (ac-ft/yr), a 94% reduction in flow between basins.

The hydraulic flow systems in the County have been characterized into three conceptual hydrologic systems from north to south (Lewis and West, 1995): the North Santa Fe County (NSFC) aquifer system, the MSFC aquifer system, and the Estancia Valley (EV) aquifer system. These hydrologic flow systems are shown in Figure 4-8. The NSFC system extends from the north to the center of the County and is bordered on the south by the Cerrillos Uplift and the erosional truncation of the Santa Fe Group in the Galisteo Creek drainage basin. The MSFC occurs coincident with the Galisteo Basin except in the northern portion of the Galisteo Basin which contains Santa Fe Group formations. The eastern portion of the MSFC extends into the Pecos Basin. The MSCF is structurally complex and was not considered an aquifer system by Lewis and West (1995). The EV aquifer system coincides with the Estancia Valley surface drainage basin and is composed of valley fill sediments overlying the Madera Limestone, the Abo Formation, the Yeso Formation, the Glorieta Sandstone, the San Andres Formation, and the Dockum Group.

In terms of water level trends, ground water heads in the NSFC are reported to be stable with the exception of those areas near large well fields such as the Buckman well field and the Municipal well field. Johnson et al. (2004) performed a detailed review of water level trends in the NSFC. Their review identified a zone of drawdown around the Municipal well field with documented head decline rates from 6.4 ac-ft/yr to as low as 0.2 to 0.3 ac-ft/yr in areas at the perimeter of this zone. Their study identified that drawdown appeared to be least in the shallow wells, which is largely the impact of relative distance from the pumping horizons and in the wells that have the highest transmissivity and storativity. Johnson et al. (2004) documented the drawdown rates of 0.7 ac-ft/yr 1,000 feet beneath the pumping horizon at St. Michaels. Heads near the Buckman well field have declined since they were installed with declines of 9 to 10 ac-ft/yr over the last 15 years (Johnson et al. 2004). Head trends are mixed in the MSFC, except in the vicinity of Galisteo, where declines are reported on the order of 1 ac-ft/yr. In the EV aquifer system, hydrographs in the valley fill and in the western portion of the Madera Limestone have been declining consistently between 1.4 and 1 ac-ft/yr since the 1940s.

4.4 Recharge

Conceptually, for alluvial basins in the southwest, the mountains are generally considered the source of recharge and the sink is a structural and topographic alluvial basin adjacent to the mountains. Under natural conditions, it is expected that recharge in the study area would be comprised of mountain-front recharge and diffuse or areal recharge. Mountain-front recharge is the combination of water percolating into the alluvial basin–fill from surrounding hillsides and water flowing out of tributary mountain watersheds and seeping into the ground near edges of the alluvial basin–fill. For the purposes of this study, these two types of mountain-front recharge are combined. The volume and timing of mountain-front recharge is directly related to runoff of precipitation in the upland areas. The sources of areal recharge in the study area are infiltration of precipitation falling directly in the alluvial basin and infiltration of excess artificial irrigation of agricultural crops and residential areas. The hydrologic model varies both mountain-front and areal recharge in proportion to the patterns of precipitation recorded at representative sites in and around the Española Basin.

Through model calibration, water-balance methods, and field measurements, Hearne (1985), Anderholm (1994), Wasiolek (1995), Kernodle et al. (1995), Duke Engineering and Services (DE&S) (2000) Shomaker et al. (2001) and McAda and Barroll (2002) have provided estimates of mountain-front and associated tributary recharge in the region. Wasiolek (1995) developed estimates of mountain-front recharge for five tributaries in the Sangre de Cristo Mountains; estimates from the other studies are more regionally based. Table 4-5 provides a summary of mountain-front recharge rates from various investigations in the region.

In arid alluvial basin settings, little natural direct recharge occurs in non-mountainous areas because of a high evaporation potential combined with less precipitation. The recharge that does occur is expected to be from seepage into arroyo channels associated with localized rainfall events. The chloride mass balance work of Anderholm (1994) supports this concept. Several studies, including those of Keating et al. (2002) and Shomaker et al. (2001), determined threshold elevations below which no areal recharge would occur except through arroyo channels. McAda and Wasiolek (1988) and Frenzel (1995) modeled areal recharge using broad zonations based on the presence of major rock types present at the land surface. Frenzel (1995) estimated recharge rates range from 0.02 in/yr in the Pajarito Plateau and Tesuque Formation to 0.05 in/yr in the Cerros del Rio volcanic field west of the City to 0.5 in/yr in the Santa Fe River and Galisteo Creek areas where the Ancha Formation sediments exist. Shomaker et al. (2001) applied areal recharge only in the mountain regions and in the Cerrillos Hills area southwest of the City. Table 4-6 provides a summary of areal recharge rates implemented in previous models in the basin and also the field measurement results of Anderholm (1994).

4.5 Natural Aquifer Discharge

Natural aquifer discharge occurs from three basic processes: discharge to streams and rivers (baseflow), discharge to springs, and discharge through evapotranspiration (ET). Within the hydrologic model domain, another type of discharge occurs related to subsurface discharge from the active model domain to areas not modeled. As discussed earlier in this section, discharge from the Española Basin to Middle Rio Grande Basin has been reduced in recent studies and is now thought to be less than 1,000 ac-ft/yr (Sanford et al., 2004). From the range of recharge estimates in the Española Basin, inter-basin discharge makes up less than 2% of the flow balance. This means that the Española Basin acts as an isolated basin where recharge occurring within the basin largely discharges within the basin as a result of stream and spring discharge and ET and pumping after development began.

Natural aquifer discharge is a key aspect of ground water management because natural aquifer discharge is the ultimate source of capture for ground water production in a basin. If a ground water system is pumped at a volumetric rate greater than the potential ground water which can be captured, the system will become physically unsustainable meaning that ground water levels will never equilibrate.

Table 4-7 provides a summary of stream gain, loss, and ET estimates in ac-ft/yr. The table is organized by the major streams in the study region. Included in the table is the time period the estimate is considered applicable with predevelopment representing times prior to resource development and modern representing times after development. The table includes results from numerous field studies and models as indicated in Table 4-7.

The Rio Grande is generally considered to be gaining north of San Felipe Pueblo (Plummer et al., 2004; Yapp, 1985). The general rule of thumb cited in many reports and perhaps originating with Spiegel and Baldwin (1963) is a gain of 1 cubic foot per second (cfs) per mile (724.4 ac-ft/yr per mile) within the Española Basin. This results in a discharge of approximately 28,285 ac-ft/yr which matches closely to the discharge predicted by the McAda and Wasiolek (1989) model of 28,500 ac-ft/yr for predevelopment conditions. McAda and Wasiolek (1989) simulated a 5.6 % reduction in Rio Grande baseflow as a result of resource development.

There is significant uncertainty as to whether the Santa Fe River was perennial in predevelopment times. McAda and Wasiolek modeled the predevelopment Santa Fe River with 4,700 ac-ft/yr gain and 5,434 ac-ft/yr loss in the higher reaches. The Shomaker (2001) model of the El Dorado region provided a predevelopment water balance of the Santa Fe River and the Galisteo Creek. This model simulated a loss for these two rivers of 8,256 ac-ft/yr with a gain or discharge to rivers, streams, and ET of 11,425 ac-ft/yr for a net gain of 3,169 ac-ft/yr.

Most attempts to characterize gain on the Santa Fe River in modern times result in a net gain of from 4,700 to 5,700 ac-ft/yr. This gain is balanced by a loss of 8,500 to 1,500 ac-ft/yr. In modern time, there are two perennial reaches on the Santa Fe River: Santa Fe Lake to the bridge at Alameda/Camino Cabra and between the water treatment plant (WTP) and La Bajada gage.

CDM/LWA (1998) described the following conditions for the Santa Fe River in modern times. Through the urban reach, the Santa Fe River is typically a dry, dewatered channel except during snowmelt and storm runoff. CDM/LWA (1998) report that the water budget for the river at La Bajada consists of effluent discharges from the City's wastewater treatment plant and springs in the Santa Fe Canyon. The discharge flow averages 9 cfs but is adjusted by seepage losses to the riverbed and banks. The springs restore about 3 cfs to the river, with the result that the flow at the La Bajada gauge generally closely mimics the hydrograph of wastewater discharge, except for spikes caused by storm runoff.

The Tesuque River has been characterized as a stream which has both gaining and losing segments. Work performed in regional planning efforts found that the Tesuque watershed was closely balanced in modern times between discharge (baseflow and ET) and loss. Work performed by DBS&A found that loss exceeded gains by at least a factor of two although they did not explicitly count ET as discharge. The Pojoaque was modeled by McAda and Wasiolek (1989) and in predevelopment conditions they reported discharge exceeding losses by 2,600 ac-ft/yr which is similar to the results of Frenzel (1995).

Galisteo Creek is ephemeral and little hard information is available on its flow balance. Modern discharge is reported to be very small, ranging from 130 ac-ft/yr in the Upper Galisteo to 3,640 ac-ft/yr in the Lower Galisteo. Loss data are highly uncertain but have been reported to range from 1,000 ac-ft/yr in the Upper Galisteo to 5,000 ac-ft/yr in the Lower Galisteo. Shomaker (2001) reports, in their El Dorado report, that streams in the San Marcos Arroyo feeding into Galisteo Creek gain approximately 335 ac-ft/yr.

Springs can also be an important discharge mechanism in a ground water basin and springs such as La Cienega are a cultural feature. Many times significant spring flow occurs near modeled streams so the springs are not explicitly modeled. Prior models of the basin have only tried to handle La Cienega. Discharge associated with La Cienega, Cienega Creek, and the Santa Fe River in the Cienega area were modeled by McAda and Wasiolek (1989) and Frenzel as a specified flux equal to 6.5 cfs (4,059 ac-ft/yr). How much of this flow is attributed to La Cienega is not known to the authors. The OSE (Core, 1995) modified the La Cienega area to be treated as drain cells such that pumping capture could be assessed.

Table 4-8 summarizes spring flow measurements from identified springs in the model area. Flows are generally less than 1 cfs, with Cienguilla being the highest measured discharge of 581 ac-ft/yr in 1953 and springs as low as 3 ac-ft/yr such as Galisteo Spring measured in 1973.

Although Table 4-8 includes estimates of stream gains and losses from previous models in the study area, it is instructive to compare the steady-state flow balances from the two fully documented models in the study region, the McAda and Wasiolek (1989) model and the Frenzel (1995) model. Table 4-9 presents the predevelopment (steady-state) flow balance for each of these models.

First, model inflows can be compared. Estimates of recharge (mountain front, stream losses, and diffuse) range from 50,500 ac-ft/yr in McAda and Wasiolek (1989) to 32,310 ac-ft/yr in Frenzel (1995). For comparison, summing up recharge sources from Table 4-5, the estimated recharge from mountain front and stream losses would be approximately 49,000 ac-ft/yr which is closer to the McAda model estimate. Mountain front recharge in the McAda model makes up 77% (41,400 ac-ft/yr) of the inflow whereas it only makes up 42% (22,458 ac-ft/yr) of the inflow in the Frenzel model. Diffuse recharge makes up 14% (7,700 ac-ft/yr) of the McAda model inflow whereas diffuse recharge makes up only 8% (3,477 ac-ft/yr) of the inflow in the Frenzel model. Streams and model boundaries in the McAda model account for 4,400 ac-ft/yr or 8.2% of the model inflow whereas streams and boundaries account for 15,648 ac-ft/yr or 38% of the model inflow. In summary, the amount of recharge through precipitation within the basin is much less in the Frenzel model with stream inflows (losses) and boundary inflows becoming more of a relative inflow component.

In terms of model outflow, both models have stream/spring/ET discharge as the highest outflow component. However, the magnitudes are significantly different because of the reduced recharge in the Frenzel model and the increased boundary flows and stream losses in the Frenzel model. The McAda model discharges approximately 69% of inflow to streams/springs/ET with 27,100 ac-ft/yr to the Rio Grande. The Frenzel model discharges approximately 42% of model inflow to streams/springs/ET with 11,374 ac-ft/yr to the Rio Grande. Model boundary outflow in the McAda model is approximately 28% of the outflows (14,800 ac-ft/yr) whereas they make up approximately 43% (17,894 ac-ft/yr) of the outflow in the Frenzel model.

The McAda model estimates that there were approximately 12,600 ac-ft/yr of underflow to the Santa Domingo Basin. The Frenzel model estimated this flow to be approximately 8,800 ac-ft/yr. Some of these boundary flows may exit to the Rio Grande prior to entering the Santa Domingo because of the location of these model boundaries. In their model of the Middle Rio Grande Basin, McAda and Barroll (2002) set the flow from the Española Basin as a boundary flux of approximately 14,000 ac-ft/yr. Sanford et al. (2004) re-calibrated the McAda and Barroll (2002) model for the Middle Rio Grande based on environmental tracer data and adjusted recharge from the Española/Hagan Basin to the Middle Rio Grande to approximately 770 ac-ft/yr, a 94% reduction in flow between basins. This appears to be consistent with the most recent hydrogeological interpretation of the connection between the basins by the USGS (Minor, in press).

5.0 CONCEPTUAL MODEL OF GROUND WATER FLOW IN THE MODEL AREA

The conceptual model for ground water flow in the model area is based on the hydrogeologic setting, described in Section 4. The conceptual model is a simplified representation of the hydrogeological features that govern ground water flow in the aquifers in the County. These include the hydrogeology, the controls on ground water flow, hydraulic boundaries, recharge, natural discharge, and anthropogenic stresses such as pumping. Each of the elements of the conceptual model is described below.

5.1 Geologic Setting

The geologic setting for the conceptual model is described in Sections 4.1.2 and 4.1.3. The complex geology in this area controls the rate of movement and the volume of water available for development in this area. The SFCM is unique with respect to other regional models developed for the area in that it explicitly attempts to honor the geologic setting in the study area as it is known today. Further discussion on geologic controls on ground water movement follows.

5.2 Geologic Controls on Ground water Movement

The following are among the numerous geologic controls on ground water flow that have been studied for the Española Basin: confining beds resulting in artesian conditions (Purtymun and Johansen, 1974), dipping Santa Fe Group beds causing preferential flow parallel to the strike (Hearne, 1985), and cemented fault zones acting as barriers to flow (Spiegel and Baldwin, 1963; Blake et al., 1995). At the local scale, any or all of these factors are likely to be contributing to the nature and direction of ground water flow and may be important to a conceptual model of the area.

Rifting has produced many faults in the Española Basin (Kelly, 1978). Numerous studies have hypothesized the hydrologic significance of these fault zones. On the one hand these faults have been suggested to be barriers to flow (Spiegel and Baldwin, 1963); on the other, some suggest that these faults are conduits for enhanced flow (Blake et al., 1995). Direct evidence of faults serving as barriers to flow has been documented in the Santa Fe area (Spiegel and Baldwin, 1963) and in Ojo Caliente (Vuataz et al., 1984), where springs are located adjacent to faults which impede ground water flow.

Dan Koning of the NMBMMR has mapped numerous faults in the Tesuque Formation (Johnson et al., 2004) that may have significance in the development of the conceptual model. The major faults and related structures mapped by Koning include: 1) the Pojoaque fault system and associated Los Barrancos monocline; 2) the Jacona fault system and associated Los Barrancos monocline; 3) the Las Dos fault; 4) the San Isidro Crossing fault system; 5) the West and East Buckman faults; and 6) structures along the present-day Sangre de Cristo Mountain front.

Field mapping and characterization studies in conjunction with laboratory results indicate that faults in the Santa Fe Group are major structural and hydraulic heterogeneities in the subsurface due to several factors. These factors include the physical juxtaposition of sedimentary units with different hydraulic properties; the cementation and entrainment of lithologic material along the fault zone; and the persistent presence of clay-rich fault cores that have as much as six orders of magnitude lower permeability than the surrounding sandstone aquifer host rock. Johnson et al. (2004) documented anisotropic drawdown associated with the City well field in the city limits, and attributed it to the effects of faults acting as hydraulic barriers. The degree to which faults are acting as barriers to flow within the study area is highly uncertain. As additional drawdown in the basin and additional monitoring is performed, the importance of faults as barriers to flow may become more apparent.

5.3 Conceptual Hydraulic Flow Systems

Ground water flow in the basin has been described by ground water monitoring of hydraulic heads. The majority of the wells completed in the study area are shallow with depths less than 1,000 feet. In addition, the vast majority of the head measurements available for the region are for unconfined heads representative of the water table. As a result, the vertical distribution of heads and the knowledge of vertical hydraulic gradients is limited. Conceptually, gradients within the Santa Fe Group would be expected to be down in the highlands near the areas of mountain front recharge. Moving towards the Rio Grande, vertical gradients would be expected to reverse from downward near the mountains to upward nearing the Rio Grande. Most models of the region have some decay of hydraulic conductivity with depth which results in less ground water flow at increasing depths within the aquifers. The hydraulic conceptual flow systems in Santa Fe County have been divided into three conceptual hydrologic systems which have been described in Section 4.3.

5.3.1 Recharge

The Santa Fe Group aquifer generally receives recharge from the eastern Precambrian uplift and, to a lesser degree, from the western Jemez volcanic uplift. Additional recharge may occur in higher elevation streams and arroyos and in areas of stream capture. Areas away from the uplands or arroyos are not expected to receive appreciable recharge unless they do so as a result of human-induced activities (i.e., discharge from a waste-water treatment plant). In arid alluvial basin settings, little natural, direct recharge occurs in non-mountainous areas because of a high evaporation potential combined with less precipitation. The recharge that does occur is expected to be from seepage into arroyo channels associated with localized rainfall events. The chloride mass balance work of Anderholm (1994) supports this concept. Several studies, including those of Keating et al. (2002) and Shomaker et al. (2001), determined threshold elevations below which areal recharge would only occur through arroyo channels.

5.3.2 Natural Aquifer Discharge

Natural aquifer discharge occurs from three basic processes, discharge to streams and rivers (baseflow), discharge to springs, and discharge through ET. Within the study area, another type of discharge occurs related to subsurface discharge from the active model domain to areas not modeled. Recent studies have determined that discharge from the Española Basin to the Middle Rio Grande Basin may be significantly reduced relative to previous estimates (Sanford et al., 2004). This implies that that the Española and Galisteo basins collectively act as an isolated basin where recharge originating from with the basin dominantly discharges in the basin as stream and spring discharge and ET.

Estimates of discharge to streams vary widely for the region. In addition, little is known regarding the decrease of aquifer discharge, through all three mechanisms, as a result on pumping in the aquifers. Spring discharge estimates are available for many of the springs in the study area. However, many of these estimates are based upon a single observation at a single point in time. Estimates of ET in the region are also lacking. However, in reaches of gaining streams it is reasonable to assume that ET would be a significant ground water sink. McAda and Wasiolek (1989) estimated that ET along the Rio Grande in their model region was approximately 5,144 ac-ft/yr. DE&S (2001) estimated that the portion of the Jemez y Sangre Planning Region within the study area had a ground water ET of 12,300 ac-ft/yr.

5.3.3 Pumping

After development, natural aquifer discharge is augmented by discharge from pumping. Domestic and municipal pumping were approximately equal in the late 1940s at about 800 ac-ft/yr each. Pumping has increased significantly since that time to greater than 25,000 ac-ft/yr in 2004, by which time domestic pumping had increased to 3,199 ac-ft/yr. Municipal pumping peaked in 2002 at 15,110 ac-ft/yr. Other types of pumping include community water systems and irrigation wells which made up another 5,000 to 6,000 ac-ft/yr by 2004.

Large portions of the study area are minimally impacted by pumping; however, knowledge of predevelopment conditions is limited, and some portions of these aquifers have experienced significant drawdown. In these regions, stream base flow, spring flow, ET, and cross-formational flow are expected to have decreased with development.

5.4 Conceptual Flow Balance of Model Region

SIn a natural aquifer system unaffected by anthropogenic activities, the aquifer system is in a long-term dynamic equilibrium condition generally referred to as a steady-state condition (or predevelopment). In this predevelopment state, aquifer recharge is balanced by aquifer discharge resulting in no net change in ground water storage. Recharge may include areal recharge from precipitation, cross-formational flow from adjacent water bearing formations, and, potentially, stream losses. Discharge includes stream base flow, spring flow, ET, and ground water subsurface flow.

Human activities alter the dynamic equilibrium of the predevelopment flow system through pumping withdrawals, changes in recharge through development and irrigation return flow, and changes in vegetation. Generally, ground water withdrawals due to pumping have the most significant impact on aquifer hydraulics. The water removed by pumping is supplied through decreased ground water storage, reduced ground water discharge, and sometimes increased recharge. Generally, increased recharge as a source of water to pumping wells is negligible compared to decreased ground water storage and decreased aquifer discharge (Alley et al., 1999). If pumping stays relatively constant, a new steady-state condition will be established. In this new equilibrium, the source of the pumped water will be drawn completely from either reduced discharge or increased recharge, again the latter of which is usually negligible. Bredehoeft (2002) terms these two volumes as capture. The sources of discharge, which are ultimately captured by pumping, include stream base flow, spring flow, ET, and ground water subsurface boundary flow.

Bredehoeft (2002) defined sustainable yield (i.e., a sustainable pumpage) as being equal to the rate of capture. In the situation of sustainable aquifer dynamics, the pumping rates in the basin are being matched by the capture in discharge with a net result of water levels becoming stable (albeit at a lower level than pre-development). It is important to note that a sustainable yield may not be a desirable future state of an aquifer, and therefore, may not represent an optimal yield. For example, a sustained yield could result in decreased discharge to streams (stream-flow capture) that would prove to be undesirable. If a basin is continually pumped at a rate (total pumpage) that is greater than the basin's discharge rate (discharge capture), then water levels will continually decline and natural discharge will diminish. This condition was referred to as an unstable basin by Freeze (1969).

To evaluate the SFCM flow balance, estimates of predevelopment inflows and outflows were used to conceptualize the predevelopment ground water flow balance, or the steady state condition, of the model region. Based on studies of the model area (McAda and Wasiolek, 1989; Frenzel, 1995; and DE&S, 2001), inflow to the basin was conceptualized from areal recharge, mountain front recharge, stream loss (sometimes lumped with mountain front recharge), and subsurface boundary components. Outflow was conceptualized from components consisting of streams and springs, the Rio Grande, ET, and the subsurface boundary. With the exceptions of estimates for ET and subsurface boundary flow, the estimates used in the steady-state conceptualization were derived from the studies in which they were reported. Because ET was not specifically accounted for in the McAda and Wasiolek (1989) or Frenzel (1995) models, and because DE&S (2001) estimated ET losses for the Jemez y Sangre region but not the Velarde Basin, the estimate for conceptual ET flow, was obtained by subtracting stream and spring gains and subsurface boundary outflow from net outflow, posited to be equal to net inflow. The estimate for the subsurface boundary outflow was based upon the work of Sanford et al., (2004) but was decreased to account for the location of the current model boundaries and current conceptualization of subsurface discharge. Table 5-1 presents the conceptual ground water flow balance, including the flow components and estimates, for the model region.

Although the estimates presented in Table 5-1 are uncertain because of their dependencies upon the studies on which they are based, and especially with respect to differences between predevelopment and historical conditions (i.e., transient), they present a conceptual partitioning of the primary basin inflows and outflows within the study region based upon available information, the boundaries of the SFCM, and current hydrogeologic understanding. In this partitioning, the predevelopment ground water discharge volume available for capture in the model region is approximately 45,000 ac-ft/yr, the dominant source being stream and spring gains (33,000 ac-ft/yr), with ET (11,000 ac-ft/yr) and subsurface boundary flows (1,000 ac-ft/yr) making up the difference. Under the assumption of steady-state conditions, the conceptual outflow from the region is equal to the conceptual inflow, which is also 45,000 ac-ft/yr, with 30,000 ac-ft/yr from mountain front recharge, 7,000 ac-ft/yr from areal recharge, 5,000 ac-ft/yr from stream losses, and 3,000 ac-ft/yr from subsurface ground water inflow.

Current pumping within the study area is approximately 25,000 ac-ft/yr, or roughly half of the conceptually available discharge. How much a decrease in storage and capture of discharge have balanced historical pumping in the study area remains uncertain as does the nature of capture in the Buckman wells, which may be surface water with a source outside of the basin. Interestingly, the conceptualization of ground water flow balance in the model region estimates that the Rio Grande is the flow component for approximately 24,000 ac-ft/yr, or 53%, of the 33,000 ac-ft/yr outflow to stream and springs. This estimate is consistent with a gain of approximately 1 cfs across the model area.

5.5 Conceptual Model Summary

From a review of the conceptual controls for ground water flow in the study region, several key conceptual issues can be identified for consideration in the SFCM. These items will be briefly discussed in bullet form below.

- It is expected that at the large scale, lithologic heterogeneity will have a significant effect on ground water flow within the region. As a result, development of the SFCM attempted to account for depositional controls through the mapping of hydrostratigraphy and accounting for bedding structures through horizontal to vertical hydraulic conductivity anisotropy.
- The geology in the Santa Fe Embayment is very complex. Ground water flow is largely controlled by the complex structure and formation and aquifer juxtapositions. As a result, the SFCM was not able to be a standard layer approach and required composite properties to account for the complex aquifer structure.
- There is significant uncertainty in hydraulic properties at the model scale for formations other than the Santa Fe Group. Hydraulic properties for the all units are very uncertain at depths greater than 1,000 feet.
- Faults are a potential control on ground water flow. Therefore, the SFCM includes major faults.
- Recharge to the model will come from three primary sources, mountain front recharge, stream losses, and areal or diffuse recharge.
- Natural aquifer discharge is an uncertain, though important conceptual aspect of ground water flow in the study area. Conceptually we expect approximately 70% or greater of the basin discharge to occur to streams and springs, with the Rio Grande acting as the largest sink. Ground water ET is highly uncertain but is expected to be an important discharge mechanism before resource development.

6.0 MODEL DESIGN AND PARAMETER IMPLEMENTATION

This section describes how the conceptual model defined in Section 5 is translated into the numerical model. Issues related to model design (i.e., number of model layers) and initial model parameterization (i.e., hydraulic properties) are described in this section.

An important aspect of the Española Basin, especially in the Santa Fe Embayment area, is the complex geology and structure present. A particular area of interest in this study consists of the regions within the County south of the Santa Fe River which are characterized as having a complex assemblage of Tertiary basin fill overlying eroded, faulted Mesozoic and Paleozoic formations. Intruded within the sedimentary units are Tertiary intrusive volcanic units. As a result, geologic units in the model area are discontinuous. Most finite-difference codes (including MODFLOW) were designed to handle continuous aquifers and aquitards where each aquifer or aquitard is able to be assigned to a continuous model layer. However, many potential aquifers within the model domain are not continuous within the model domain, making the classical layered approach impossible.

As a result, a different approach has been implemented for this hydrologic model. The approach to hydrologic model development starts by developing a three-dimensional geologic model comprised of the modeled HSUs. The HSUs being included in the model are defined in Table 4-2. Once the geologic model is developed, the hydrologic model is intersected with the model grid to define which HSUs are resident in each model grid. Hydraulic properties are defined at each HSU scale. Then, composite properties are developed based on HSU properties and the relative juxtapositions and proportions of each HSU in each model cell

6.1 Model Layers and Grid

As discussed above, the complexity of the geology within the model domain precludes a layer-aquifer approach to model layering. As a result, hydrologic model layers were developed to be of uniform thickness. The hydrologic model layers were tied to the pre-development water table surface in an attempt to avoid significant wet-dry oscillations during model convergence.

A map of estimated pre-development conditions was developed and is based on the maps presented by Spiegel and Baldwin (1963), Mourant (1980), Frenzel (1995) and DBS&A (1994). The surface was smoothed and forced to lie at or below land surface. The resulting pre-development surface is shown in Figure 4-7.

Layering thicknesses were based on existing models of the region, particularly the Frenzel (1995) and CDM (2002) models. The model contains nine layers, with layer thicknesses (from top to bottom) of 100, 100, 275, 325, 475, 725, 1,000, 1,200, and 1,400 feet. Specifically, the top of layer 1 was based on the USGS digital elevation model (DEM) elevation averaged within each model cell and the base of layer 1 was set at 100 feet beneath the pre-development surface. This resulted in model layer 1 having variable thickness but an initial (pre-development) saturated thickness of 100 feet.

The model grid was designed to have a grid size dimension from 1 mile to as small and 0.25 mile. Consistent with the requirements of MODFLOW, the grids are rectilinear. The smallest grid size of 0.25 miles was selected based upon maintaining a reasonable size simulation grid. The smallest grid dimensions were applied in and around large pumping centers such as the

Buckman well field and the Santa Fe well field and in areas of the model where improved resolution was desired. The model grid has 313,956 grid cells (9 layers, 228 rows, and 153 columns). The number of active grid cells is 286,308. Figure 6-1 is an illustration of the model grid.

6.2 Geologic Model

As discussed above, geologic controls on the nature and extent of the principle aquifers within the Española Basin play an important role in the assessment of water resources. The primary focus for the development of the geologic model described in section 0 was to provide a rationale for parameterization of the hydrologic model. Depositional environments and volcanic events provided the basis for selecting the HSUs included in a representative geologic column (Table 4-2). This common geologic column of HSUs was used as the basis for defining the three-dimensional geologic model developed in the Ground water Modeling System (GMS) software environment through the use of surface geology, available regional cross-sections, aeromagnetic data, and unpublished work in the region connecting the Española and Santa Domingo Basins. Using a Geographic Information System (GIS)-based methodology to integrate the wide variety of geologic data, the previously defined grid and layering was then superimposed on the geologic model to begin the process of assigning the hydraulic parameters within the hydrologic model grid.

Available NMBGMR and USGS quadrangle maps, cross sections, and well logs were compiled for this study (Section 4.0 and Figure 4-1). Available geologic maps and well information were imported into the GMS environment as georeferenced images. Information from these images was then used to provide data control at the ground surface for the construction of a three dimensional geologic model. Lithology and geologic units described by the geologic maps were categorized based on the HSUs. Similarly, cross sections provided with quadrangle maps were used to establish subsurface relationships. A borehole (stick) model was constructed based on available well and boring information as well as interpreted stratigraphy from cross sections. Information from boreholes along the section lines was included where available including the wells referenced in Section 4-1. To increase the data coverage, synthetic boreholes were also developed from estimations of geologic unit contacts and thicknesses along cross section lines. The borehole model was then used to develop schematic cross-sections that linked the data from the various sources. Figure 6-2a provides the approximate lines of section for the schematic cross sections illustrated in Figure 6-2b. The cross sections illustrated in Figure 6-2b define the interpreted structural hierarchy of the basin. The sections shown in Figure 6-2b include borehole data derived from actual wells and synthetic boreholes inferred from various cross sections.

Geophysical data collected from various studies were also compiled during the process of the geologic model development. The data includes basin-wide aeromagnetic data from Phillips and Grauch (2004) and other gravimetric surveys within the transfer zone between the Española and Santo Domingo Basins (Minor et al, in press). In general, the data provided in these studies provides an estimate of the structure and form of the basin bedrock. However, some of the more recent geophysical data (Minor et al, in press) also provide some estimates of the thicknesses of the more recent Cerros del Rio and other volcanic units that overlie deeper basin sediments. Figure 6-3 shows the surface derived from the combination of these datasets. Contour elevations indicate deep basin sediments (greater than 10,000-foot depth) in the northern portion of study area, while the sediments are significantly shallower in the southern portion of the basin within the remnants of the uplifted Galisteo paleobasin. The narrow basin transfer zone in the western portion of the map along the Rio Grande is bounded on the east by fault zones that include the Tano and La Bajada faults.

Within the geologic model, the only fault with major offset explicitly represented was the La Bajada fault zone in the western portion of the model. Although this fault has a variable dip, ranging from approximately 20 to 90 degrees where measured (Sawyer et al, 2002 and Maynard et al, 2002), to simplify the geologic model construction the fault was assigned a single vertical dip of 90 degrees along the main trace of the fault described by Sawyer et al. (in press). Other fault traces within the basin with less structural offset were more easily represented in the flow model using the hydrologic flow barrier (HFB) package within MODFLOW.

Construction of the three dimensional geologic model used the horizon approach within GMS based on superposition principles where each of the HSUs was assigned a hierarchical position based on depositional history (Section 4-1). Surfaces and solid models of each of the HSUs were created from the interpreted datasets integrated within the software, as illustrated in Figure 6-4. The upper bound of the geologic model was derived from a DEM of the topography, while the lower bound the model corresponded to the elevation of the bottom of the flow model grid. The lateral extents of the geologic model were placed outside of the extents of the flow model grid. To maintain the offset along either side of the La Bajada fault, independent solid models were constructed on either side of the fault trace. Similarly, separate models of intrusive igneous zones in the southern portion of the model were developed based on known and estimated lateral extents of these zones and then integrated into the rest of the solid models. The solid models of each HSU were then mapped to the model grid for development within the MODFLOW HUF package. A representative flow model column shown in Figure 6-4 depicts HSU structure mapped across the grid column and the translation of the HSUs to initial hydraulic conductivity used in the flow model development.

6.3 Initial Hydraulic Properties

The HUF2 Package was used to apply the hydraulic properties within the model. The HUF2 Package was chosen for the following reasons:

- The complexity of the geology, particularly in the southern portion of the model domain, is not amenable to the typical layer-aquifer approach to parameterization;
- Aquifer test data and previous modeling efforts suggest that hydraulic conductivity decreases with depth within the model domain;
- Assigning parameters, primarily HSUs, results in a minimal number of model parameters for calibration.

The HUF2 Package allows material properties to be varied by HSU and computes composite properties for each of the active model cells. The effective horizontal K_h within a model cell is the weighted arithmetic mean of the K_hs of all the HSUs in that cell. The weighting is dictated by the thickness of each HSU within the cell. The effective vertical hydraulic conductivity (K_v) within a model cell is the weighted harmonic mean of the K_vs of all the HSUs in that cell.

The HUF2 package allows hydraulic conductivity to decrease with depth within a single HSU. Hydraulic conductivity is assumed to decay exponentially with depth and, using land surface as the reference surface, may be computed as:

$$K_{depth} = K_{surface} 10^{-\lambda d} \qquad (6.1)$$

where

K_{depth} = hydraulic conductivity at depth d,
$K_{surface}$ = hydraulic conductivity at land surface,
λ = depth-decay coefficient, and
d = depth below land surface.

The only HSU with sufficient data to fit a depth decay coefficient was Lithosome S of the Tesuque Formation. As a result, a depth decay coefficient and the value of 0.0012 was used as an initial estimate for all HSUs. For the Ancha, Espinaso, Galisteo, and Tesuque Lithosome B units, a few concurrent depth and conductivity data existed and, using a λ of 0.0012, an initial value for $K_{surface}$ was fit through linear regression. For all other HSUs the initial reference conductivity value had to be estimated based on relative differences in the median K_h from Table 4-3. This process assumed that well depths, although not reported, were comparable between HSUs and maintained a hierarchy in the relative differences in conductivity from one unit to the next. Table 6-1 summarizes the initial estimates for the $K_{surface}$ and λ parameters to be used in the model. Initial model simulations investigated the sensitivity of the depth decay parameters. Those that were found to be sensitive were varied in calibration (see section 0). Note that $K_{surface}$ is a fitting parameter with no physical significance. For example, the value of $K_{surface}$ was reduced by 25% in the first 100 feet from ground surface and by 94% at a depth of 1,000 ft.

In transient simulations, aquifer storage must be specified. The HUF2 package calculates the effective storage term within a model cell as the weighted arithmetic average of the storage terms of all the HSUs in that cell. For convertible layers, the HUF2 package uses the location of the water table, computed during each outer iteration, to recalculate the storage and conductivity terms using only the portions of the HSUs within the cell that lie beneath the water table. Very little data exist for storage parameters for the HSUs in the model area. Initial estimates were based primarily on values from previous modeling reports. Table 6-1 summarizes initial estimates of specific yield (unconfined) and specific storage (confined) coefficients for each of the HSUs in the model. Conceptually, the HSUs may be broken up into two groups regarding unconfined storage parameters: alluvial sediments with a specific yield approaching the material porosity and bedrock units with a specific yield more indicative of fractures. The specific storage values used are consistent with those used by Shomaker et al. (2001).

The hydraulic parameters discussed above were anticipated to be key calibration parameters in the SFCM. Parameters were adjusted by HSU and, in the case of the Tesuque, zones within an HSU. If target data warrant it, additional zonation, whereby material properties vary within a given HSU, can be added in the future stages of calibration.

A series of faults exist within the model domain. The majority of faults trend primarily north-south and many are conceptualized to result in zones of significantly lowered permeability (Johnson et al., 2004). To simulate the effect of these faults, the MODFLOW Horizontal Flow Barrier (HFB) package (Harbaugh et al., 2000) was used.

A coverage of the fault traces at land surface was generated from a compilation of existing fault maps (Grauch and Bankey, 2003; Johnson et al., 2004). The fault coverage was screened to include only faults with lengths greater than 4,000 meters to eliminate minor faults. From comments provided by the OSE, the Barrancos fault was added to the fault traces considered in the model. Figure 6-5 shows the remaining faults which were included in the HFB package. The faults were assumed to penetrate the entire model depth and to be vertical in orientation. The first assumption is considered adequate because the model will likely be insensitive to faults within the lower conductivity materials at depth within the model. The second assumption is necessary due to a lack of information describing the fault slopes and is considered adequate based on the lateral scale of the model grid blocks compared to the estimated horizontal offset of the fault slopes.

The HFB (fault) conductances are unknown and therefore were considered in model calibration as free parameters. A free parameter is a parameter which will be allowed to be adjusted during calibration. HFB conductances have been lumped together to be applied uniformly for a given fault or a group of neighboring faults. An initial sensitivity analysis, where fault conductances for Los Barrancos fault were lowered until an effect upon model targets is observed, was performed to develop initial conductance estimates. All other faults were inactivated but left in the model for consideration by other investigators.

6.4 Lateral Boundary Conditions

Specified flux, no-flow, and head-dependant flux boundary conditions were used to describe the interaction of the active model area with regions beyond the model domain. The types and locations of boundary conditions used in layer 1 of the model are depicted in Figure 6-6. Figure 6-7 shows the types and locations of the boundary conditions used for layers 2 through 9. An implicit no-flow boundary is assumed beneath layer 9.

The eastern boundary of the active model domain, from the Santa Cruz River in the north to the southern extent of the Sangre de Cristo mountains in the south, is described by a specified flux boundary condition representing the mountain-front recharge from the Sangre de Cristo mountains. The western boundary, from Santa Clara Creek in the north down to the southern extent of the Jemez mountains in the south, is described by a specified flux boundary condition representing the mountain-front recharge from the Jemez mountains. The determination of these recharge fluxes is discussed in section 0. The stream boundary conditions are head-dependant flux boundaries and are also discussed in section 0.

The MODFLOW general-head boundary (GHB) package (Harbaugh et al., 2000) was used to represent the head-dependent flux boundary conditions at the remaining portions of the lateral boundary of the model. The GHB package requires specification of a hydraulic head within the model cell and a conductance.

The northern boundary of the model is defined by Santa Clara Creek and the Santa Cruz River and is a GHB. Insufficient gage data existed for these streams to be included in the Stream package however, both streams are perennial. To approximate the stream stage elevation in each model cell, the DEM elevations at the location of the stream polylines were averaged for each model cell and the average elevation was used to represent the GHB head. GHB cells are assigned to Layers 1 through 9 in the northern boundary. The streams are considered natural ground water divides near the surface and the streams run roughly parallel to the direction of flow coming in as mountain-front recharge from the eastern and western boundaries and discharging to the Rio Grande.

The southeastern, southern, and southwestern boundaries of the model, from the southern extent of the Sangre de Cristo mountains wrapping southward to the southernmost extent of the model and northward past the La Bajada constriction to the southern extent of the Jemez mountains, is described by a GHB. The pre-development water table surface was used to represent the GHB head. GHB cells were applied to Layers 1 through 9.

The initial conductances of all the GHB cells were based on the initial values of effective K_h within the model cell. The depth decay applied to the hydraulic conductivity dictates that the conductance will decrease with depth and the majority of the flow through the GHBs will occur in the uppermost layers. The conductances were adjusted during calibration through a multiplier that was kept uniform across groups of GHB cells. In this way, the number of adjustable parameters is kept to a minimum during calibration (see Sections 8 and 9). The current locations of the groups of uniform adjustment for calibration are shown in Figure 6-8. Groups 1 and 2 represent Santa Clara Creek and the Santa Cruz River, respectively. Groups 3, 4, and 5 represent different portions of the southern boundary through which little flow is expected to occur. Group 6 represents the region where ground water flows out from the Santa Fe basin into the Santa Domingo basin along the Rio Grande alluvial deposits. Group 7 represents the region west of the Rio Grande through which little flow is expected to occur. The initial conductance ranges for each of the GHB conductance groups were developed based on a hydraulic conductivity of 1 ft/d at ground surface with depth decay equivalent to what was used for the hydraulic conductivity field. The reason for using a conductivity of unity was to allow simple modification of conductance groups during calibration.

6.5 Implementation of Recharge

Mountain-front and areal recharge are simulated in the model using the MODFLOW Recharge package. The details on how each type of recharge is distributed spatially in the model are described in the subsections below.

6.5.1 Temporal Variation in Recharge

Both the mountain-front and areal recharge are based on precipitation in the region. Both mountain front and areal recharge are varied with time as inputs to the model to account for the natural variation in precipitation within the region. The approach for varying the conditions over time involved determining the average annual precipitation for the western, central, and eastern portions of the model domain separately. Then, for each subregion, recharge at a given time was calculated as the ratio of that time periods deviation from the mean precipitation. Therefore, if precipitation in a given year was 10% above average, then recharge would be 10% over the average model recharge value. The details of this process follow.

Four precipitation gages were used for each area of interest, except for the west boundary where three gages were used. The areas of interest were defined as the East boundary, representing the Sangre de Cristo Mountains; the West boundary, representing the Jemez Mountains; and Areal recharge, representing the interior portions of the model. Table 6-2 provides a list of the gages used for each region, their period of record, average precipitation for each station and average precipitation for each region.

The average precipitation value for each region was used to calculate an annual recharge coefficient (monthly recharge coefficients for 2002–2004) based on the percent deviation from the average for each region and the initial recharge values used. The recharge coefficients are computed as follows:

Recharge coefficient = (Total Precipitation for Given Time Period) / (Total Average Precipitation)

The monthly recharge coefficients are also based on the Total Average Yearly Precipitation. Table 6-3 and Table 6-4 present the annual recharge coefficients for 1948–2001 and monthly coefficients for 2002–2004, respectively. Coefficients of 1.0 are applied to the years 1946 and 1947 since no precipitation data were available for those years.

6.5.2 Spatial Variation in Mountain-Front Recharge

The initial values used for the eastern and western mountain-front recharge were estimated from water balance studies where they were available and on values from calibrated models for areas where field studies were not available. Wasiolek (1995) provided estimates of mountain-front recharge for five tributary basins in the Sangre de Cristo Mountains. Shomaker (2001) provided estimates of mountain-front recharge for the Sangre de Cristo Mountains south of the Santa Fe River. Frenzel (1995) provided estimates of mountain-front recharge for the Sangre de Cristo and Jemez Mountains. These sources were used to define zones along the east and west model boundaries, with each zone simulating a constant flux as the initial condition. In addition to the major mountain-front recharge zones from the Sangre de Cristo and Jemez Mountains, recharge from the Ortiz porphyry belt to the southwest of Galisteo creek was also applied to a portion of the southwest model boundary.

6.5.3 Spatial Variation in Areal Recharge

Areal recharge was applied using a zonal approach, with uniform recharge within a given zone. The areal recharge zones were delineated based on two criteria: the surface geology and the presence of irrigated acreage.

It was assumed that the surface geology in the region correlates to the density of arroyos present. It was also assumed that the arroyos are the surficial locations where areal recharge occurs but that, at the scale of this model, the focused source could be areally spread. Two zones were defined and assigned different initial areal recharge rates. To the northwest of the Rio Grande, a rate of 0.035 in/yr was applied and to the southeast of the Rio Grande, over the remainder of the model domain, a rate of 0.05 in/yr was applied.

Regions within the model domain that contain irrigated acreage are delineated separately since the volume of irrigation-based recharge can be significant compared to native recharge. Irrigated acreage within the study area was identified using 1996 digital orthophoto quarter quadrangle (DOQQs) and natural-color Landsat imagery refined with USGS 7.5-minute digital raster graphic (DRG) topographic quadrangles. The irrigated lands were superimposed on the model grid to delineate model cells where irrigation was simulated. Model cells that contained 50% or more irrigated lands were included. OSE water usage reports (Sorensen, 1982; Wilson, 1986; Wilson, 1992; Wilson, 1997; Wilson, 2003) were used to estimate irrigation-based recharge. The OSE water usage reports include detailed tables for irrigation withdrawals and irrigation depletions by key irrigated areas within each county. Data from the Pojoaque and Santa Fe irrigated areas were used to estimate irrigated region recharge rates since these fall completely within the model area. Irrigation water potentially available for recharge was determined from the difference in total irrigation withdrawals and total irrigation depletions, the latter assumed to be used from crop consumptive use. Generally about twice as much water is withdrawn as is reported to be used consumptively by crops. It was assumed that approximately half of the irrigation water not used consumptively runs off as surface flow and returns to nearby streams and half percolates into the ground to become recharge.

The recharge rate was calculated by dividing the volume assumed to recharge by the irrigated acreage reported in the OSE reports. The resulting recharge is approximately 6 in/yr. This rate is consistent with what was used in the Middle Rio Grande Basin ground water model (McAda and Barroll, 2002). Areal recharge in the irrigated areas of the model will not vary over time. This is because irrigation practices are assumed to have remained constant over time and therefore the excess irrigation water that is potentially available for recharge should also stay constant over time relative to the error in the estimate. Figure 6-9 shows the areal recharge zones including the irrigated acreage areas, and initial recharge rates. Some of the irrigated acreage near Santa Fe includes large lawn and grass areas; for the purposes of this modeling effort they are also assumed to produce a ground water recharge rate of 6 in/yr.

A zone of higher areal recharge (0.5 in/yr) was applied to the Cerrillos Hills in the southern portion of the model domain. This accounts for the recharge mound apparent in the pre-development water levels and resulting from the higher elevation of the Cerrillos Hills. This recharge boundary is likely in part a result of poor boundary location and poor adherence of the physical conditions to the boundary assumptions.

Another potential source of recharge is from septic tanks. The septic tank recharge is factored into domestic well pumping rates through a reduction in total domestic pumping (see Section 6.6.2).

6.5.4 Ground water Evapotranspiration

Ground water can be a source of ET when the water table surface is within the root zone of native and irrigated plants. It is a potentially significant physical discharge process in the lower elevations of the basin near the existing surface water systems. The ET package of MODFLOW was implemented to simulate this process. An elevation mask was used to constrain ground water ET to elevations below an elevation of 6,400 ft above mean sea level (amsl). Below an elevation of 6,400 feet amsl, the maximum allowable ET rate was varied linearly with a rate of 5 in/yr occurring at the lowest elevation within the model domain and a rate of 0 in/yr occurring at an elevation of 6,400 feet amsl. An extinction depth of 20 ft was used.

6.6 Ground water Pumping

For the purposes of the SFCM, all aquifer pumping is categorized in three ways: municipal, domestic, or other water systems. The following sections provide background on how each was approached conceptually and describes how the pumping was implemented in the model. The implementation of pumping was performed in collaboration with CDM who developed the approach and values described in this section.

6.6.1 Municipal Pumping

Municipal well fields located within the model domain were identified. The Utilities Department or equivalent at Santa Fe, Buckman, Los Alamos and El Dorado well fields was contacted to obtain historical municipal pumping records and well information for each of their wells. Historical well production data were collected for the years 1947 through 2004, as applicable for the given water system. Where data gaps existed, other sources of information were investigated including the OSE WATERS database and previous modeling report for the area.

Municipal pumping records and well information were collected for each of the wells in the Santa Fe, Buckman, Los Alamos, Guaje, Pajarito, and El Dorado well fields. Historical data were gathered from City production reports, Frenzel (1995), County of Los Alamos production reports, Eldorado Utilities production reports, and Shomaker et al. (2001).

Municipal production data from each source were compiled into a single database and average production rates were computed for each model stress period. Stress periods are annual from 1947 through 2002 and then monthly from January 2002 through December 2004. All rates were converted into consistent units of cubic ft per day (cfd). Table 6-5 contains well information and production data, respectively, for the municipal wells that were included in the ground water model. Municipal well production was distributed using the Multi-Node Well (MNW) package in MODFLOW. This package uses the screen top and screen bottom elevations to assign pumping to model layers in proportion to the transmissivity of each model layer screened by a well.

6.6.2 Domestic Pumping

The domestic and other low-capacity pumping, defined herein as domestic wells, was extrapolated from data contained in multiple sources. The first is the WATERS database obtained via the OSE website, screened to remove the exploratory, observation, and municipal wells. This database was queried on predetermined time intervals by 'Start Date' in the database to identify when domestic wells were installed. Domestic well production data have been estimated in the 2001 and 2003 Jemez y Sangre Water Plans as well as in OSE water usage reports (Sorensen, 1982; Wilson, 1986; Wilson, 1992; Wilson, 1997; Wilson, 2003). These sources quantify domestic well production over time for a given county or planning region. Total domestic production within the model domain for each predetermined interval was calculated using available data.

Often coupled with domestic wells is a septic system that allows for a portion of the amount of water pumped from a domestic well to return to the aquifer as recharge. To account for this recharge to the upper portion of the aquifer, the domestic well production rate was reduced by 45 percent. This assumes that septic system recharge occurs in the same areas where there is domestic pumping.

Using the well distribution for a given time interval, the amount of water attributed to domestic pumping was divided amongst the domestic wells known to exist according to the WATERS database. All domestic wells were assumed to be relatively shallow, averaging less than 100 ft of penetration below the water table surface, and are assigned to model layer 1.

Domestic pumping rates were obtained from OSE water usage reports (Sorensen, 1982; Wilson, 1986; Wilson, 1992; Wilson, 1997; Wilson, 2003). These reports list domestic water use by county.

The model domain does not coincide with county boundaries, therefore population estimates from U.S. Census 2000 tracts were used to arrive at an approximate model domain population. The entire population of any tract, fully or partially within the model domain, was counted toward the model domain population. Total domestic usage for each county was then derived by multiplying total domestic usage by the ratio of model domain population to total population. This number likely overestimates actual domestic pumping because of the inclusive use of census tracts. The population ratio was assumed to remain constant in time.

Domestic usage within model domain:

$$\frac{P_M}{P_T} = \frac{Q_M}{Q_T} \rightarrow Q_M = Q_T \frac{P_M}{P_T} \tag{6.2}$$

where:

P_T = Total population of the given county (from OSE reports)
P_M = Population in the model domain of the given county (from census tract estimation)
Q_T = Total domestic well pumping in the given county (from OSE reports)
Q_M = Domestic well pumping in the model domain of the given county (unknown)

To estimate domestic pumping for 1947–1979, an exponential curve was fit to the 1980–2000 domestic water use data and back-extrapolated to 1950. The value for 1950 was used for 1947–1955, the value for 1960 was used for 1956–1965, the value for 1970 was used for 1966–1975, and so on. Historic and estimated domestic water usage within the model domain by county is shown in Table 6-6 and Figure 6-10.

The domestic pumping rate is distributed spatially to the well locations identified by the WATERS database and evenly distributed among them. The spatial distribution of domestic wells reported in WATERS was used to approximate the actual spatial distribution of population using domestic wells, as the true number of domestic wells is most likely underestimated in WATERS, especially in pre-basin years (OSE, 2000). The total domestic pumping in a given year reported in Table 6-6 was reduced by 45 percent to account of septic system recharge as assumed in OSE water usage reports. To distribute the resultant domestic pumping spatially and temporally, the total domestic pumping, less the amount assumed to recharge, is divided evenly amongst the domestic wells identified via the WATERS database, Table 6-7. The "effective" domestic pumping rate ranges from a high of 6.72 ac-ft/yr in 1950 to a low of 0.63 ac-ft/yr in 1995. Domestic usage by time interval is illustrated in Figure 6-11.

Domestic well production was distributed using the MNW package in MODFLOW. However, it is assumed that all wells occur in the upper model layer, which contains 100 ft of saturated aquifer thickness under predevelopment conditions.

6.6.3 Other Pumping

Other significant well pumping identified in the region can be classified in two categories: community water systems and agricultural pumping. Production and well information was gathered from Shomaker et al. (2001), OSE water usage reports (Sorensen, 1982; Wilson, 1986; Wilson, 1992; Wilson, 1997; Wilson, 2003), the WATERS database, and County records. This data were compiled to provide an estimated spatial and temporal representation of non-municipal and non-domestic pumping.

Community Water Systems

Four sources were used to identify community wells within the model domain. These sources were used collectively to identify community water systems. Shomaker et al. (2001) identified 28 community water systems within the southern portion of the modeling domain. A second source used to identify community water systems was the OSE water usage reports (Sorensen, 1982; Wilson, 1986; Wilson, 1992; Wilson, 1997; Wilson, 2003). The OSE reports identify 40 additional community water systems located within the model domain. The data provided by two other sources, the County and the OSE WATERS database, identified seven and one additional community water systems respectively. A database of the community water systems included in the SFCM is provided in Table 6-8, including location and pumping rates.

Where pumping rate data conflicted between the sources identified in the previous section, preference was given to values reported in Shomaker et al. (2001), then the OSE reports, then from the County report, and finally from the OSE WATERS database. Shomaker et al. (2001) recently compiled a database of community wells with location and pumping data and this was supplemented with wells identified in OSE reports since it does not include location information. The OSE WATERS was used to identify any wells that had not been identified in previous sources and to determine well location.

For each community water system, an average annual production rate was determined from available data. Pumping begins at a particular well at the earlier of the well completion date or the first year production data are reported. Pumping stops only for those community water systems that appear in at least one OSE report and do not appear in any subsequent OSE reports. The last year of pumping is the last year of the interval associated with the last report in which the community water systems appears. In rare instances, a community water system is omitted from an OSE report, but later reported (e.g. reported in 1980 and 1990, but not in 1985). In these cases, the average annual pumping rate is used for years of the omission. The annual average pumping rate is used for the lack of available production data. In the case were model stress periods are monthly, the production rates in community water system wells are assumed to be constant throughout the year.

Well completion information for a majority of the community water systems is not readily available. Based on information provided in Shomaker et al. (2001), community system wells were completed in layers 1 through 3 of the model (approximately 400 to 1,000 ft deep). Community water systems well production was distributed using the MNW package in MODFLOW.

Agricultural Pumping

The locations of agricultural wells were determined using the OSE WATERS database. The database was queried for wells located in the model domain that had a primary use code of IRR, indicating irrigation well and a diversion amount greater than 5 ac-ft/yr. A total of 39 wells was found in the database. A list of these wells is provided in Table 6-9.

Information on the amount of ground water pumping for irrigation has been reported every 5 years since 1980. The OSE water usage reports (Sorensen, 1982; Wilson, 1986; Wilson, 1992; Wilson, 1997; Wilson, 2003) were used to identify historical irrigated acreage within the study area. Based on these studies, the amount of irrigated acreage has remained relatively constant over time. Total agricultural pumping is estimated by the sum of the WATERS reported diversions to be 1,554 ac-ft/yr. Agricultural pumping rates are assumed to remain constant over time in the model.

Agricultural pumping was distributed according to WATERS diversion amounts. For the years 2002–2004 when the model converts to a monthly period, production rates were doubled and applied in the assumed 6-month growing season months of April through September. It is assumed that agricultural wells penetrate up to 200 ft into the aquifer system based on predevelopment water levels. Agricultural well production was distributed using the MNW package in MODFLOW.

7.0 MODELING APPROACH AND CALIBRATION TARGETS

Ground water models are inherently non-unique, meaning that multiple combinations of hydraulic parameters and aquifer stresses can reproduce measured aquifer water levels. The approach used to calibrate a ground water model is essentially the calibration philosophy employed to address issues that arise because of the model's non-unique nature. To address these issues, calibration should use as many hydraulic parameters and aquifer stresses as possible, specify the measures by which the calibration will be quantified, and assess those observed parameters and stresses ("calibration targets") that may subject the calibration to uncertainty. The approach to calibration used for the SFCM, SFCM calibration targets and measures, and SFCM calibration uncertainties are discussed in this section.

7.1 Calibration

An accepted approach to calibration for ground water modeling involves the process of producing agreement between water levels and aquifer discharge simulated in the model and water levels and aquifer discharge measured in the field through the adjustment of independent variables (typically hydraulic conductivity, storativity, and recharge). This approach usually includes performance of a sensitivity analysis, which entails re-simulating aquifer conditions under systematically varied calibrated parameters and stresses. Parameters that strongly change the simulated aquifer heads and discharges are viewed as important parameters to the calibration. The SFCM was calibrated and a sensitivity study was performed in a manner consistent with this approach.

7.1.1 Calibration Approach

To reduce the impact of non-uniqueness, a method described by Ritchey and Rumbaugh (1996) was employed to calibrate the SFCM. This method consists of the following:

- Calibrating the model using parameter values (i.e., hydraulic conductivity, storativity, and recharge) that are consistent with measured values
- Calibrating to multiple hydrologic conditions, and
- Using multiple calibration performance measures such as hydraulic heads and discharge rate to assess calibration.

The method used to calibrate the SFCM additionally involved using historical information, as available, to define parameters and limiting the number of parameters being estimated through calibration.

The method used for model calibration was automated by using PEST (Doherty, 2002), a calibration software package. PEST was successfully used to calibrate the model's steady-state phase; however, because of the limitations described in Section 1.3, calibration of the transient model has been limited to date. Manual calibration was also performed to improve model fit to stream and spring discharge measurements.

Measured hydraulic conductivity and storativity data were used for the initial estimated parameter fields. With the exception of parameters for the Tesuque formation, hydraulic conductivity parameters provided in 0 of this report offered limited data for analysis of geologic units in the model area. To address these limitations, initial estimates for hydraulic conductivity in these units were made using previous models and by constraining analogous type formations and values through a ranking hierarchy. Although vertical hydraulic conductivity can be a function of grid scale, it is not measurable at the model scale and therefore cannot be well constrained. For the SFCM, literature estimates of vertical anisotropy and results from other models developed in the Española Basin were used to constrain initial vertical hydraulic conductivity. Unfortunately, vertical hydraulic conductivity can be a function of grid scale making a direct comparison between models problematic. , Specific storage and specific yield also are not well characterized in the region or at the scale of the model. In the SFCM, data for these parameters were based upon results from Shomaker (2001).

Recharge has not been directly measured in the study area and is arguably not measurable at the model scale. However, basin yield studies have been performed for many of the watersheds in the study area and several models have estimated recharge for the region. Studies of and estimates for regional aquifer discharge through streams, springs, and ground water ET also provide a lower bound on recharge. Recharge was developed largely from these studies and models. The initial recharge estimates are within plausible ranges based upon the available data and relevant literature.

A challenge in calibrating a model as complex as the SFCM is the large number of active grid cells for which horizontal and vertical hydraulic conductivity and storativity are being estimated. Because these parameters are estimated for each grid cell, the number of potential unknowns is equal to the number of grid cells, and this number far exceeds the number of observations available for calibration purposes. The result is an inherently non-unique calibration. To deal with this issue, the calibration process began with an assumption that the hydraulic conductivity for a given HSU can be described by a single unknown, posited as the hydraulic conductivity of the specific HSU at the ground surface ($K_{surface}$). This method assumes homogeneity within a given HSU at a common elevation. The issue was also addressed during application of the depth decay model to hydraulic conductivity by holding the depth decay constant and then reviewing its sensitivity during calibration to see if it warranted adjustment. This calibration approach limited adjustments to parameters to global adjustments rather than local (cell to cell) adjustments. Due to time constraints, local adjustment of parameters to improve local residuals for SCFM calibration has yet to be performed. However, local model over-calibration does not guarantee a notably better predictive model, especially when one has calibrated to levels below the error in the observations (Freyberg, 1988).

The SFCM was calibrated over two time periods, one representing steady-state conditions and the other representing transient conditions. Predevelopment conditions were used for the steady-state model in hopes of recreating aquifer conditions before significant resource development. No pumping stresses were applied to the predevelopment model to ensure consistency with the assumption of steady-state conditions before significant resource development. For our purposes, predevelopment conditions were assumed to be conditions before 1947, when total production from the model domain was less than 2,500 ac-ft/yr or a factor of ten less than produced by 2004 pumping.

The transient calibration period ran from 1947 through 2004, with annual stress periods from 1947 through 2002 and monthly periods from January 2002 through December 2004. Pumping estimates based upon historical records were changed in each transient stress period, as were estimates for recharge.

The model was calibrated through a range of hydrological conditions. The steady-state predevelopment model represents a period of equilibrium where recharge and aquifer discharge through streams and cross-formational flow are in balance (see section 0). Under these conditions, the amount of recharge to the aquifers is in equilibrium with the amount of discharge from the aquifer. The transient calibration period (1947 through 2004) represents a period of development when portions of the aquifers have been developed resulting in loss of storage, declining heads, and capture of discharge. Some of the aquifer discharge observed under steady-state predevelopment conditions is captured as a result of reduced base flow, decreased cross-formational flow, and decreased ET.

7.1.2 Calibration Targets and Calibration Measures

Hydraulic head (water level) was the primary target used to calibrate he hydrologic model; however, stream and spring gain-loss estimates were also used. To ensure that model head distributions were consistent with hydrogeologic interpretations and accepted conceptual models for flow within the aquifers, hydrographs were developed to compare simulated heads to measured heads at specific observation points through time and head distributions for select time periods were plotted on maps. Stream calibration targets were derived from field studies and from previous models. The calibration targets were based upon aquifer-to-stream gains and losses and not gaged stream flows.

Traditional calibration measures, such as the mean error (ME), the mean absolute error (MAE), and the root mean square error (RMSE) (Anderson and Woessner, 1992) quantify the average error in the calibration process. ME is the mean of the differences between measured heads (hm) and simulated heads (hs):

$$ME = \frac{1}{n} \sum_{i=1}^{n} (h_m - h_s)_i \qquad (7.1)$$

where

n = the number of calibration measurements.

The MAE is the mean of the absolute value of the differences between measured heads (h_m) and simulated heads (h_s):

$$MAE = \frac{1}{n} \sum_{i=1}^{n} \left|(h_m - h_s)_i\right| \qquad (7.2)$$

where

n = number of calibration measurements.

The RMSE is the square root of the average of the squared differences between measured heads (h_m) and simulated heads (h_s):

$$RMS = \left[\frac{1}{n} \sum_{i=1}^{n} (h_m - h_s)_i^2\right]^{0.5} \qquad (7.3)$$

where

n = number of calibration measurements.

The difference between h_m and the simulated h_s is termed a residual.

The RMSE was used as the basic measure of calibration for heads. The required calibration criterion for heads is an RMSE that is equal to or less than 10 percent of the observed head range in the aquifer being simulated (greater than 200 feet). The RMSE is useful for describing model error on an average basis but, as a single measure, it does not provide insight into spatial trends in the distribution of the residuals.

An examination of the distribution of residuals is necessary to determine if they are randomly distributed over the model grid and not spatially biased. Post plots of head residuals were used to check for spatial bias by indicating the magnitude and direction of mismatch between h_m and h_s. Distributions for h_s were also compared to the head distributions developed from the field measurements (h_m). Finally, scatter plots were used to determine if the head residuals are biased based on the magnitude of the observed head surface.

7.1.3 Calibration Target Uncertainty

Calibration targets are uncertain. In order to avoid "over-calibrating" a model, calibration criteria should be defined consistent with the uncertainty in calibration targets. The primary calibration target in ground water modeling is hydraulic head. Uncertainty in head measurements can be the result of many factors, including measurement error, scale errors, and various types of averaging errors, both spatial and temporal. A generally accepted rule for the calibration criteria for head is an RMSE less than or equal to 10 percent of head variation within the aquifer being modeled. Head differences across the aquifers in the study area are on the order of 7,400 to 5,200 feet. This leads to an acceptable RMSE of approximately 200 feet. Comparing this RMSE to an estimate of the head target errors shows the level of calibration the underlying head targets can support.

Measurement errors are typically on the order of tenths of feet, and at the SFCM scale can be insignificant. However, measuring point elevation errors can be significant. In the model construction process, ground surface elevations must be averaged to the model grid. The SFCM grid dimensions range from 1 to 0.25 miles. The elevation data is up-scaled from a 30 meter DEM. This up-scaling process can result in errors that can average 10 to 20 feet and may greatly exceed 20 feet in areas with higher topographic slopes.

Horizontal to vertical hydraulic conductivity ratios within aquifers can result in significant vertical gradients within individual model layers; portions of the aquifer can have head variations within a single model cell on the order of tens of feet. A single model cell has one head. On average, in areas away from large pumping centers, this scale effect is expected to be on the order of 10 to 20 feet. Horizontal gradients relative to the grid scale also account for up to 20 feet of head error with even greater errors near pumping centers.

To address the error associated with representing a pumping well within a grid cell, the Multi-Node Well Package (Halford and Hanson, 2002) was used. When the potential head errors are added up, the average error in model heads could be as much as 50 feet, an estimate that does not account for the uncertainty in observed heads. This uncertainty is created by the fact that many wells in the study area are completed in multiple, transmissive zones, with the result that the observed well water level is a composite head, less a representative of either aquifer than a function of integrated aquifer transmissivities and heads. To account for composite heads, model heads were weighted by transmissivity. For a given well, which penetrates n model layers, the composite simulated head H^* was calculated as:

$$H^* = \frac{\sum_{i=1}^{n} H_i K_i b_i}{\sum_{i=1}^{n} K_i b_i} \qquad (7.4)$$

where

H_i = the simulated hydraulic head at model layer i
K_i = hydraulic conductivity at model layer i
b_i = total screen length within model layer i.

The composite simulated head error analysis is semi-quantitative in nature. However, it properly identifies potential errors associated with simulated heads predicted by the model and observed heads. In addition, the analysis suggests that calibrating the SFCM to a RMSE value of less than 30 to 50 feet would constitute over-calibration of the model, and parameter adjustments to reach that RMSE would not be supported by the hydraulic head uncertainty.

7.2 Sensitivity Analyses

A sensitivity analysis was performed on the steady-state calibrated model to determine the impact of changes in a calibrated parameter on the predictions of the calibrated model. A standard "one-off" sensitivity analysis was performed. This means that hydraulic parameters or stresses were adjusted from their calibrated "base case" values one by one while all other hydraulic parameters were unperturbed. A transient model sensitivity analysis was not performed and should be performed in the future.

8.0 STEADY-STATE MODEL

The steady-state model is representative of predevelopment conditions. In predevelopment, aquifer inflow from recharge and streams is balanced by ground water to surface water discharge, ET, and discharge from the Española Basin to the Santa Domingo Basin. Predevelopment conditions were used for the steady-state model in hopes of recreating aquifer conditions as they were before significant resource development. Consistent with the assumption of predevelopment steady-state conditions, no pumping stresses were applied to the predevelopment model. For our purposes, predevelopment conditions were assumed to be conditions before 1947 when total production from the model domain was less than 2,500 ac-ft/yr or a factor of ten less than 2004 pumping. In 1947, anthropogenic discharges would have been less than 5% of basin inflows; for simulation purposes, these discharges are considered negligible.

Calibration of the steady-state model was performed using PEST. The parameters allowed to be modified by PEST to improve model fit were hydraulic conductivity, the depth decay coefficient, horizontal and vertical anisotropy in hydraulic conductivity, stream conductance, GHB conductance, and HFB conductance. The hydraulic conductivity was the most sensitive parameter and it was varied individually for each HSU and Tesuque lithosome (see section 0). Table 8-1 provides the calibrated hydraulic conductivities as compared to the initial estimates. As can be seen, most were decreased in calibration if they were changed at all.

The depth decay coefficient was varied globally and by HSU but was eventually fixed at its initial value due to correlation between it and other hydraulic parameters and a lack of deep head measurement with which to constrain depth decay. Horizontal anisotropy was activated only for the Tesuque formation; the value was set to 1 for all other HSUs. Vertical anisotropy was varied globally. Because of a lack of quantitative flow targets for the pre-development case, the stream and GHB conductances were fixed at their initial estimates for the PEST calibration. All the horizontal flow barriers except those describing Los Barrancos fault were inactivated and the HFB conductances at Los Barrancos were calibrated to match a steep head gradient observed across the fault. A total of 184 hydraulic head observations were used as calibration targets in PEST.

The following subsections provide the calibration model results and the results of a sensitivity analysis identifying the model parameters to which the steady-state model calibration is most sensitive.

8.1 Calibration Results

As discussed in Section 7, calibration is the process of adjusting model parameters to produce agreement between water levels and aquifer discharges simulated in the model and water levels and aquifer discharges measured in the field. The steady-state model results are discussed in this section in terms of heads, stream flows, and the model water budget.

8.1.1 Heads

For head targets, the water-level elevation was calculated based on the measured water-level depth using the grid-block as averaged elevation from the model. This adjustment was made to reduce potential errors induced by averaging ground-surface elevation over a grid-block.

Figure 8-1 shows the steady-state head surface results combined with the predevelopment head surface. This figure illustrates that the simulated steady-state heads show good general agreement with the predevelopment head surface generated to develop the model layering. The model is generally wet with a bias in simulated high heads relative to the observed values. This bias is reflected in the mean error of 23.3 feet (Table 8-2). This bias was able to be decreased during calibration; however, the amount of dry cells in layer one became very large. This could be an acceptable condition, although it makes model execution much slower and less stable. Based upon the concept that predevelopment head targets should be biased low, the high bias was accepted. The RMSE (Equation 7.3) for the steady-state model heads is 95.2 feet. The head range in the observed model heads is 1,958 feet, giving an RMSE range of 0.049 or 4.9%, well within the calibration objectives defined in section 7.

Figure 8-2 plots a cross plot of simulated heads versus observed heads. From a review of Figure 8-2 one can see that the SFCM does a good job of reproducing heads in both the high and low elevations, but the general high simulated head relative to observed is manifested in points falling dominantly over the 45 degree line of perfect fit.

Figure 8-3 plots the steady-state residuals where the head residual is defined as:

$$residual = h_s - h_m \tag{8.1}$$

where

h_s = simulated head
h_m = measured head

Because most of the target heads are composite heads (completed across more than one HSU or model layer) and because most observed heads are completed within 500 feet of the water table, the residuals and the calibration statistics are developed based on all 184 head values, independent of model layer. A review of Figure 8-3 shows that the residuals tend to be positive. Again this is a condition of a wet model with a positive mean error. Residuals in the Santa Fe Embayment tend to be within 100 feet, with the exception of a very low simulated head in the Cerrillos Highlands which would be difficult to fit with the poor vertical resolution in the model layering relative to shallow heads topographically controlled.

8.1.2 Streams

Table 8-3 shows a summary of stream calibration targets from various sources (described in more detail in Section 4.7). The uncertainty associated with stream flow targets is exceedingly high, especially when considering predevelopment times. However, because the potential for stream capture is the primary issue related to pumping in the basin, consideration of flow, no matter the uncertainty, is a requirement. Figure 8-4 shows the flow values for the stream reaches in the steady-state model which are also discussed along with the total flow targets. In Figure 8-4, gains are positive and losses are negative and the units are in ac-ft/yr. One can easily convert to cfs by dividing by 724.

The model fit with the Rio Grande gains is reasonable. An assumption of approximately 31.5 miles of the Rio Grande in our model area and a gain of 1 cfs (Speigel and Baldwin, 1963) yields a target of approximately 28,000 ac-ft/yr. The simulated gains are 22,846 ac-ft/yr which compares well. The under-prediction of Rio gains may result from the wet nature of the model causing too great of gains in the Rio tributaries. The spatial distribution of flows shows stronger gaining conditions in the higher elevations of the river valley with weaker gains southward in the basin. This is intuitive. Gains vary between grid cells from approximately 500 ac-ft/yr (0.5 cfs) to < 50 ac-ft/yr (less than a tenth of a cfs).

A comparison to the Santa Fe River simulated gains and losses relative to the targets suggests that the model is under predicting both gains and losses based upon current knowledge. The distribution of flow on the Santa Fe River shows gaining conditions near the mountains, in the Santa Fe canyons region, and near the confluence with the Rio Grande.

Gains on the Tesuque are reasonable with losses being low compared to published sources. Pojoaque gains are high but close to those prescribed in McAda and Wasiolek (1989) but losses are extremely low, consistent with high simulated heads in the region. A review of the distribution of gains and losses on the Tesuque and Pojoaque show that most losses are clustered in the highest reaches of the streams and is conceptually reasonable.

The Galisteo flows are very uncertain. A comparison of the combined flows for the Santa Fe River and Galisteo streams from Shomaker (2001) compares well in terms of gains with the model but under-predicts the losses. The discrepancy in stream losses among studies and models may in part be a result of how each accounts for stream loss versus mountain front and arroyo recharge. Head residuals are high in the southern model area, but are not severely too high. Figure 8-4 shows that stream losses are occurring in the highest elevations and in the lower elevations of the stream with gaining segments in between.

8.1.3 Water Budget

Table 8-4 summarizes the water budget for the model on a layer basis. Table 8-5 provides the same water budget on a layer basis, expressed as a percent of the total model inflow, or outflow. Table 8-5 gives the various sources and sinks as percentages of the total water entering or leaving the model and for that reason does not include layer top and bottom flows included in Table 8-4. A review of Table 8-5 reveals that flow decreases with depth, a finding consistent with the conceptual model and a direct product of the use of depth decay in the model hydraulic conductivity calibration method. Essentially flow has decreased to zero in layers below layer 6. The reason for developing the model to the depths simulated was to try to develop a consistent geologic model. It was expected that the lower model layers would be insignificant with respect to fluxes.

Table 8-6 compares the total SFCM model water balance and compares it to the conceptual water balance developed in Section 5 of this report. The highest percentage of recharge occurs as mountain front recharge at 63% of inflows which is similar to our conceptual estimate. Areal recharge makes up 20% of the inflows which is high relative to the conceptual estimate (16%). Stream losses were 5% of the model inflows which compares to the conceptual estimate of 11% but we have seen a consistent under-prediction in losses. Boundary inflows are higher than our conceptual estimate at approximately 12% of inflows.

Outflows to the model show better across the board agreement with the conceptual estimates with streams and springs making up a total 77% of outflows compared to our estimate of 73%. The ET and boundary outflows also show very close agreement with the conceptual estimates at 22% and 3%, respectively.

8.2 Sensitivity Analysis

A sensitivity analysis was performed for the calibrated steady-state model. A sensitivity analysis provides a means of formally describing the impact of varying specific parameters or groups of parameters on model outputs. In this sensitivity analysis, input parameters were systematically increased and decreased from their calibrated values while the change in head was recorded. Four simulations were completed for each parameter varied, where the input parameters were varied either according to:

$$sensitivity\ value = (calibrated\ value)(factor) \tag{8.2}$$

$$sensitivity\ value = (calibrated\ value)(10^{factor-1}) \tag{8.3}$$

and the factors were 0.5, 0.75, 1.25, and 1.5. For parameters which typically vary by orders of magnitude and are usually lognormally distributed, Equation (8.3) was used. These parameters included the hydraulic conductivity parameters, the vertical anisotropy and the conductances in the faults, GHB, and stream cells. Equation (8.2) was used for the depth decay coefficients and for horizontal anisotropy. For the output variable, we calculated the mean difference (*MD*) between the base simulated head and the simulated head calculated for the sensitivity simulation for each layer. The equation for calculating the *MD* is:

$$MD = \frac{1}{n}\sum_{i=1}^{n}\left(h_{sens,i} - h_{cal,i}\right) \tag{8.4}$$

where

$h_{sens,i}$ = sensitivity simulation head at location i
$h_{cal,i}$ = calibrated simulation head at location i
n = number of locations compared

Two approaches were considered in applying Equation 8.4 to the sensitivity of output heads. First, the heads in all active gridblocks were compared between the sensitivity output and the calibrated output. Second, the composite heads only at wells where measured targets were available (i.e., n = number of targets) were compared. A comparison between these two methods can provide information about the bias in the target locations, (i.e., a similar result suggests adequate target coverage). For the steady-state analysis, 41 parameter sensitivities were completed. The parameter names along with a description are listed in Table 8-7.

Completing the sensitivity analysis involved perturbing each of the 41 parameters by the four factors. Along with the base case, this required running the steady-state model a total of 165 times.

Figure 8-5a and Figure 8-5b illustrate the sensitivity results with *MDs* calculated from just the composite heads at wells with target measurements. It is clear from this figure that the model is much more sensitive to depth decay in the non-bedrock units (KDEP_MOST) and horizontal conductivity in Tesuque Lithosome S (MHK_2_Tts) than any of the other parameters. When the KDEP_MOST parameter is decreased, simulated head swiftly drop well out of the range of the observations. A similar result occurs when the horizontal conductivity in Tesuque Lithosome S is increased. The next most sensitive parameters are the horizontal conductivities in the Ancha formation and Tesuque Lithosome ACU, followed by horizontal anisotropy parameter. The most sensitive stream conductance parameter is that for the Upper Santa Fe River, however, it is less sensitive than the aforementioned hydraulic conductivity parameters. The simulated heads are relatively insensitive to changes in the fault and GHB conductances and the depth decay in the Precambrian and Intrusive units.

Figure 8-6a and Figure 8-6b shows the sensitivity results with MDs calculated from all active cells in the model. These figures indicate similar order of the most important variables. However, the sensitivities for the hydraulic conductivities in HSUs other than the Tesuque are significantly higher relative to that in the Tesuque. This indicates inadequate target coverage for units other than the Tesuque and that the parameters are poorly constrained in these units.

9.0 TRANSIENT MODEL

This section describes the transient model results. The transient model used the steady-state heads as the initial condition. The transient model was simulated for the time period from 1947 through 2004.

This section details the transient model results. Because the ground water model must be calibrated to steady-state and transient conditions using the same physical hydraulic properties, calibration is an iterative process between steady-state and transient models. Because of time constraints, the SFCM was not calibrated to transient conditions. As a result, the SFCM is still considered a first-order model which requires significant refinement and additional calibration activities. In this section, the results of the transient model are compared to the available calibration targets.

9.1 Hydraulic Heads

Table 9-1 shows the calibration statistics for the model across the 57-year transient period. Note that because most of the targets had incomplete records over the simulated time period, calibration statistics have been calculated using all of the data for the calibration period that were available in time and space.

The transient model remains generally wet with a bias towards higher simulated heads relative to the observed heads. The bias has been reduced relative to the steady-state model from a mean error of 23.3 feet (Table 8-2) to a mean error of 10.2 feet in the transient model (Table 9-1). The RMSE (Equation 7.3) for the transient model is 106.8 feet and is slightly higher than the RMSE for the steady-state model, which is generally the case between steady-state and transient models. The head range in the observed transient heads is 2,783 feet, giving an RMSE/range of 0.038 or 3.8%, well within the calibration objectives defined in section 7.

Figure 9.1 plots a cross plot of simulated heads versus observed heads. From a review of Figure 9.1, one can see that the model does a good job of reproducing heads above an elevation of 5,400 feet amsl. It is common to see a misfit in transient models in the lowest elevation heads. To some degree, this may be the result of the comparison of heads measured within a pumping well to heads measured within a grid cell of effective borehole radius a factor of ten or greater than the borehole where the head is measured. The misfit in the low heads needs to be further investigated.

Figure 9.2 plots the transient head residuals where the head residual is defined in Equation 8.1. For the transient model, the residuals for all measured and simulated head pairs at a given borehole are averaged for posting in Figure 9.2. The average transient head residuals indicate that the model is generally too wet in the Galisteo Basin and near the Buckman well field. Within the Santa Fe region, the model tends to have a good distribution of both low and high residuals. Because the results described in this section are with no additional calibration over what was performed for the steady-state model, the residuals will be improved with transient calibration.

Figure 9.3 plots select hydrographs comparing simulated and observed heads. The hydrographs were selected to provide an indication of how the model reproduced transient heads across the model domain and areas with significant drawdown (i.e., pumping centers). (Appendix B provides a full set of hydrographs.) In general the model does a good job of reproducing regional trends as indicated in the selected hydrographs. This is particularly true at Buckman No. 3. The model performs a little worse in the Santa Fe metropolitan area as shown by the Alto Well hydrograph. The model tends to under-predict heads in early time at this well. The model also does not reproduce the maximum drawdown of the late 1980 and early 1990s. In general, the model reproduces head trends well. However, as can be seen in Figure 9.2, there are regional head biases in the model which should be addressed in further model revision and calibration.

Figure 9.4 provides a plot of drawdown simulated in the model from 1947 through 2004. The initial steady-state heads are used as the initial heads. The model shows significant drawdown in the large pumping centers of the model including the Guaje, Owati, Pajarito, Los Alamos, Buckman, and Municipal well fields. Drawdown at the Buckman and Municipal well fields exceeds 50 feet on a regional basis. A good portion of the model shows little drawdown. Drawdown from the Municipal wells appears to intersect other pumping centers to the southwest and towards the southeast with a large region of the model having the water table fall greater than 10 feet.

Figure 9.4 also provides insight into issues related to the transient model. In areas where mountain front recharge is being applied, heads are increased with time in an effort to maintain specified transient fluxes. The mountain front recharge boundary condition requires revision. In the southwestern area of the model, heads increase several feet over the transient model period. This increase could be the result of several factors which require investigation. These include aquifer properties, boundary conductances, areal recharge rates, and losing streams.

9.2 Water Budget

Table 9-2 provides a comparison between the steady-state flow balance volumetric fluxes along with volumetric fluxes in 1956 (dry year), 1985 (a wet year), and 2004 (the end of the transient simulation period). It is important to note that the transient model flows are greater than the steady-state flows because of the storage term, which, by definition, is zero in the steady-state model.

From a review of Table 9-2, one can see that in the dry year of 1956, recharge was very low relative to the steady-state. Pumping in 1956 was approximately 8,652 ac ft and, with the dry conditions and the steady increase in pumping from the 1940s through the 1950s, a significant amount of water is being supplied from storage (28,390 ac-ft/yr) which is reflected in declining water levels in the region. In 1985, simulated recharge was at a maximum (61,180 ac-ft/yr) and a significant amount of water was going back into storage which was likely the result of both increased recharge and a steep decline in pumping from 1981 through 1983. By 2004 a significant amount of water is being supplied by storage (33,634 ac-fet/yr), which reflects the continued increase in pumping that occurred from 1985 through 2004.

It is interesting to note that, for most years, recharge is a greater flow input to the model domain than storage. However, in dry years, such as 1956 and 2004, this trend is reversed. It is also interesting to note that drain (spring) flows decrease across the simulation period. Table 9-3 provides the cumulative inflow and outflow volumes for the model from 1947 through 2004. From this table, one can see that recharge is the single highest inflow volume (65%) with storage being second at 21% of total model inflow. Stream loss and boundary flows make up the remainder of model inflows. The dominant outflow volume is streams at 53% of model outflows. This is followed in magnitude by both wells and ET at 19% each. It is clear that a significant amount of the volume of pumping is being supplied through storage decreases (inflows) which are observable in water level declines. Sources of model discharge are generally decreasing as a result of capture, but these volumes are small (10% or less) relative to the entire model flow volume and are poorly discerned in the global water balance.

10.0 DECISION SUPPORT FOR WELL SITING

A decision support system (DSS) based on a site suitability analysis was developed to identify promising areas for water supply well sites based on a variety of criteria such as the locations of existing supply wells, streams, springs, existing infrastructure, and population centers, as well as areas of favorable geology. Land ownership was also considered. As a final step, potential water supply well locations were simulated using the SFCM to evaluate the potential effects of siting a supply well at the target locations.

10.1 Decision Criteria

The DSS was based on four general decision criteria:

- Development of a sustainable water supply,
- Minimizing impact to existing users,
- Minimizing impact to streams and springs, and
- Cost.

Each of these decision criteria was then broken down into specific decision criteria that were used to build the DSS. These specific decision criteria were as follows:

1. Areas of favorable hydrogeology,
2. Proximity to existing population (close proximity is desirable),
3. Proximity to existing and proposed water conveyance infrastructure (close proximity is desirable),
4. Proximity to existing supply wells and large water-right holders (close proximity is not desirable),
5. Proximity to existing domestic wells (close proximity is not desirable),
6. Proximity to streams (close proximity is not desirable),
7. Proximity to springs (close proximity is not desirable),
8. Proximity to areas of existing ground water contamination (close proximity not desirable), and
9. Property ownership

Each decision criterion was represented as a grid, or matrix, of suitability scores that covered the study area. The grid cell size was 100 meters by 100 meters. A normalized suitability score between 0 and 100 was assigned to each grid cell, with 100 indicating the most suitable areas based on the specific suitability criterion of interest.

10.1.1 Areas of Favorable Hydrogeology

Areas of favorable hydrogeology were identified based on the occurrence of four target aquifers: the Ancha, Espinaso, Galisteo, and Tesuque. The geologic model developed for this project was used to develop a grid of aquifer thickness for each target aquifer. Multiplying the thickness of the aquifer at each grid cell by the target aquifer's hydraulic conductivity (an average, homogeneous hydraulic conductivity was assumed for each aquifer) provided transmissivity grids for the target aquifers. Next the transmissivity grids for each aquifer were weighted with respect to relative depth. The deepest portions of any aquifer (relative to the depth of the tops of all four aquifers throughout the area) were assigned a 0 weighting, and the shallowest portions were assigned a weighting of 1. The intervening portions were assigned a value between 0 and 1 depending on depth. The logarithm of the depth-weighted transmissivity score at each grid cell was then calculated to compress the values into a smaller range of values, since the depth-weighted transmissivity varied over several orders of magnitude. Finally, the log depth-weighted transmissivities of all four target aquifers were summed together to produce a matrix of composite depth-weighted transmissivities. These values were then normalized to suitability scores ranging from 0 through 100. Figure 10-1, Figure 10-2, Figure 10-3, and Figure 10-4 present the aquifer grids. The colors of the grids represent relative thickness, ranging from red, indicating the absence of the aquifer, to green, indicating the presence of the aquifer at its thickest. The normalized values are presented in Figure 10-5.

10.1.2 Proximity to Existing Population

Population data were derived from United States Census Bureau block group data for 2004. Blocks were selected which had a 2004 population greater than 300 people/square mile. These areas were used to represent the most densely-populated areas in Santa Fe County. The shortest distance to any block group was calculated using a GIS-based method for each grid cell. The values were then normalized to a suitability score from 0 (farthest) to 100 (closest), since from a cost perspective it is desirable to develop water supplies that are as near as possible to populated areas. The results of this analysis are presented in Figure 10-6.

10.1.3 Proximity to Existing and Proposed County Water Service Areas

This suitability score for infrastructure was developed to evaluate proximity to existing and proposed infrastructure that could be used to convey water from County supply wells. Areas that are closest to existing or proposed County infrastructure received the highest score since proximity to infrastructure minimizes the cost of building, operating, and maintaining additional conveyance infrastructure. Information on existing and proposed County water service areas came from two different sources. The County provided with data on the locations of existing County infrastructure, and the locations of the existing Buckman pipeline, the proposed County/City raw water pipeline, and the proposed County/City treated water pipeline were estimated based on a map that appeared in a document prepared by the County and the City of Santa Fe entitled *Water Supply Projects Update – Spring 2004*.

The suitability score for infrastructure was calculated based on the normalized distance to infrastructure. Using a scale of 0 through 100, areas that are closer to infrastructure were assigned a higher (less costly and hence more suitable) score, while areas that are farther away from infrastructure were assigned a lower score (more costly and hence less suitable). The suitability score map for proximity to existing and proposed infrastructure is presented in Figure 10-7.

10.1.4 Proximity to Existing Supply Wells and Large Water-Right Holders

The proximity to existing supply wells and large water-right holders was evaluated in order to maximize the distance to any of these features when selecting proposed locations for County supply wells. It is desirable to maximize the distance to other existing supply wells and large water-right holders in order to minimize the potential for impairment or perceived impairment of these wells. The wells selected for this portion of the analysis fall into the following categories:

- Municipal supply wells
- Community water systems

- Large irrigation wells (with water rights >= 10 ac-ft/yr)

The suitability score map is presented in Figure 10-8. Areas close to existing supply wells and large water-right holders were assigned a low score, while areas farthest from existing supply wells and water-right holders were assigned the highest score.

10.1.5 Proximity to Existing Domestic Wells

Data on existing domestic wells was taken from the NM OSE WATERS database. The locations of domestic wells and the associated normalized suitability scoring are presented on Figure 10-9. Suitability scoring for this criterion is based on proximity to domestic wells; it is desirable to be as far as possible from any domestic wells when siting a production well location. As the figure shows, areas close to domestic wells were assigned a low suitability score, while areas distal from domestic wells were assigned a high suitability score.

10.1.6 Proximity to Streams

The main perennial streams in the study area were used to develop a proximity-based suitability score based on distance to the nearest stream. The streams that were considered were the Rio Grande, the Santa Fe River, the Pojoaque River, the Tesuque River, the Nambe River, Santa Clara Creek, and Galisteo Creek. The suitability score for proximity to streams was developed based on the desirability of installing any production well as far as possible from any stream. Thus, a normalized suitability score was developed based on proximity to any stream, with proximal areas scoring low, and distal areas scoring high. The suitability scoring map is presented in Figure 10-10.

10.1.7 Proximity to Springs

Similar to the suitability scoring for streams, the suitability scoring for springs was assigned to score highly those potential well sites that are as far as possible from any known springs so as to minimize spring depletions. Figure 10-11 presents springs simulated in the model along with the normalized, proximity-based scoring map, with low scores assigned to areas near springs, and high scores assigned to those areas that are as far as possible away from springs.

10.1.8 Proximity to Areas of Existing Ground water Contamination

Locations for known ground water contamination sites were taken from DE&S (2000), which presented locations throughout Santa Fe County where known contaminant releases to ground water had occurred. These were typically leaking underground storage tank and other similar sites. The site locations and site suitability scoring map are presented in Figure 10-12. Areas close to known ground water contamination sites were scored low, while areas farthest from ground water contamination sites were scored the highest.

10.2 Development of Final DSS Suitability Map

The final suitability scoring map was developed by combining DSS layers 1 through 8 (property ownership was considered separately, and will be discussed below), giving each an equal weighting. At each grid cell on the map, the site suitability scores for layers 1 through 8 were averaged. Due to the averaging process, the range of the suitability scores was diminished, from a possible range of 0 through 100, to a range of approximately 35 through 100. The final combined result is presented in Figure 10-13. Note that the color ramp in Figure 10-13 has been adjusted to reflect the range of scores from 35 (red) to 100 (green).

For the purpose of identifying promising potential well sites, a site suitability score threshold of 75 or greater was selected to indicate areas of good potential based on the DSS suitability criteria. These areas were then compared against property ownership (Figure 10-14). Department of Energy (DOE), National Park Service (NPS), and tribal lands were removed from further consideration. Finally, four potential well locations were sited in the approximate centroid of four areas that were identified as a result of the screening process. These locations are also presented on Figure 10-14.

Note that this study used a generic weighting scheme that weights all of the site suitability criteria equally. The DSS may be re-run using alternative weighting schemes in order to evaluate different stakeholder perspectives.

10.3 Evaluation of Potential Locations Using the SFCM

Once four potential well locations were selected based on the DSS suitability analysis, the model was used to simulate a pumping well at each location. Each hypothetical well was pumped at 100 ac-ft/yr (approximately 60 gpm) continuously for 40 years, and the potential pumping effect was evaluated against three metrics: (1) drawdown at the nearest supply well, (2) spring depletion, and (3) stream depletion. Note that at location 1 (see Figure 10-14) only 80 ac-ft/yr could be sustained for the full 40 years, so this value was used for implementing pumping.

The results of the simulated pumping are presented below in Table 10-1. Based on the simulation results, potential effects from a well pumping at location 1 were simulated as negligible with respect to impacts spring flow and nearby production wells, since there are no nearby springs or production wells. Depletions from the Rio Grande were simulated as 2 ac-ft/yr at 40 years. Potential impacts from location 2 were simulated as negligible with respect to impacts to springflow and stream depletion. A minor amount of drawdown (<1 foot) of drawdown was simulated at the nearest production well (Buckman 13). Simulated results from pumping at location 3 showed negligible potential impacts to spring flow, minor stream flow depletion (2 ac-ft/yr total at 40 years from the Santa Fe River and the Rio Grande), and <1 foot of drawdown at the nearest production well (Eldorado No. 1). Results from the simulation of a well placed at location 4 showed that potential impacts to spring flow and production wells would be negligible, and total stream depletions are expected to be 30 ac-ft/yr combined from the Rio Grande, Santa Fe River, and Galisteo Creek.

An engineering analysis of relative infrastructure costs for the four proposed locations was also completed. This analysis has been included as Appendix C. Note that for the purposes of costing only, the engineering analysis has assumed somewhat larger flow rates than the examples included above. If necessary, the engineering costs can be scaled accordingly depending on the final proposed pumping rates. For now, the results of the engineering analysis should be used to evaluate relative costs for the four proposed locations.

11.0 SUMMARY AND RECOMMENDATIONS

This section of the report will provide a summary of achievements in the development of the SFCM. In addition, this section discusses the limitations of the model as we perceive them at this date and also provides recommendations as to where additional work is required.

11.1 Summary

In January 2005, INTERA was retained by Santa Fe County (County) to perform a Geohydrologic Study and Regional Aquifer Evaluation. The purpose of the study was to determine potential locations for future water resource development in the County that will have minimal environmental impacts. A primary aspect of the overall geohydrologic study is the development of a model of ground water flow termed the SFCM.

As part of this study, INTERA has developed an interim ground water model. The interim status assigned to this model is due to the impact the collaborative process of model development and calibration had upon the time available for model calibration. This model was developed to support the exploration of potential water supply wells. From March 30, 2005, INTERA, on behalf of the County, started working in collaboration with the City of Santa Fe through their consultants, CDM on model development. The desire was to develop, through cooperation, a single model which could be the basis for future hydrologic studies performed by the City and the County. While conceptually this has been a noble endeavor, the practical aspects of execution have been intractable. The inherent difficulties of sharing work were exacerbated by different modeling objectives, budgets, and timelines. The model development was a committee process which in some instances has resulted in compromises which are at odds with INTERA's views and may equally be at odds with the City and their consultant's views. As a result of collaboration, the model development phase extended far too long leaving little time for model calibration and sensitivity analyses.

The focus area of the SFCM is different than other ground water models developed in the basin because the focus of this model is from Santa Fe south through the Santa Fe Embayment. The geology in the Santa Fe Embayment is complex and required a significant amount of new interpretation work and development of the first fully-three-dimensional geologic model within the basin. INTERA developed the model geologic structure, boundaries conditions, and material properties. CDM developed the recharge parameters, the stream package and the pumping data set. At this time, perhaps the most valuable aspect of the model is the three-dimensional geologic model in the Galisteo Basin. While the geologic model is uncertain in many regions, it provides a first attempt at developing aquifer-aquitard relationships and represents the work of many investigators in the region including the most recent work of the USGS. The geologic model should be further developed based upon a review by the many subject matter experts working in the basin.

The SFCM was calibrated to steady-state conditions comparing simulated to observed heads for 184 observation wells and comparing stream gain and loss. The model compared well to observed heads in the basin. The steady-state model probably over-estimates stream gains although there is significant uncertainty in stream-aquifer interactions in the basin today and certainly in predevelopment times. The steady-state model slightly over-predicts model heads.

This high bias in residuals was accepted given the fact that we were using theoretically unaffected post-development head targets to represent predevelopment conditions.

The model was also simulated across a historical transient period from 1947 through 2004. The model was not calibrated to transient conditions but was just run in the transient mode. A review of model residuals and well hydrographs show that the model performs reasonably well in the transient mode but there are some issues which will require revision which will be discussed below in Section 11.3.

A DSS based on a site suitability analysis was developed to identify promising areas for supply-well sites based on a variety of criteria including the location of existing supply wells, streams, springs, existing infrastructure, and population centers, as well as areas of favorable geology. Once four potential well locations were selected, the model was used to simulate a pumping well at each location. Each hypothetical well was pumped at 100 ac-ft/yr (approximately 60 gpm) for 40 years, and the potential pumping effect was evaluated against three metrics: (1) drawdown at the nearest supply well, (2) spring depletion, and (3) stream depletion.

The transient model was used as one component to provide a relative, not absolute, measure of potential impacts of each potential well site to surrounding environs. While the model provided a useful means for integrating hydrogeologic data collected to date and assessing potential impacts, the model as it stands currently is considered an important interim step but will require further work to be considered a reliable predictive tool. For this reason, our method for determining potential well sites was heavily weighted in geology and other physical constraints.

11.2 Limitations of Model

A model can be defined as a representation of reality that attempts to explain the behavior of some aspect of reality, but is always less complex than the real system it represents (Domenico, 1972). As a result, limitations are intrinsic to models. Model limitations can be grouped into several categories including: (1) limitations in the data supporting a model, (2) limitations in the implementation of a model which may include assumptions inherent to the model application, and (3) limitations regarding model applicability. The limitations of this modeling study and the current version of the SFCM are discussed below.

- The SFCM has attempted to model a complex hydrogeologic system south of Santa Fe. Many of the geologic units which are the subject of this study lack hydraulic property measurements.
- Many of the aquifers of potential interest to the County have very few water level measurements. The lack of sufficient water level data in these units increases the uncertainty in the calibrated hydraulic parameters in the model.
- The calibration of the SFCM at this date should be considered first-order since its conditioned to steady-state heads and a total system water balance and has not undergone needed calibration to transient water levels (see Section 11.3). Therefore, the model should be considered an important interim step as mentioned above. It is our opinion that further model calibration and refinement should be conducted prior to its application toward seeking water rights
- The model currently assumes that areal recharge occurs across the entire model domain consistent with CDM's implementation. This is an assumption which requires additional

consideration. Many investigators believe that areal recharge is limited to higher elevation and in regions with extensive arroyos. If this is true, then areal recharge in the region is limited and represents an insignificant component of the model inflows. This has ramifications with regards to water supply modeling. First, the total basin inflows, and therefore outflow, will decrease which decreases the sustainable ground water limit in the basin. Secondly, impacts of pumping will extend much further laterally as wells can no longer satisfy decreases in storage with areal recharge.

- The SFCM, as well as all other models in the basin, assume that hydraulic conductivity decreases with depth of burial. There is a body of literature to support this conceptual model in alluvial basins. However, there is little data to constrain these relations in the model area. The SFCM applied a uniform depth decay model consistently throughout the model which was based upon Tesuque data. The depth decay constant is a very sensitive parameter for steady-state model calibration which cannot be uniquely determined with inverse modeling. The McAda and Wasiolek (1989) model calibrated hydraulic conductivity of the Tesuque with a lower effective decay constant (higher conductivity at depth). The depth decay constant is very important to model behavior and also very uncertain and requires further consideration.
- The SFCM extends to significant depth throughout the model domain because it was based upon a complete geologic model. The geology and physical properties within the model are poorly understood below a depth of 2000 feet and the accuracy of the model must be considered poor below these depths.

The SFCM as currently documented in this report, provides an important interim model for the region of interest to the County. The conclusions reached using this model are considered preliminary because of the issues related to data gaps and calibration described above. The decision analysis methodology utilized to site potential exploration wells used a systematic and quantitative decision analysis technique which considered model results only as a part of the process and as a relative performance measure. As a result, we believe that the decision analysis methodology made appropriate use of the model in its current state of calibration and provided good guidance. The SFCM should be further refined based upon comments received from experts in the region and based upon improved recommendations provided in Section 11.3 below.

11.3 Future Improvements

Using models to infer future hydrologic conditions requires a commitment to develop, calibrate and validate the model to available hydrologic data. Once done, further updates to a model should be conducted when new data becomes available or when modeling assumptions or implementation issues change. Through the modeling development and calibration process, one generally learns what can be done to improve the model's performance, i.e., what data would help better constrain the model parameters and/or its calibration, or what numerical model issues need further study. Future improvements to the model will be discussed below.

- The transient model indicated that there could be boundary condition implementation issues in the southwestern portions of the model. Heads in this region increased slightly over the 57 year transient simulation period. This could be due to several factors but recommend focusing first on specified boundary heads, conductance, and expected discharge.

- In the model development phase, several questions relating to geologic structure were raised by OSE. Because of schedule considerations, proper consideration and disposition of these comments was not completed. As a result, we would recommend that disposition of these comments be completed in the future and that the appropriate changes propagate through to the SFCM as appropriate.

- We recommend further refinement of the geologic model and the SFCM in optimal well siting areas as defined by the DSS.

- Mountain front recharge as it is currently being implemented has a few issues. First, the recharge is currently being forced into Precambrian and mixed Precambrian-Tesuque grid cells. This results in non-physical heads in these cells and therefore non-physical gradients at the mountain front boundary. Secondly, it was the recommendation of the INTERA technical team to use the several studies in the region which have provided estimates of mountain-front recharge through indirect methods (modeling), water balance methods, and field measurements (Hearne, 1980; Anderholm, 1994; Wasiolek, 1995; Kernodle et. al. (1995); DE&S, 2000; Shomaker (2001) and McAda and Barroll (2002). These studies provide estimates for mountain front and tributary recharge for most, if not the entire model region. It was proposed that if we needed to augment mountain front recharge estimates for watersheds where we have no prior studies, we could use a relatively simple estimation method based upon surplus precipitation after Shomaker (2001). It was also proposed to investigate data mining techniques to see if we can develop a multivariate regression which relates basin yield to elevation and precipitation. Wasiolek (1995) found that basin recharge yields varied from 11% to 19% of precipitation in five basins within the region. We would recommend moving back to this approach. The CDM method used in this study relied heavily on Frenzel (1995).

- Diffuse recharge applied to the water table has a direct impact on unconfined drawdown cones and ultimately depletions. We would recommend a re-evaluation of areal recharge in the model. There is the potential for arroyo recharge in areas not associated with the uplands (Anderholm, 1994). A reasonable estimate of what that infiltration rate could be can be defined and that value could be upscaled (areal weighted reduction) to the model. Because arroyo recharge is a focused recharge process, it is not appropriate to apply the rate over the entire model grid unless every model grid cell contains arroyos.

- The temporal variation of model recharge is a linear deviation model based upon precipitation. This assumption is considered unrealistic and should be reviewed for revision. Conceptually, one would expect that mountain front recharge would be attenuated in its relation to annual precipitation with a lower cutoff value and an upper limit.

- The MODFLOW stream package coding should be altered to fix stream discharge at a constant rate when the aquifer head is below the bottom of the stream (i.e., losing). This would provide a means of ensuring that stream losses remain reasonable. This option was in the RIV2 package of Miller (1988) and is included in the Shomaker (2001) model. A second issue is that we would recommend varying stream flows on the basis of precipitation and available gage data in the region. They are currently average annual or average monthly flows.

- Transient calibration should be completed once conceptual issues such as boundary implementation and recharge are satisfied through calibration of the steady-state model. A transient sensitivity analysis should also be performed.

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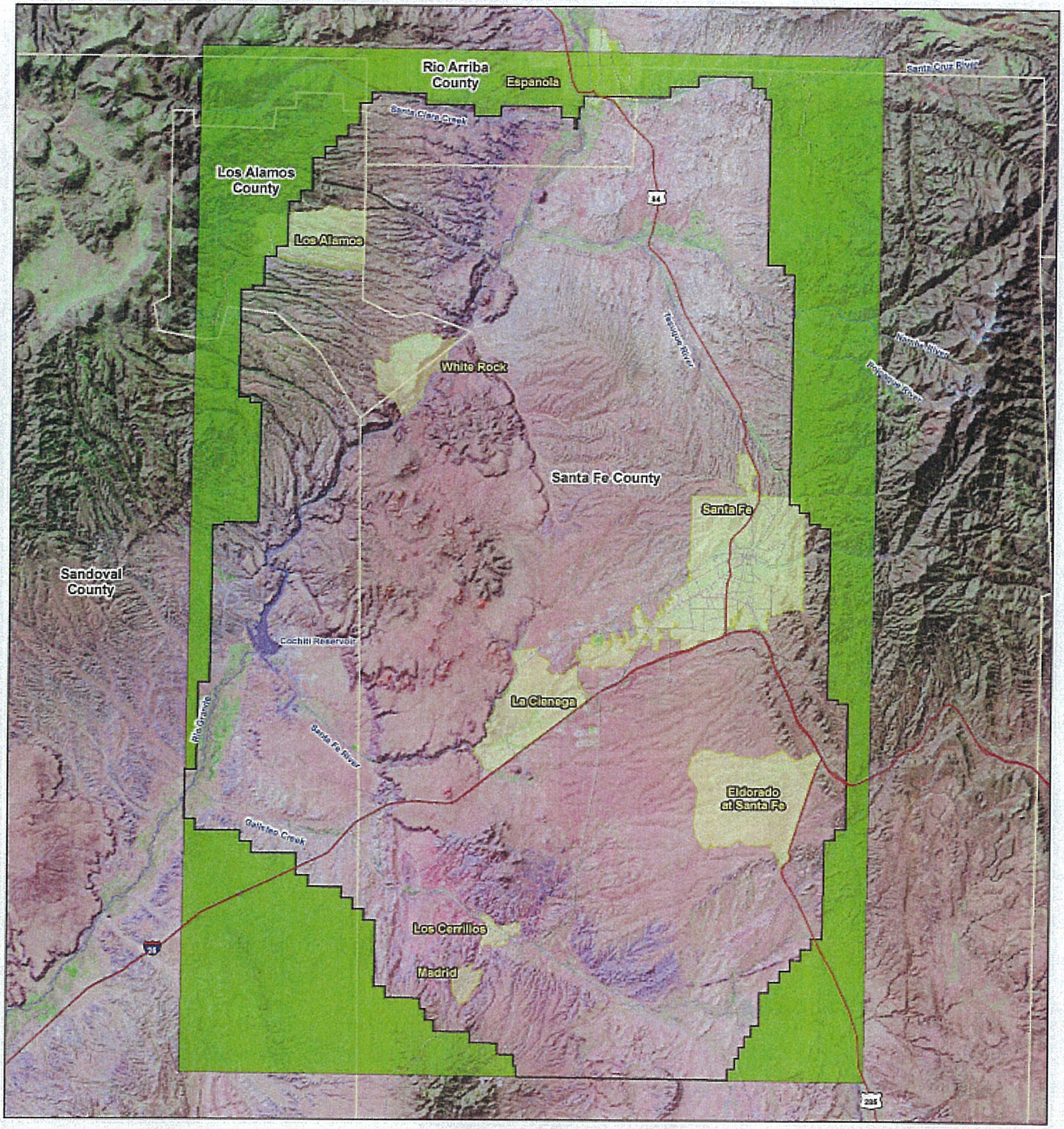

NORTH

1 inch equals 6 miles

Miles 6 3 0 6

UTM NAD 83 Zone 13, Meters

Scale 1:400,000

Legend

Model boundary with inactive areas shaded

Figure 2-1. Domain of the Active Model Grid Boundary

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

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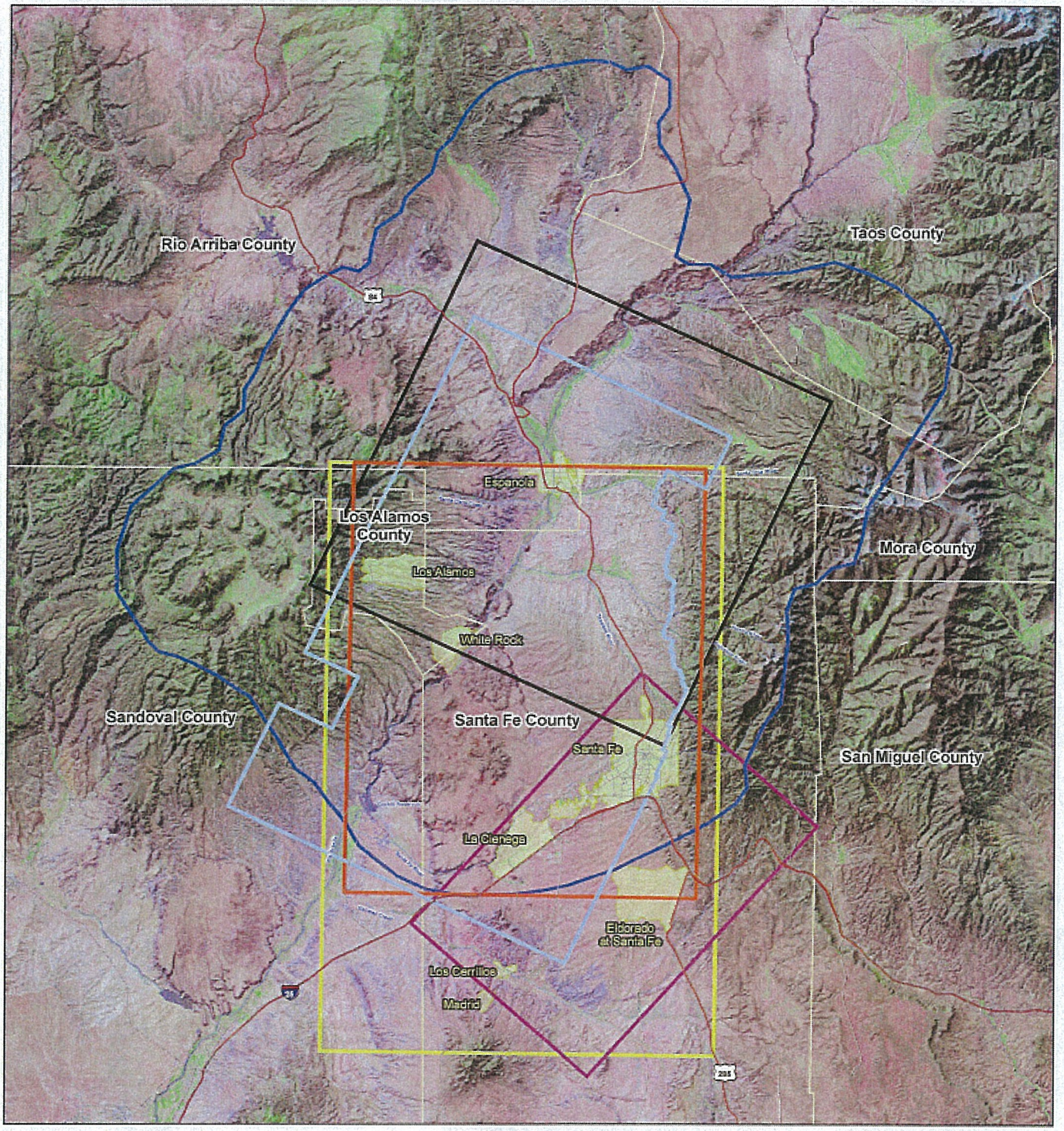

NORTH

1 inch equals 11 miles

11 5.5 0 11

Miles

UTM NAD 83 Zone 13, Meters
Scale 1:700,000

Legend

- Hearne Model (1980)
- McAda-Wasiolek Model (1988)
- Barroll-Logan Model (1998)
- Keating Model (2000)
- Shomaker Model (2001)
- SFCM Model Boundary

Figure 3-1.
Available Model Domains and Preliminary Boundary for the Active Model

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

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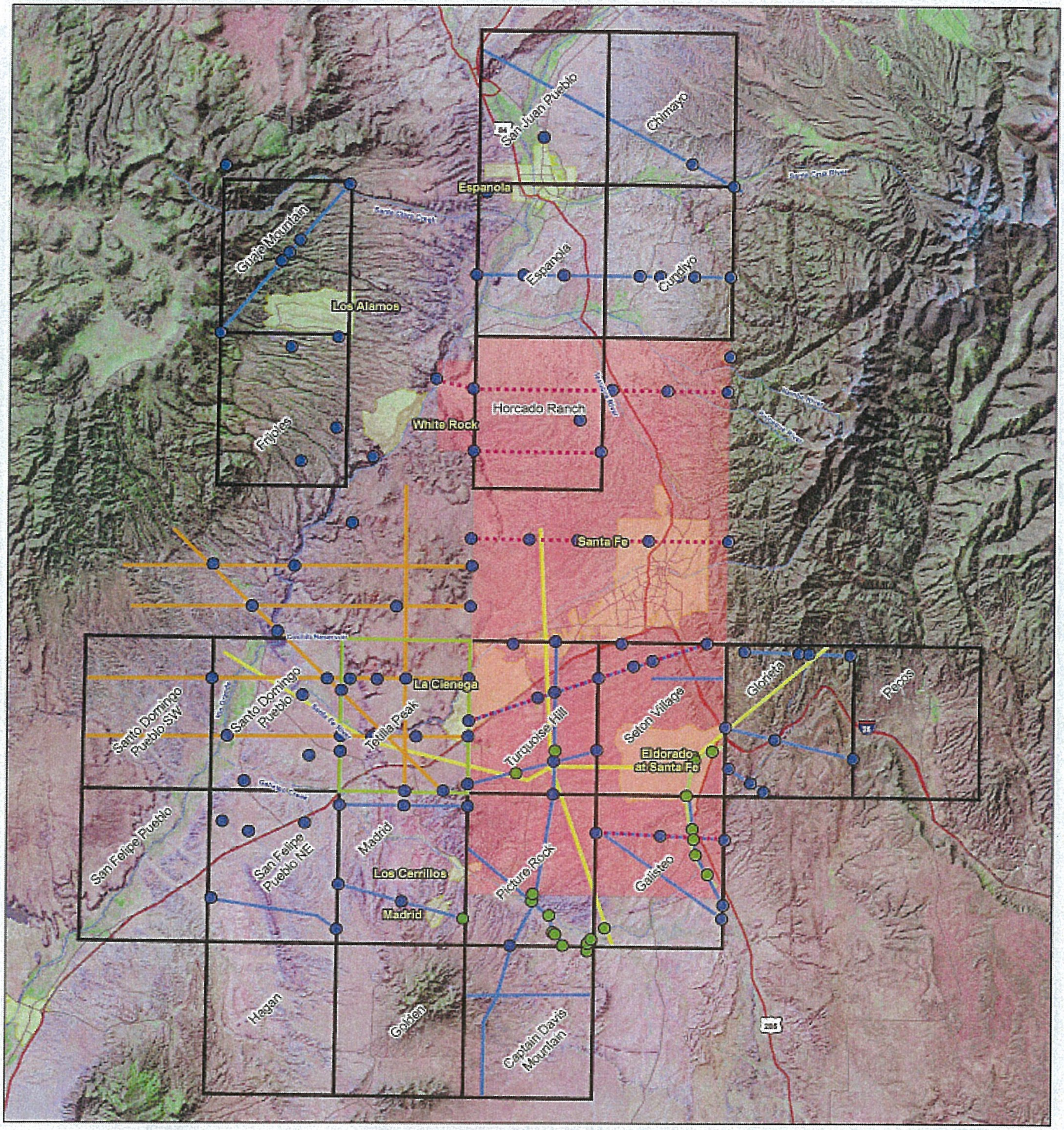

NORTH

1 inch equals 8 miles

8 4 0 8

Miles

UTM NAD 83 Zone 13, Meters

Scale 1:500,000

Legend

- Borehole
- Virtual Borehole
- USGS Tetilla Peak (Sawyer et. al., 2002)
- NMBGMR Geologic Quadrangle
- Johnson et. al. (2004) Geology Map
- Johnson et. al.
- Balleau (2000)
- Glorieta Geoscience (2002)
- NMBGMR
- Sawyer et. al. (2005)

Figure 4-1.
Geologic Maps, Lines of Sections, and Boreholes Used for Geologic Model Construction

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

SANTA FE COUNTY

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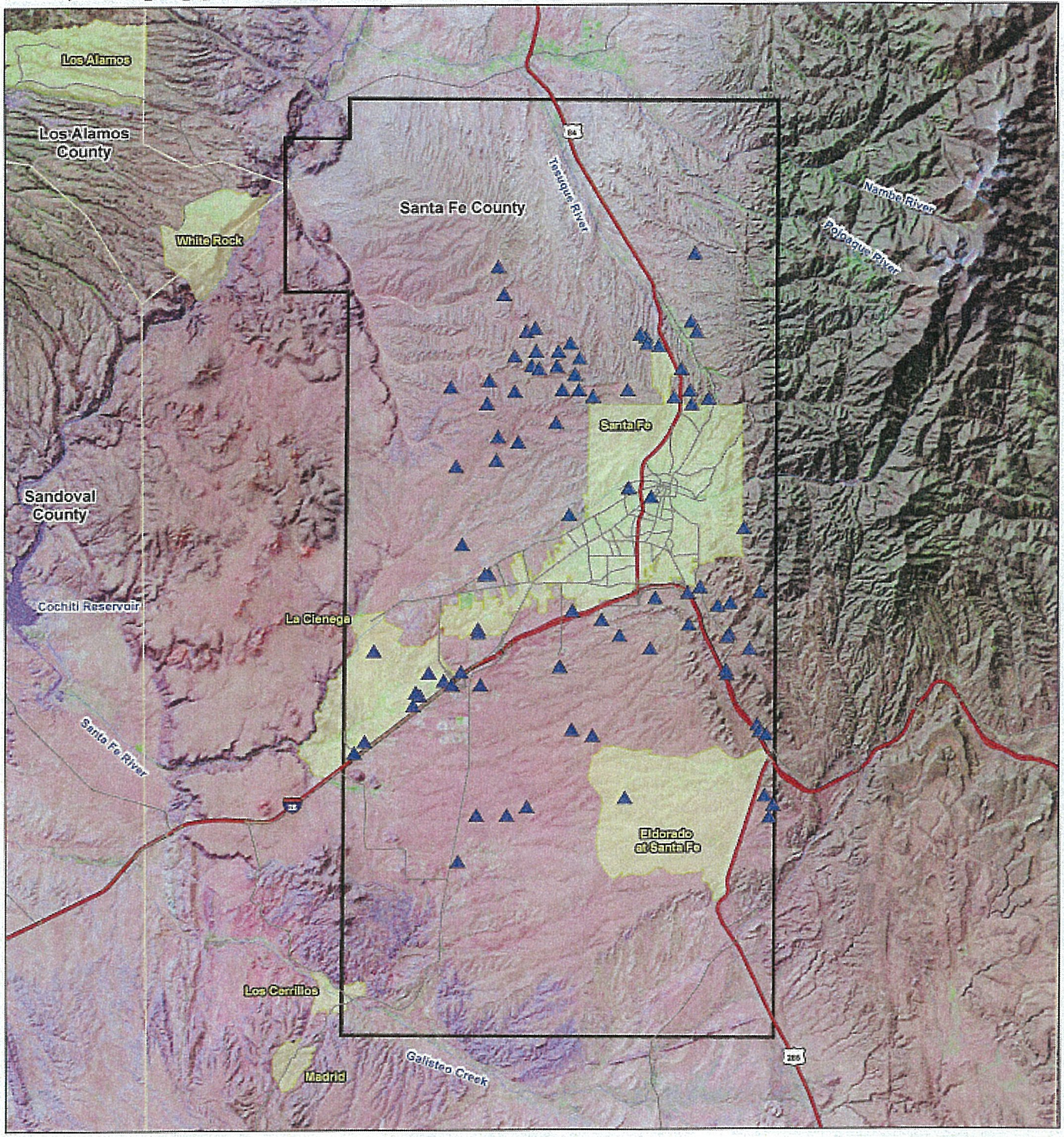

NORTH

1 inch equals 5 miles

5 2.5 0 5

Miles

UTM NAD 83 Zone 13, Meters

Scale 1:300,000

Legend

- ▲ Aquifer transmissivity measurement
- ☐ Johnson et al. (2004) study area

Figure 4-2.
Locations of Transmissivity Measurements from Johnson et al. (2004)

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

SANTA FE COUNTY

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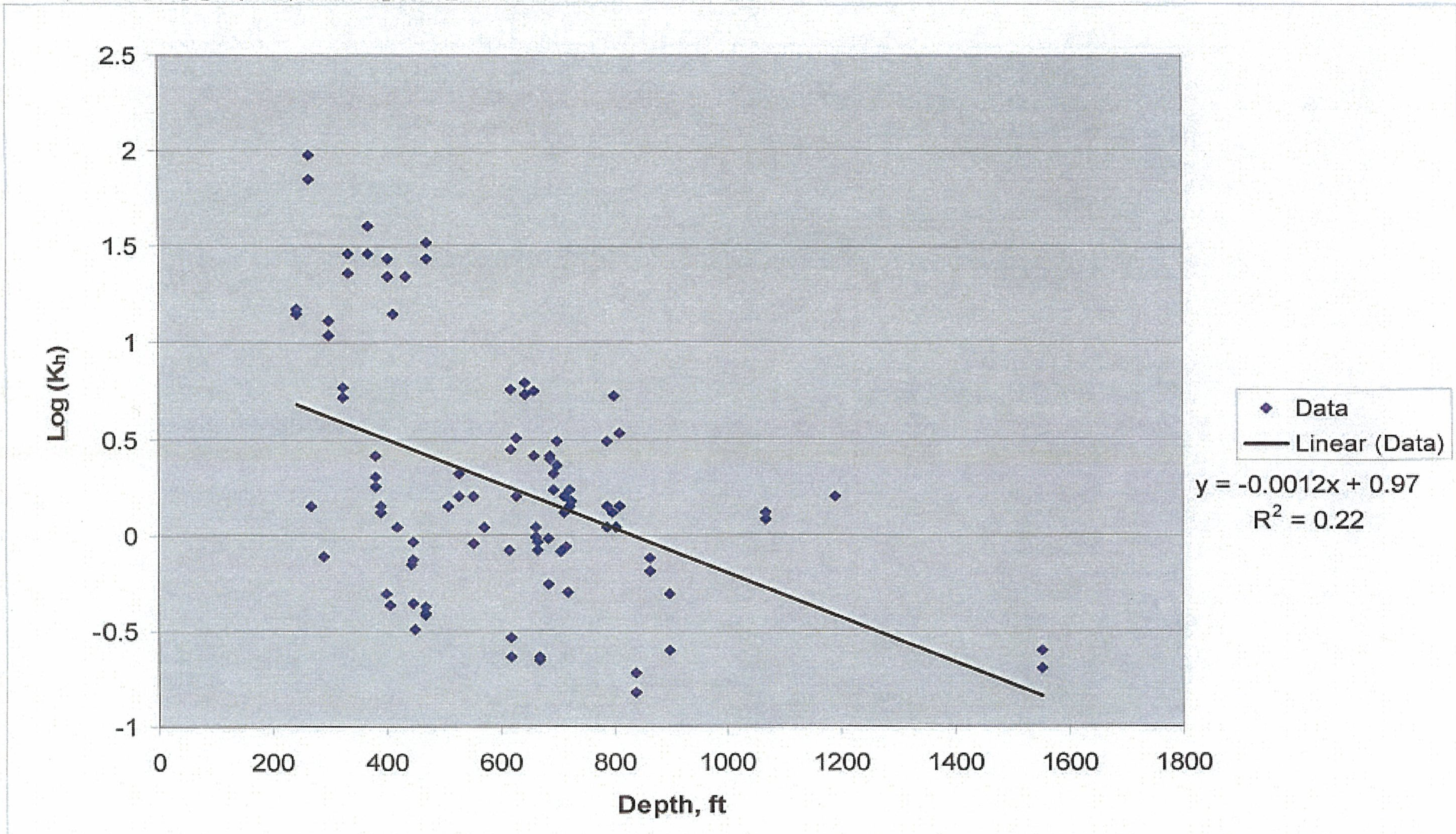

Figure 4-3.
Hydraulic Conductivity versus
Depth for Tesuque Lithosome S.

INTERA

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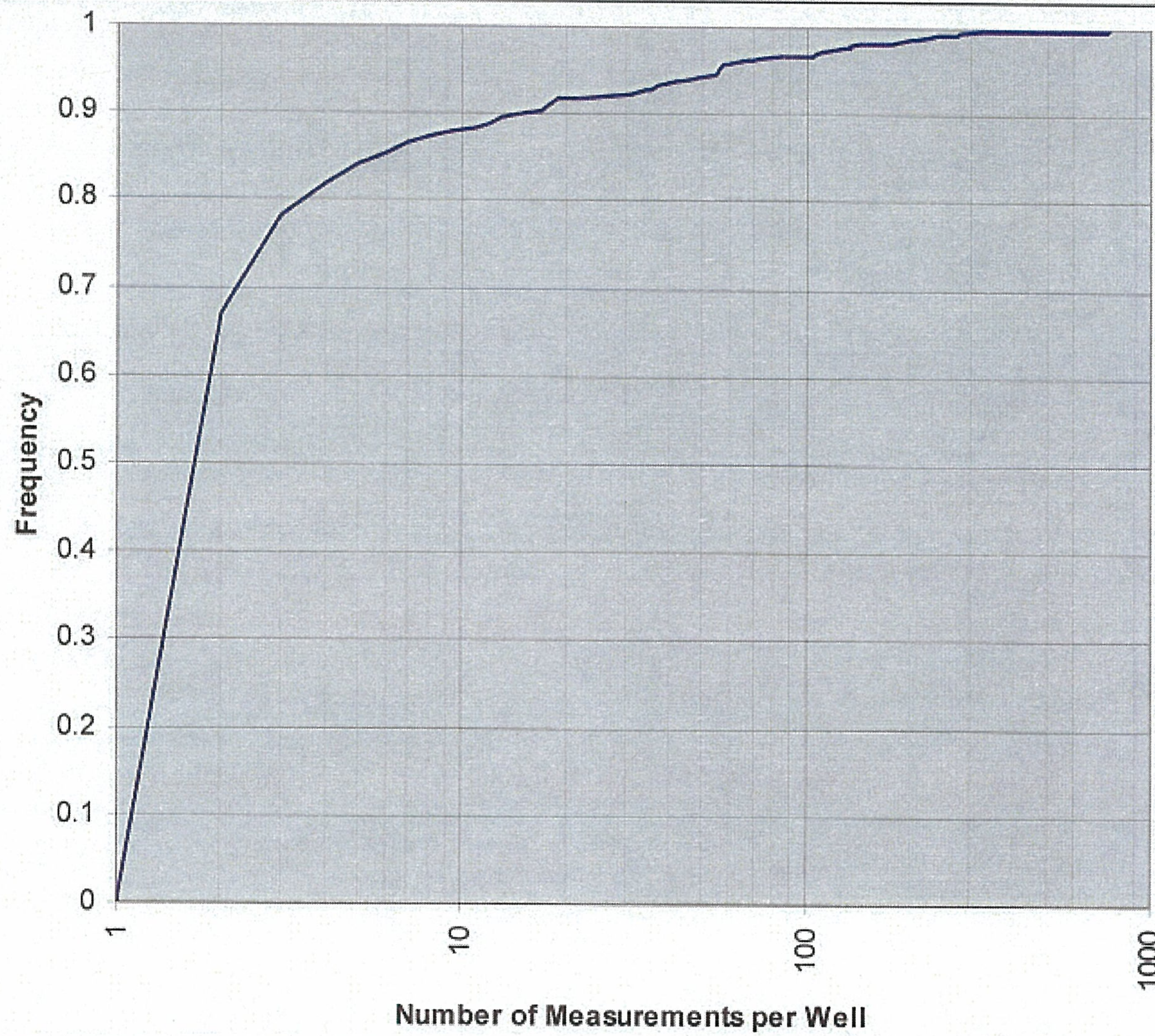

Figure 4-4.
Cumulative Distribution Function of
Number of Head Measurements per Well

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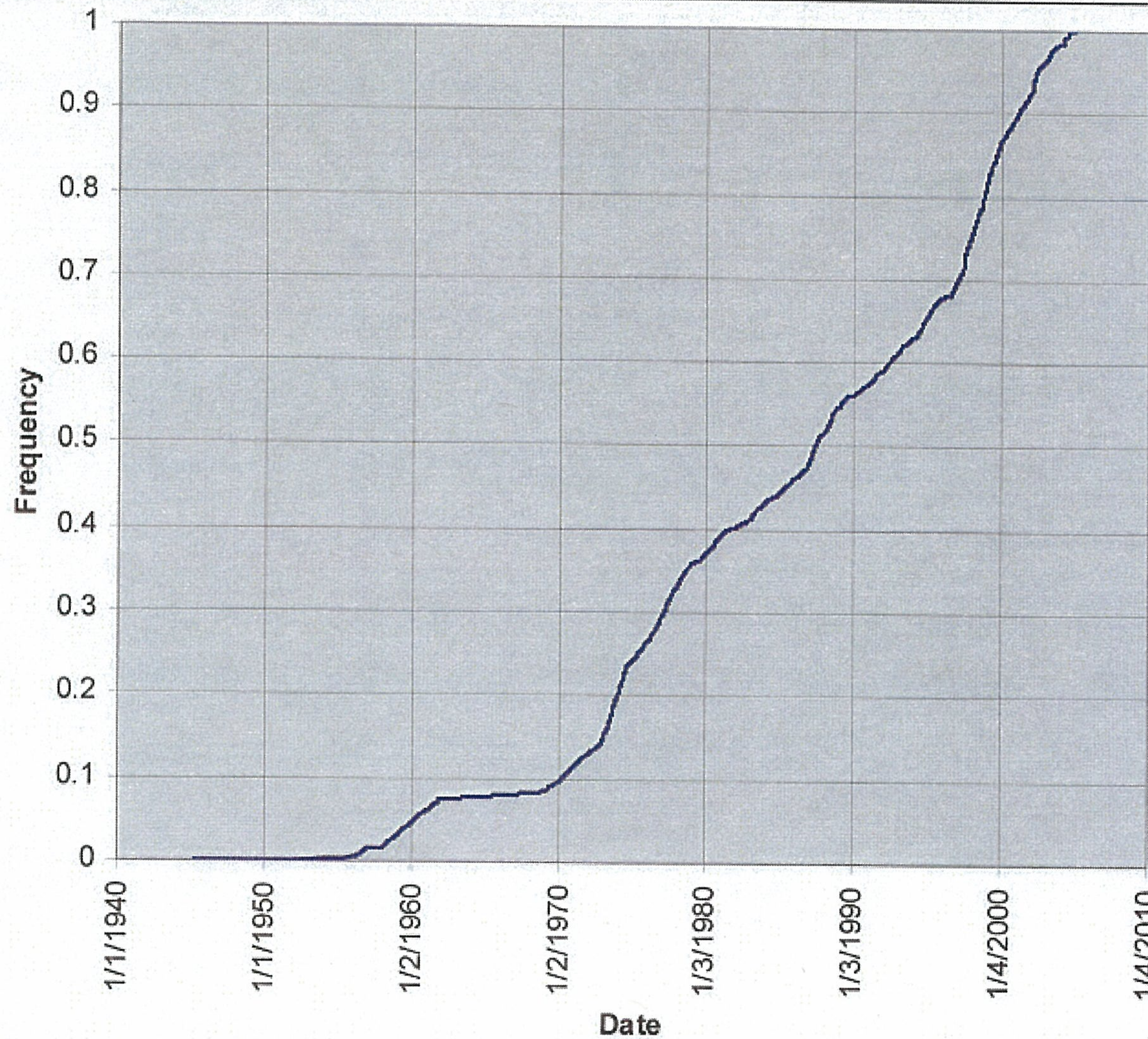

Figure 4-5.
Cumulative Distribution Function
of Initial Measurement Date

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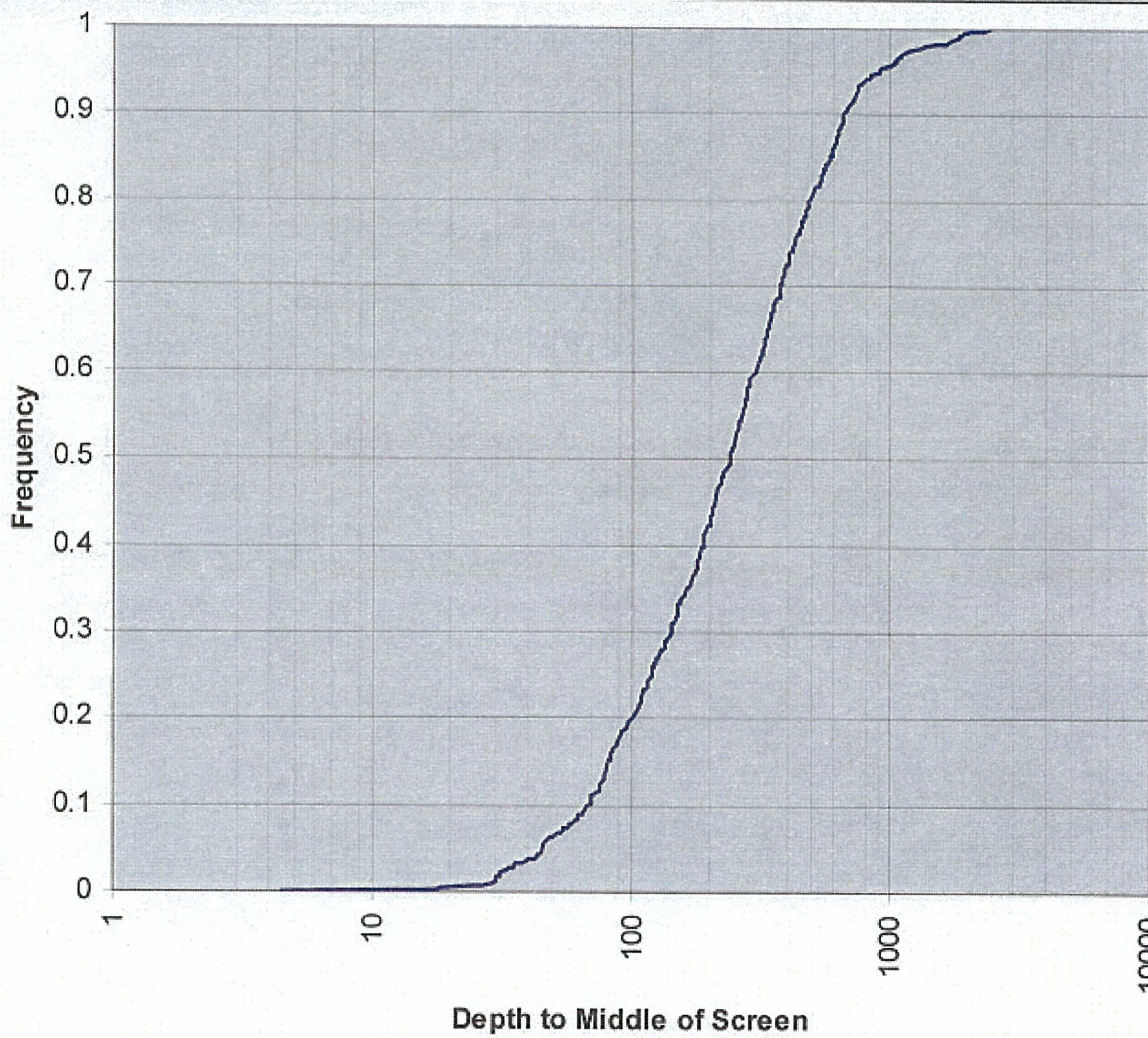

Figure 4-6.
Cumulative Distribution Function of the Depth of the Middle of the Well Screen

INTERA

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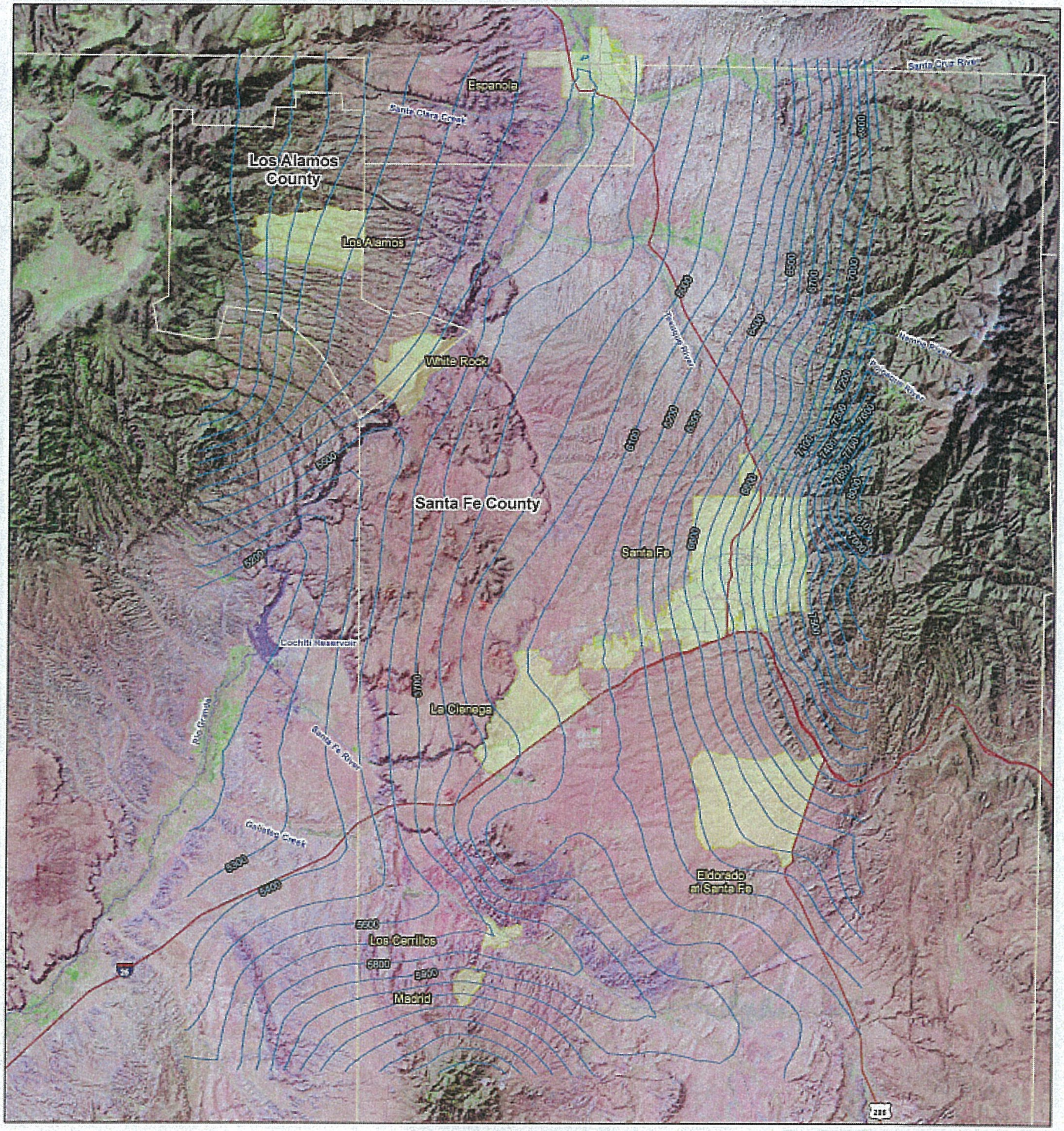

NORTH

1 inch equals 6 miles

6 3 0 6

Miles

UTM NAD 83 Zone 13, Meters

Scale 1:400,000

Legend

Groundwater Elevation, ft msl

Figure 4-7.
Smoothed Pre-Development Head Surface for Model Domain

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

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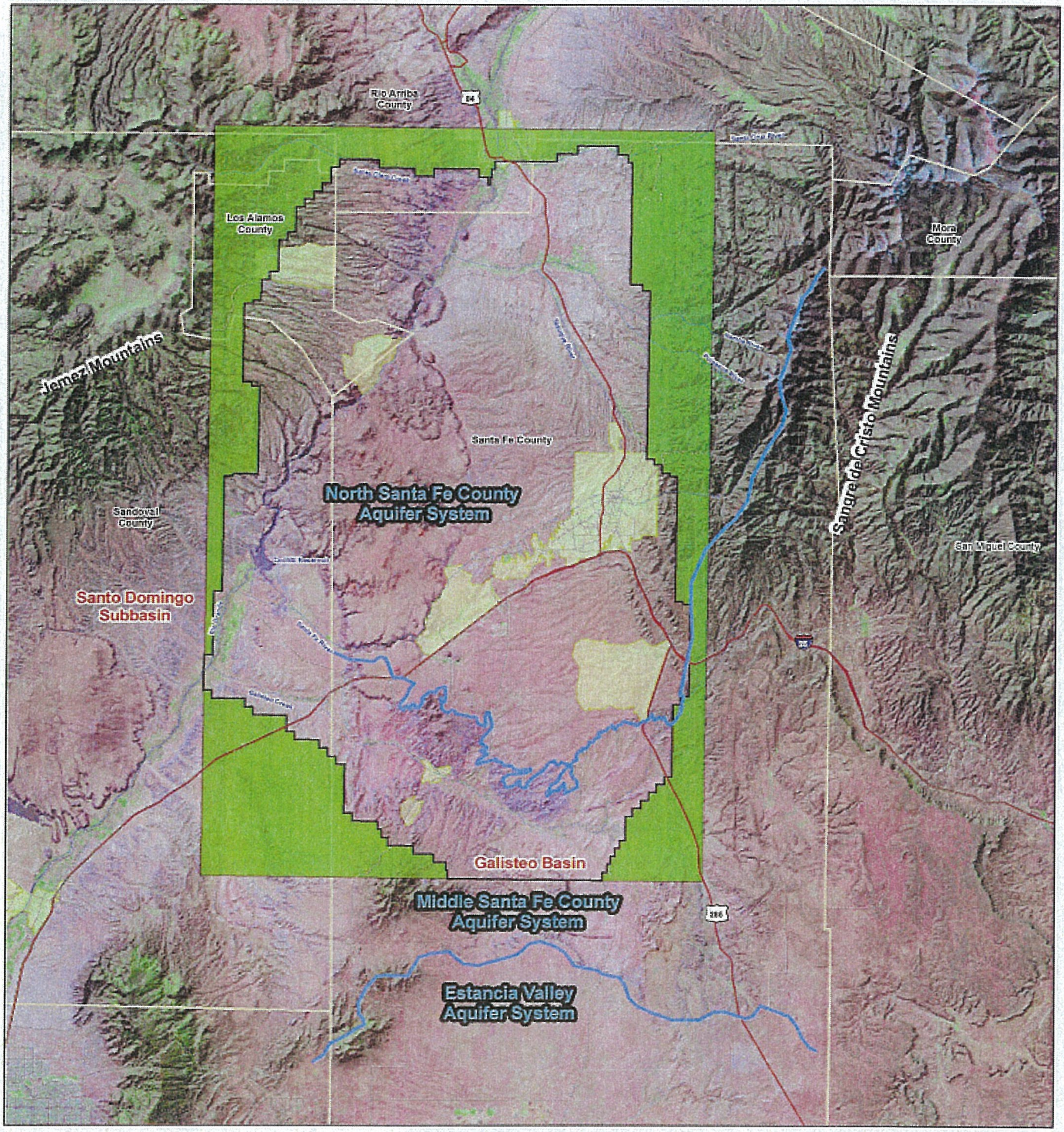

NORTH

1 inch equals 9 miles

Miles 9 4.5 0 9

UTM NAD 83 Zone 13, Meters

Scale 1:550,000

Legend

Divisions of Lewis and West (1995)

Model boundary with inactive areas shaded

Figure 4-8.
Regional Overview
and Aquifer Systems
(Lewis and West, 1995)

INTERA

Sources:
New Mexico county boundaries, roads, streams, and
cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

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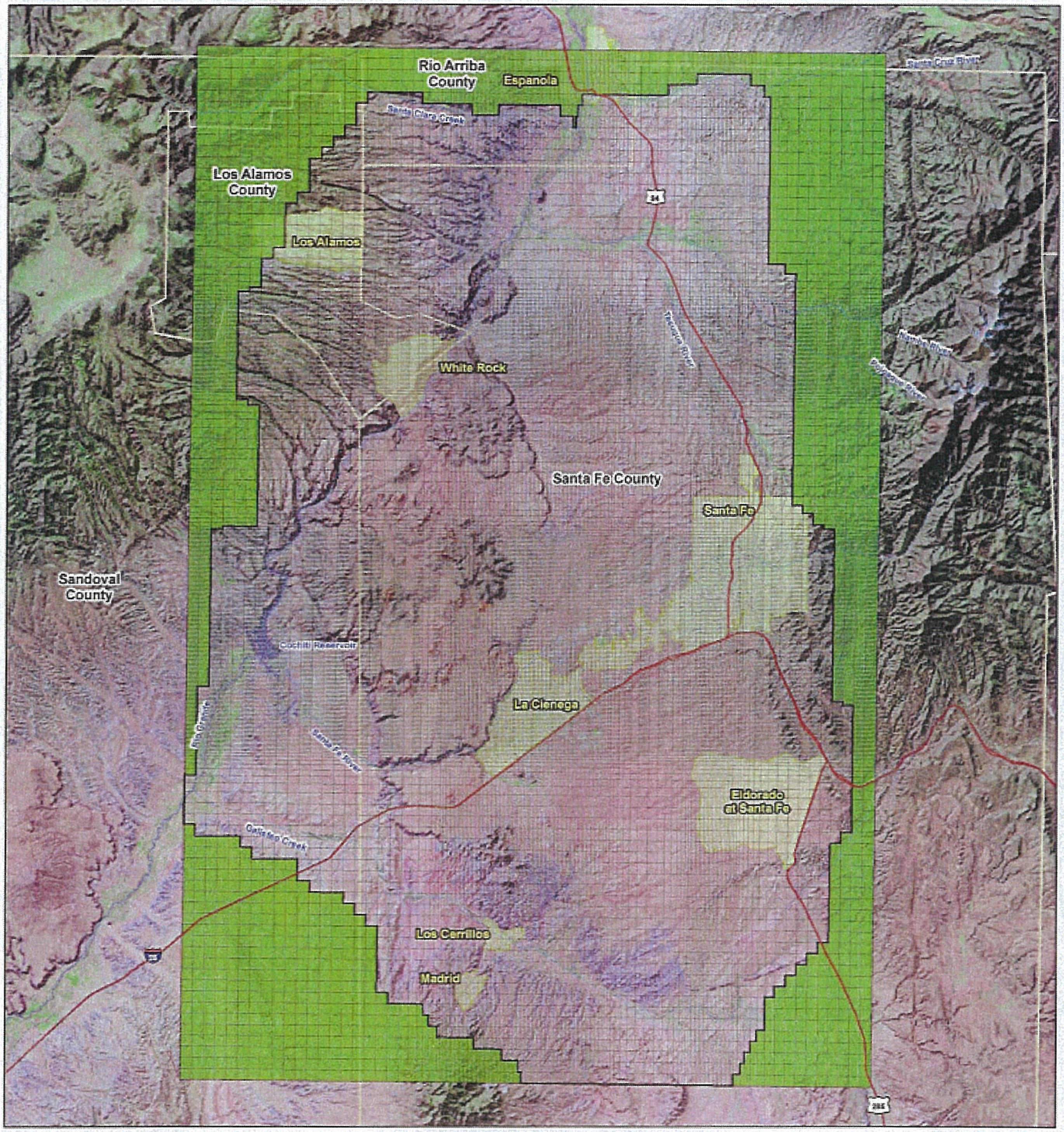

NORTH

1 inch equals 6 miles

6 3 0 6

Miles

UTM NAD 83 Zone 13, Meters

Scale 1:400,000

Legend

- Model Grid
- Model boundary with inactive areas shaded

Figure 6-1. Model Grid

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

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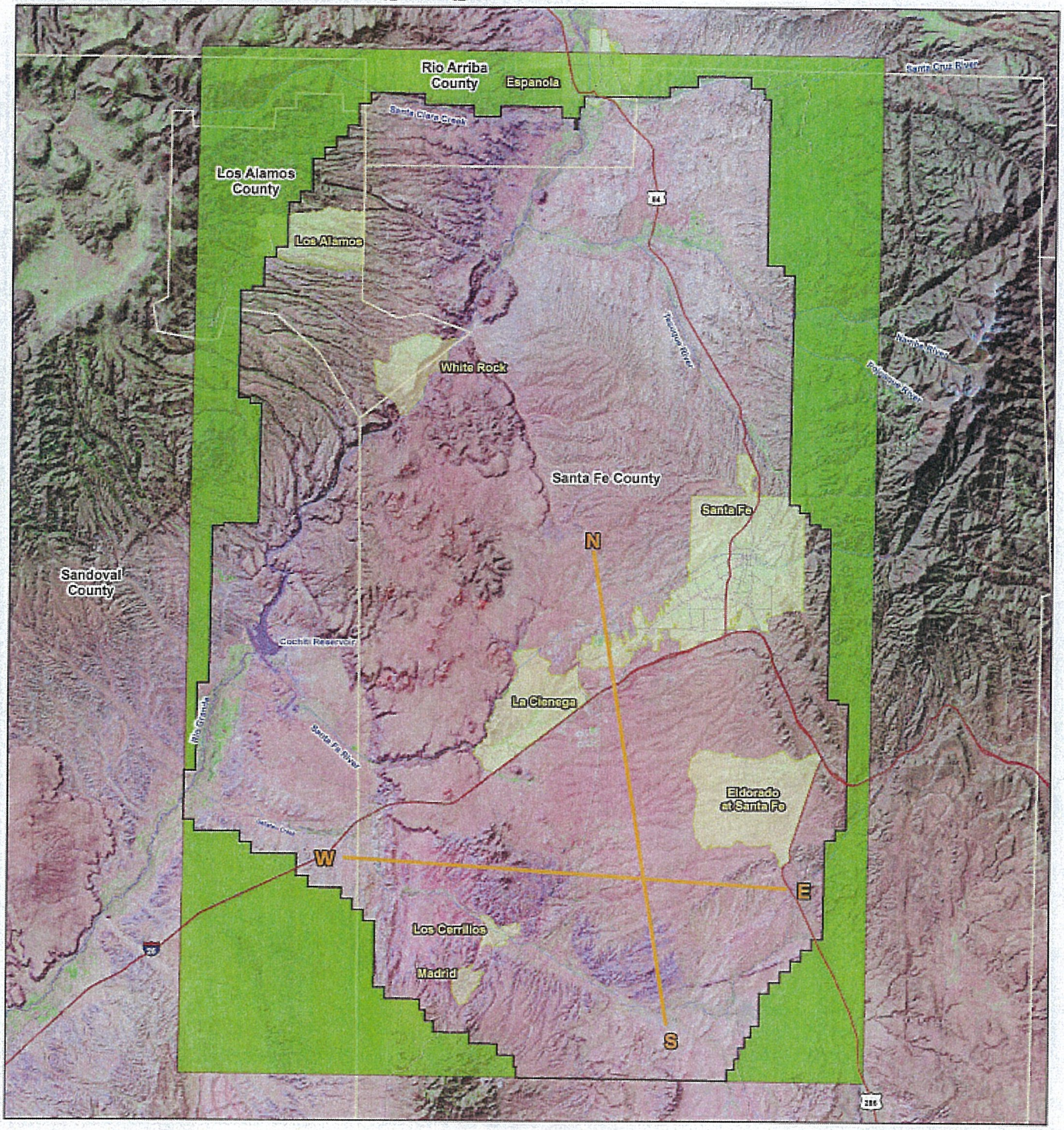

NORTH

1 inch equals 6 miles

6 3 0 6

Miles

UTM NAD 83 Zone 13, Meters

Scale 1:400,000

Legend

Model boundary with inactive areas shaded

Approximate Cross Section

Figure 6-2a.
Approximate Cross Section Location Map

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

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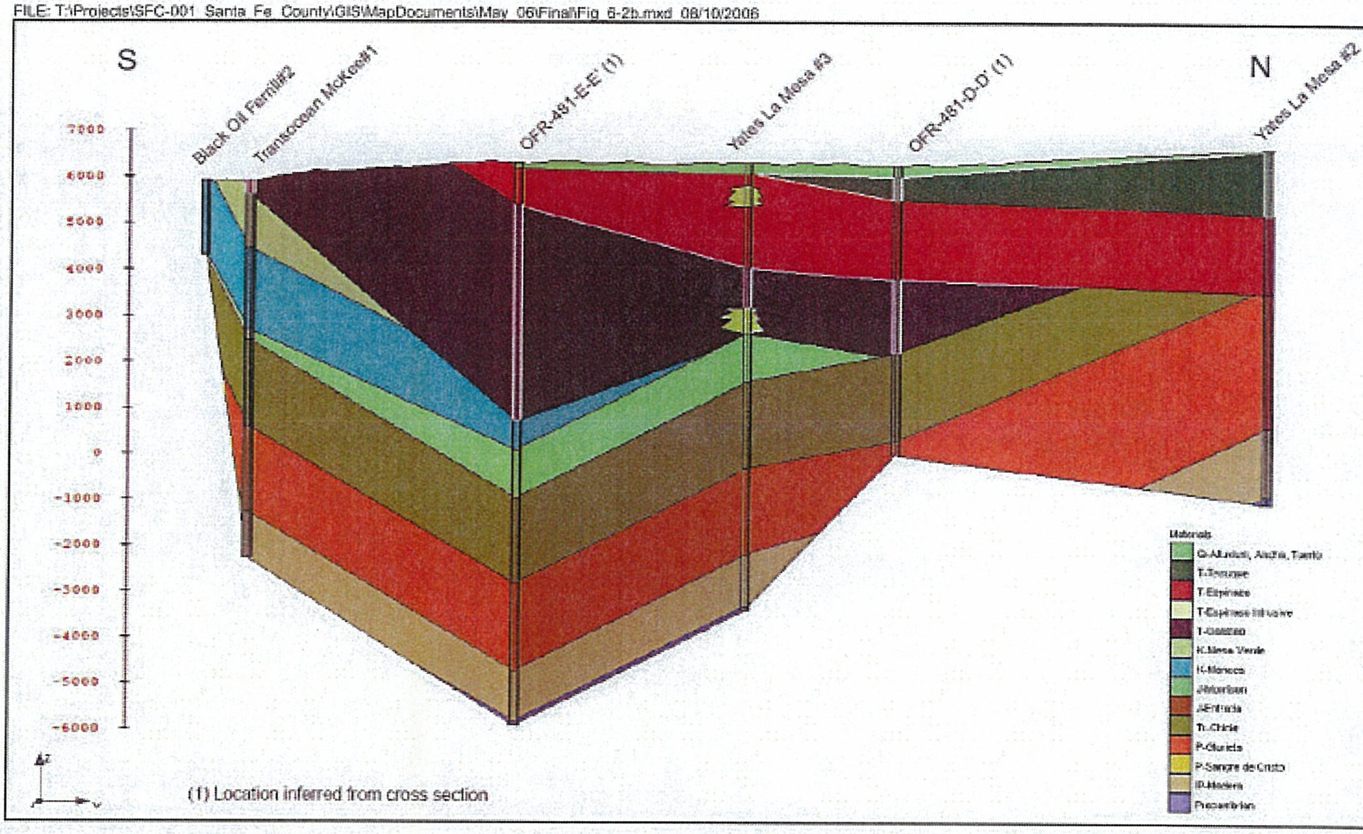
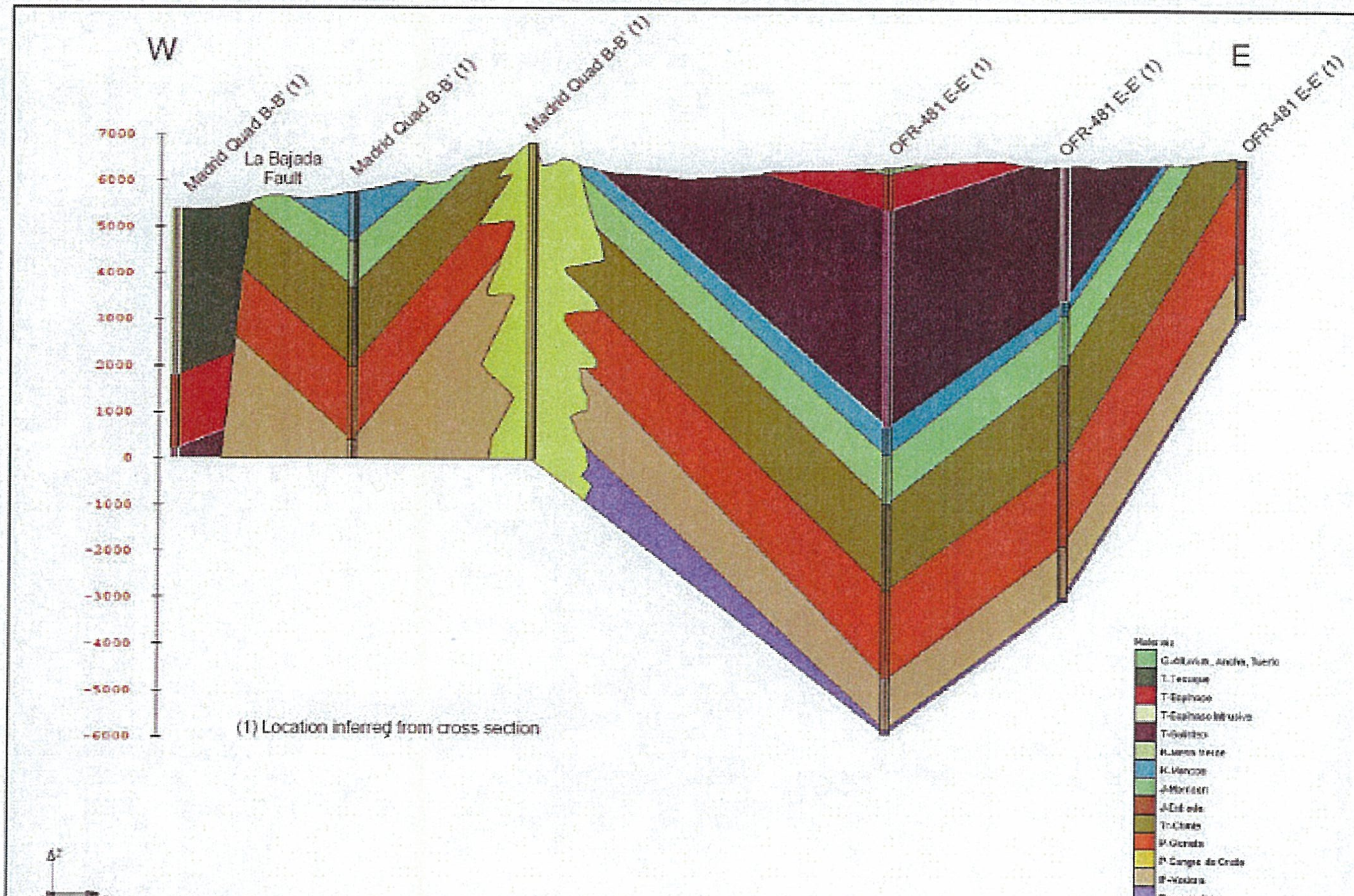


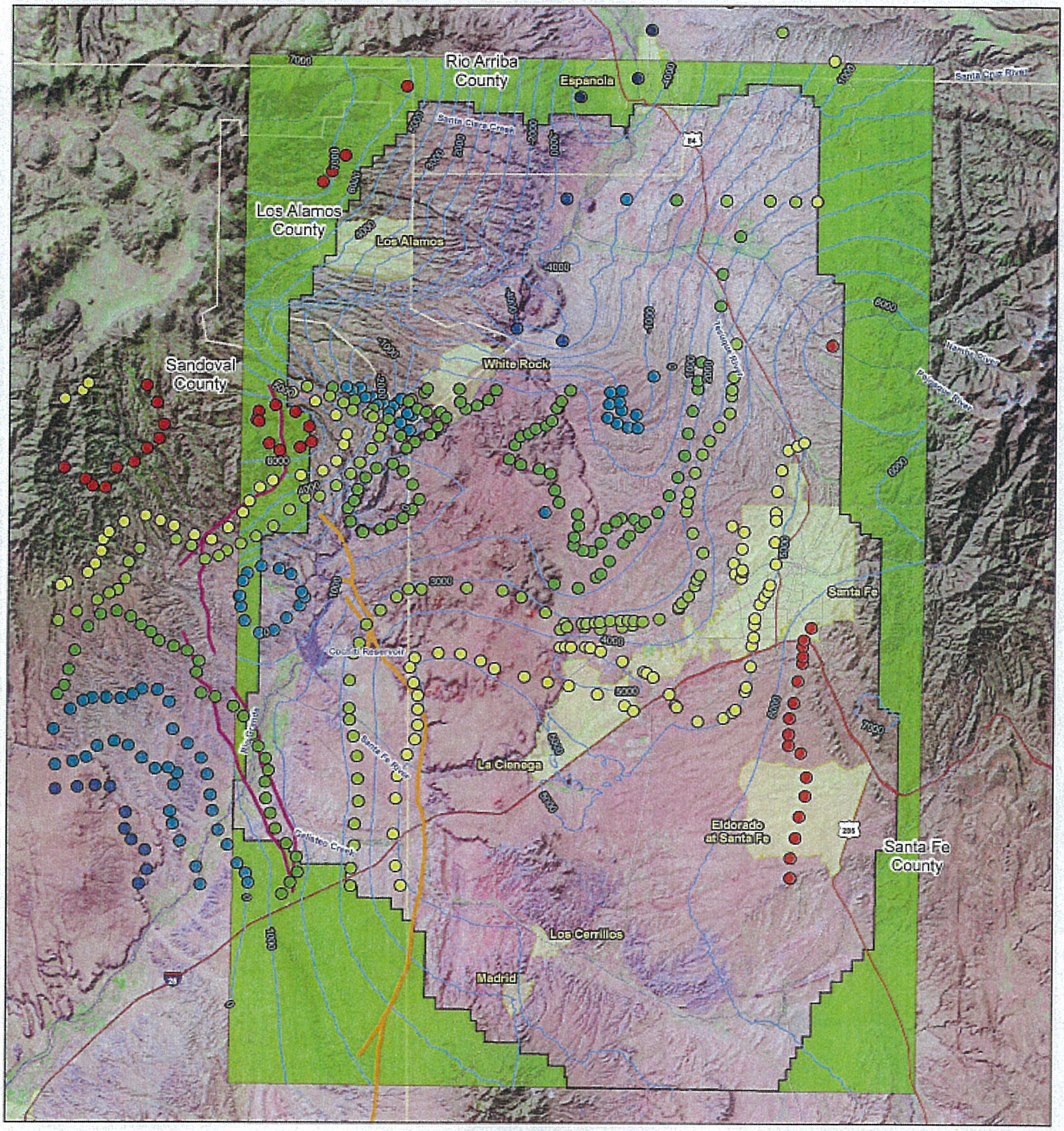


INTERA

Figure 6-2b.
Schematic Cross Sections Developed for the Southern Portion of Española Basin

SANTA FE COUNTY

FILE:T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_6-3.mxd 08/31/2006



NORTH

1 inch equals 6 miles

Miles 6 3 0 6

UTM NAD 83 Zone 13, Meters

Scale 1:400,000

Legend

- Basin Basement Contour (ft msl)
- Model boundary with inactive areas shaded
- La Bajada Fault Zone
- Parajito Fault Zone

Control Points (ft msl)

- 6000 - 8000
- 4000 - 6000
- 2000 - 4000
- 0 - 2000
- -2000 - 0
- -4000 - -2000
- -6000 - -4000

Figure 6-3.
Espanola Basin Basement Contours from Developed Geophysical Datasets

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

INTERA

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_05\Final\Fig_6-4.mxd 08/31/2006

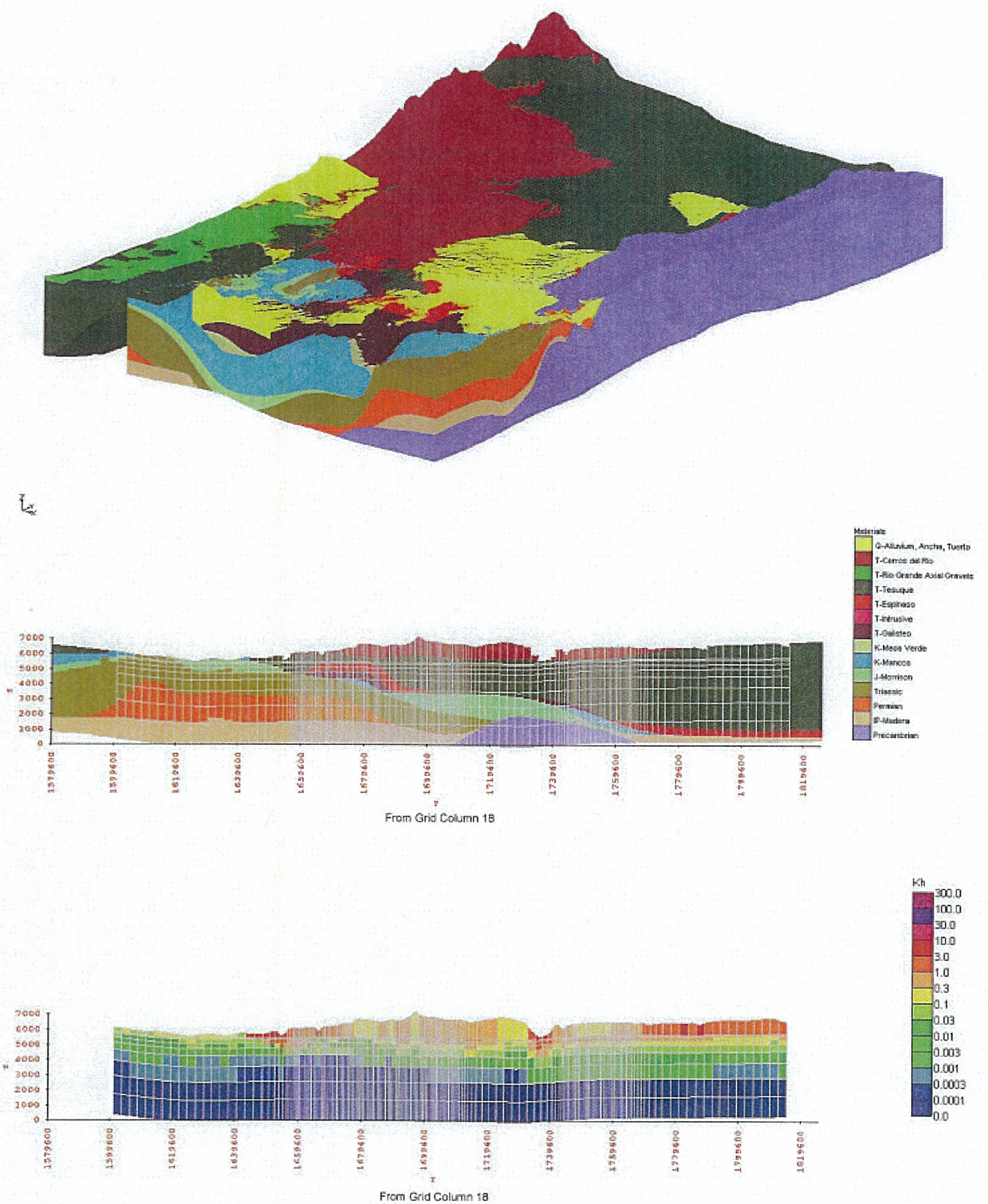
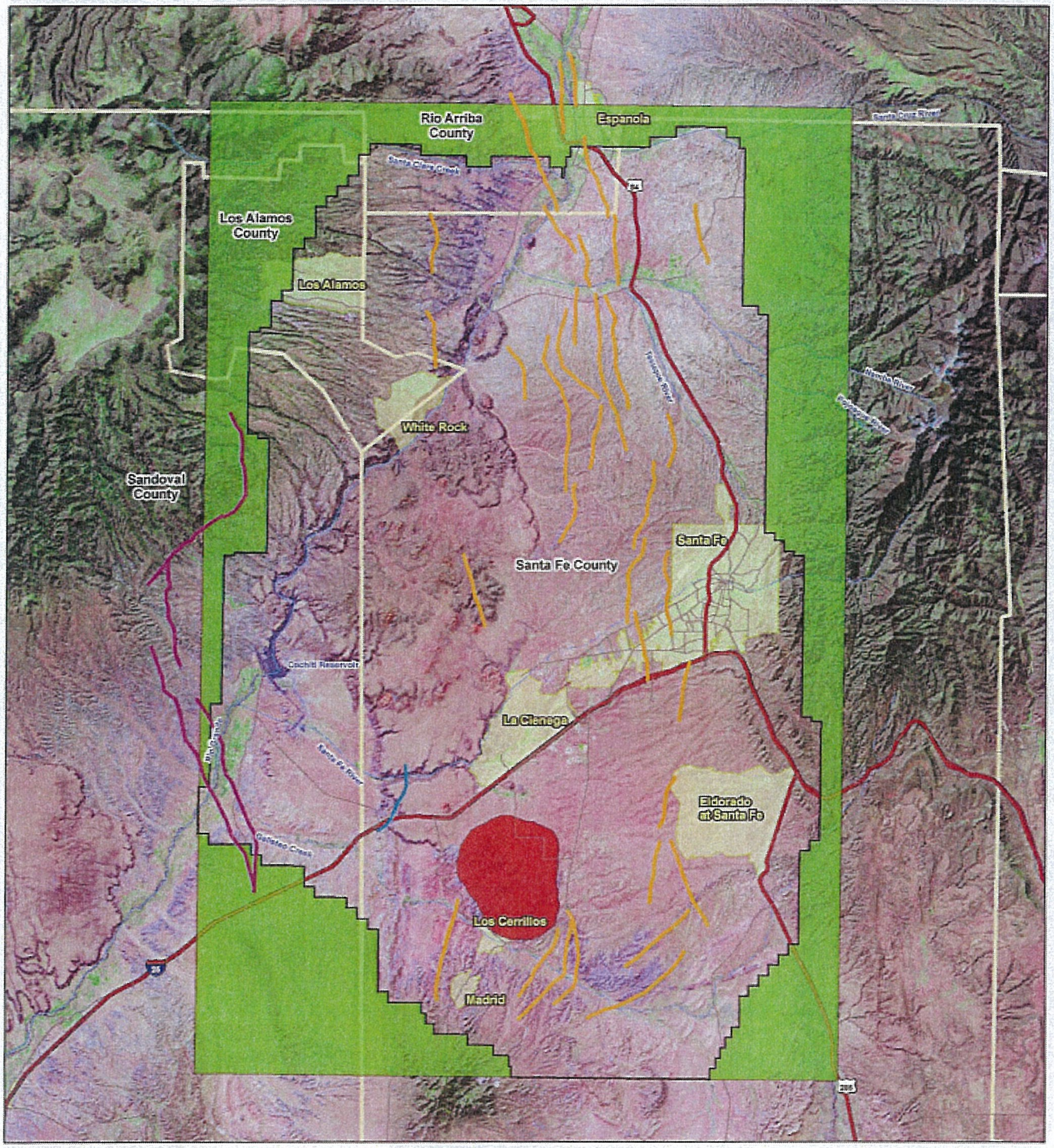


**Figure 6-4.
Three Dimensional Geologic Model and
Flow Model Grid Columns from Mapped HSUs**

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_6-5.mxd 08/10/2006



NORTH

1 inch equals 7 miles

Miles	7	3.5	0	7

UTM NAD 83 Zone 13, Meters

Scale 1:425,000

Legend

- Model boundary with inactive areas shaded
- Cerrillos Intrusion

Faults

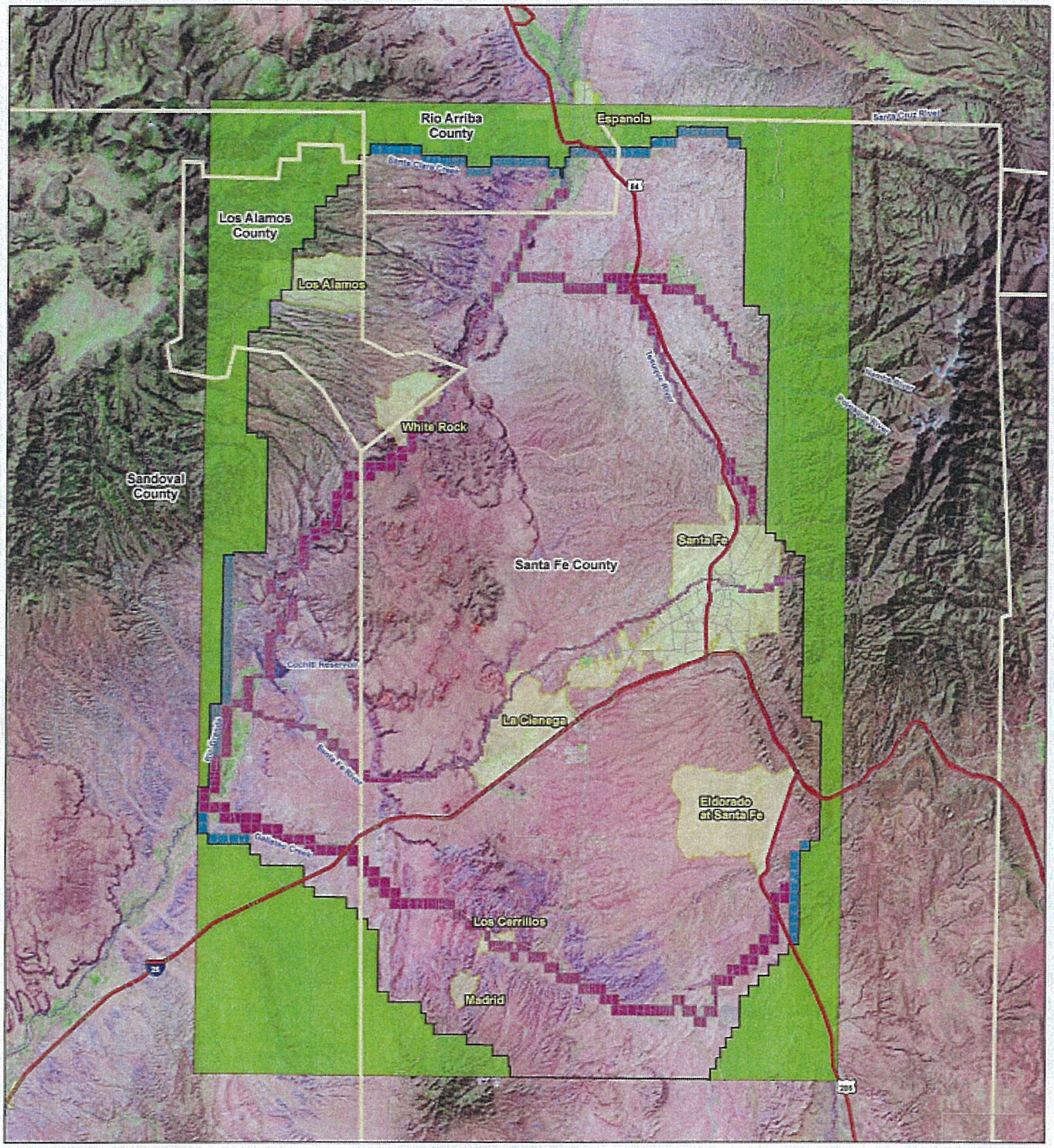
- Unidentified Fault (OFR-481, 2005)
- Parajito Fault
- Tetilla Peak Fault

Figure 6-5.
Structure and Faults Which are Implemented in the Model Using the HFB Package.

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_6-6.mxd 08/14/2006



NORTH

1 inch equals 7 miles

7 3.5 0 7

Miles

UTM NAD 83 Zone 13, Meters

Scale 1:425,000

Legend

- Model boundary with inactive areas shaded

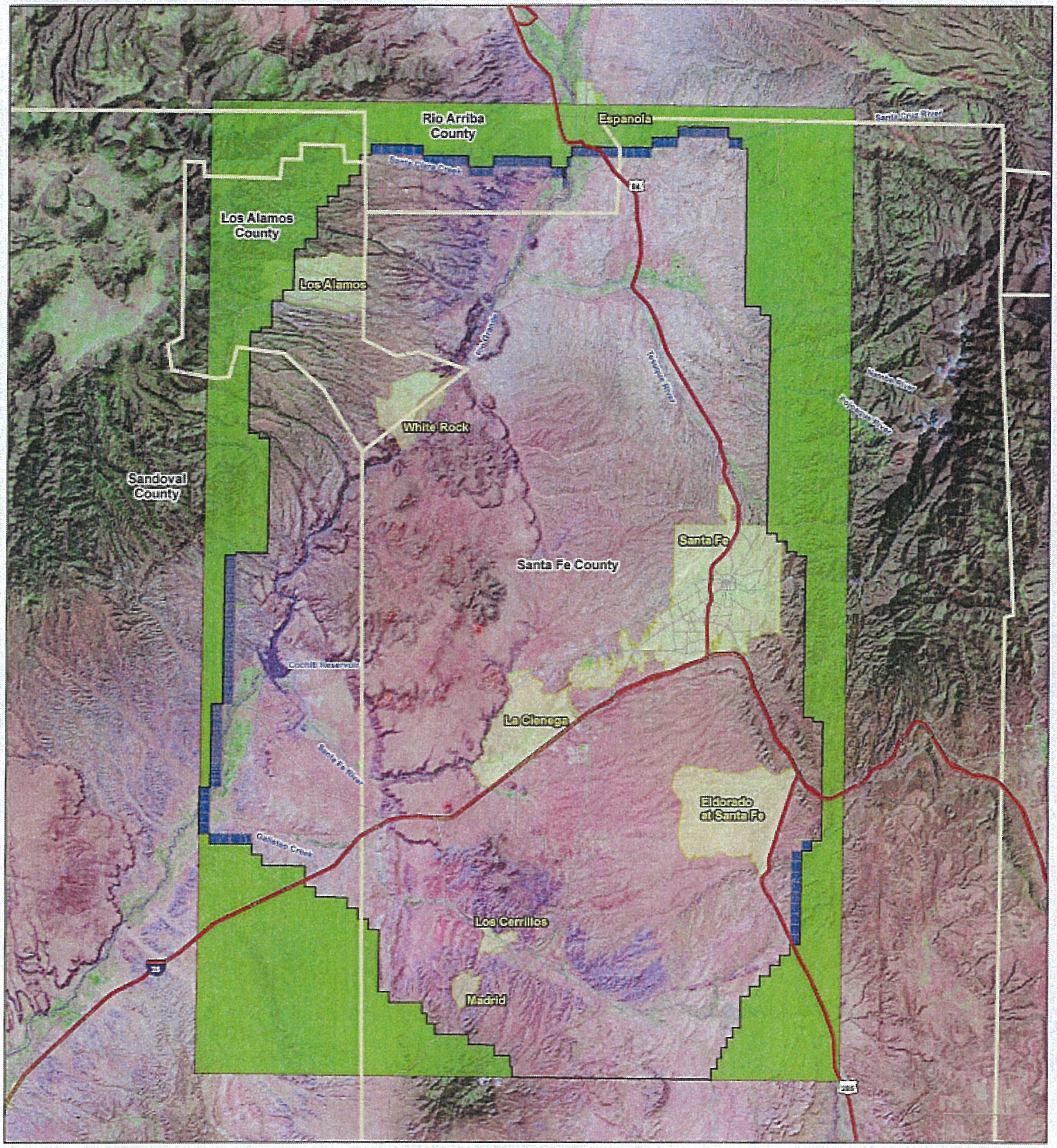
Boundary Condition

- General Head Boundary
- Stream

Figure 6-6.
Boundary Conditions
in Layer 1

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_6-7.mxd 08/14/2006



NORTH

1 inch equals 7 miles

Miles 7 3.5 0 7

UTM NAD 83 Zone 13, Meters

Scale 1:425,000

Legend

- Model boundary with inactive areas shaded
- Lateral Boundary Condition
- General Head Boundary

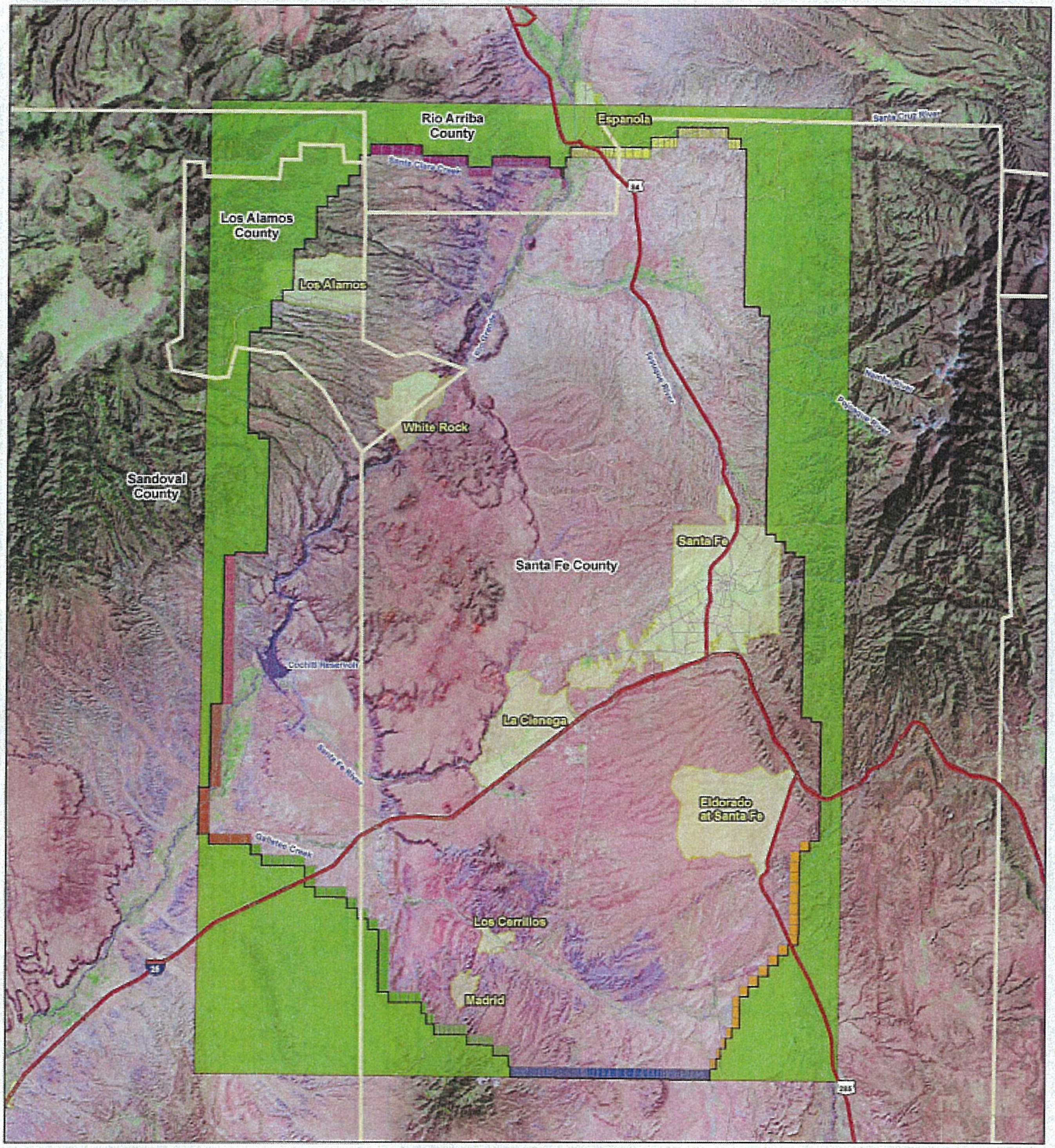
Figure 6-7. Boundary Conditions in Layers 2 through 9.

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

SANTA FE COUNTY

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_6-8.mxd 08/14/2006



NORTH

1 inch equals 7 miles

Miles 7 3.5 0 7

UTM NAD 83 Zone 13, Meters

Scale 1:425,000

Legend

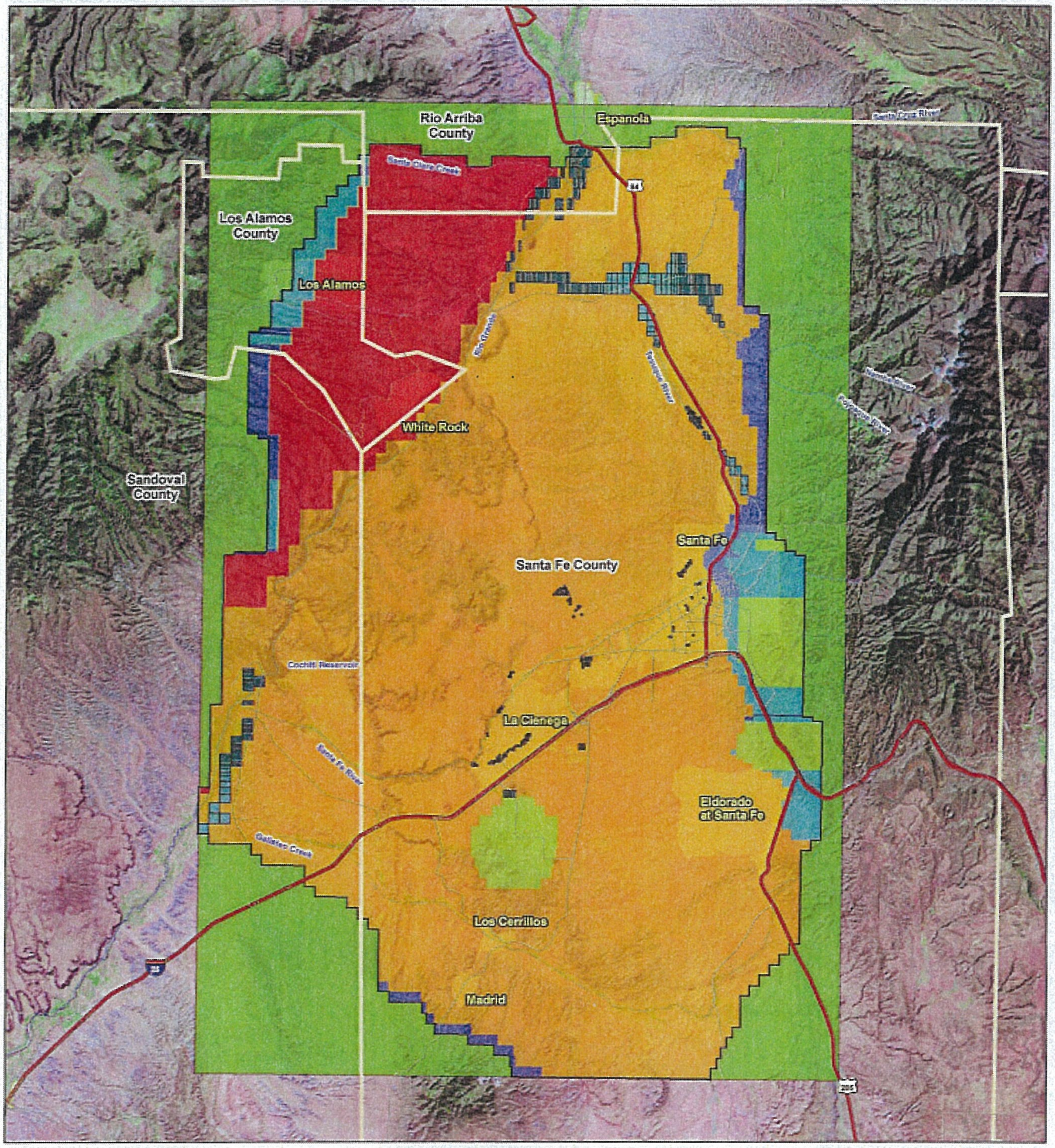
- Model boundary with inactive areas shaded
- General Head Boundary Group
  - Group 1
  - Group 2
  - Group 3
  - Group 4
  - Group 5
  - Group 6
  - Group 7

Figure 6-8. Boundary Conditions Calibration Groups.

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_6-9.mxd 08/14/2006



NORTH

1 inch equals 7 miles

7 3.5 0 7

Miles

UTM NAD 83 Zone 13, Meters

Scale 1:425,000

Legend

- Model boundary with inactive areas shaded
- Irrigated Acreage

Recharge (in/yr)

- 0 - 0.03
- 0.03 - 0.05
- 0.05 - 2.28
- 2.28 - 6.00
- 6.00 - 98.50

Figure 6-9. Initial Steady-State Distribution of Recharge.

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_6-10.mxd 08/14/2006

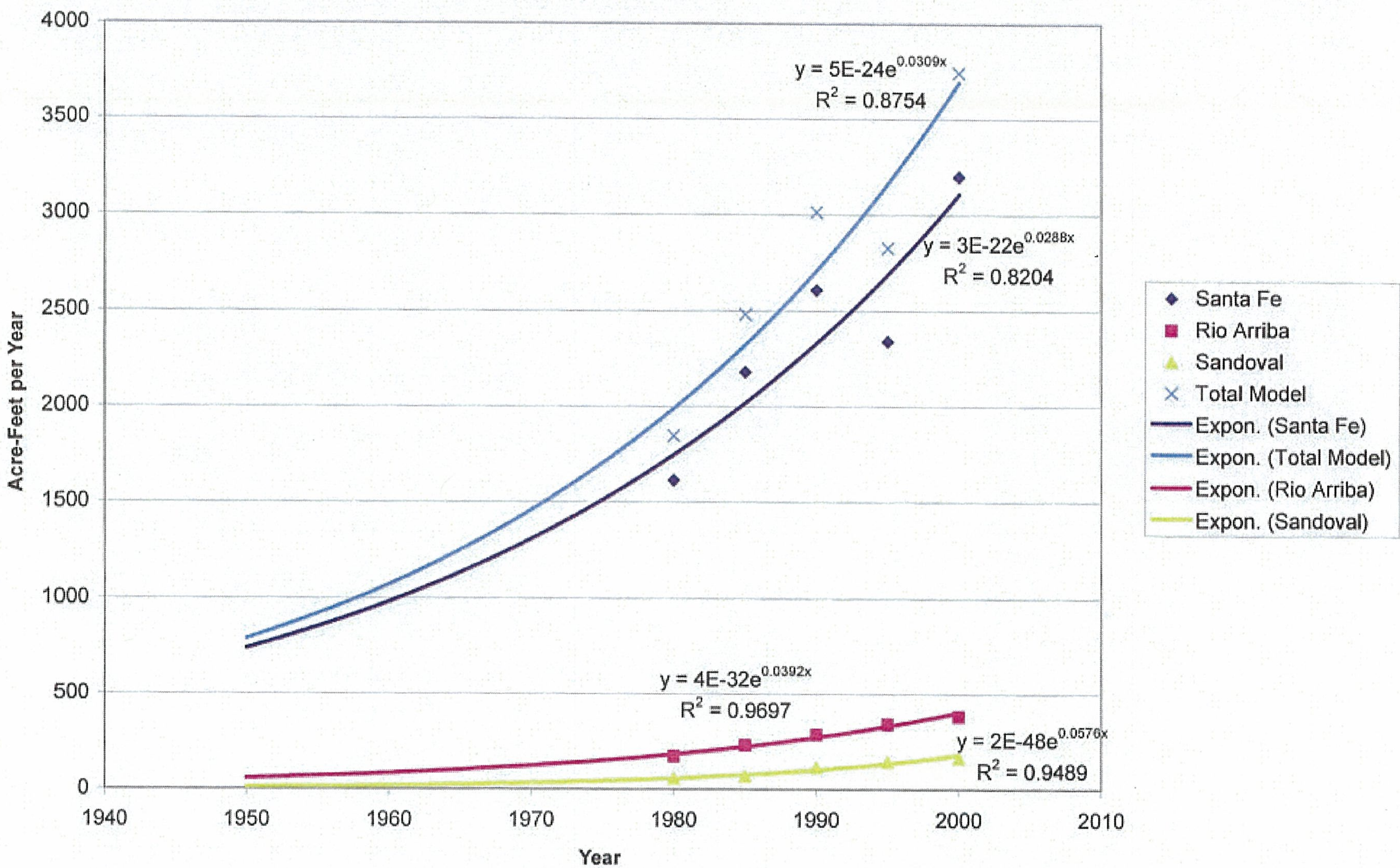


Figure 6-10.
Domestic Usage in Model Domain

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_6-11.mxd 08/14/2006

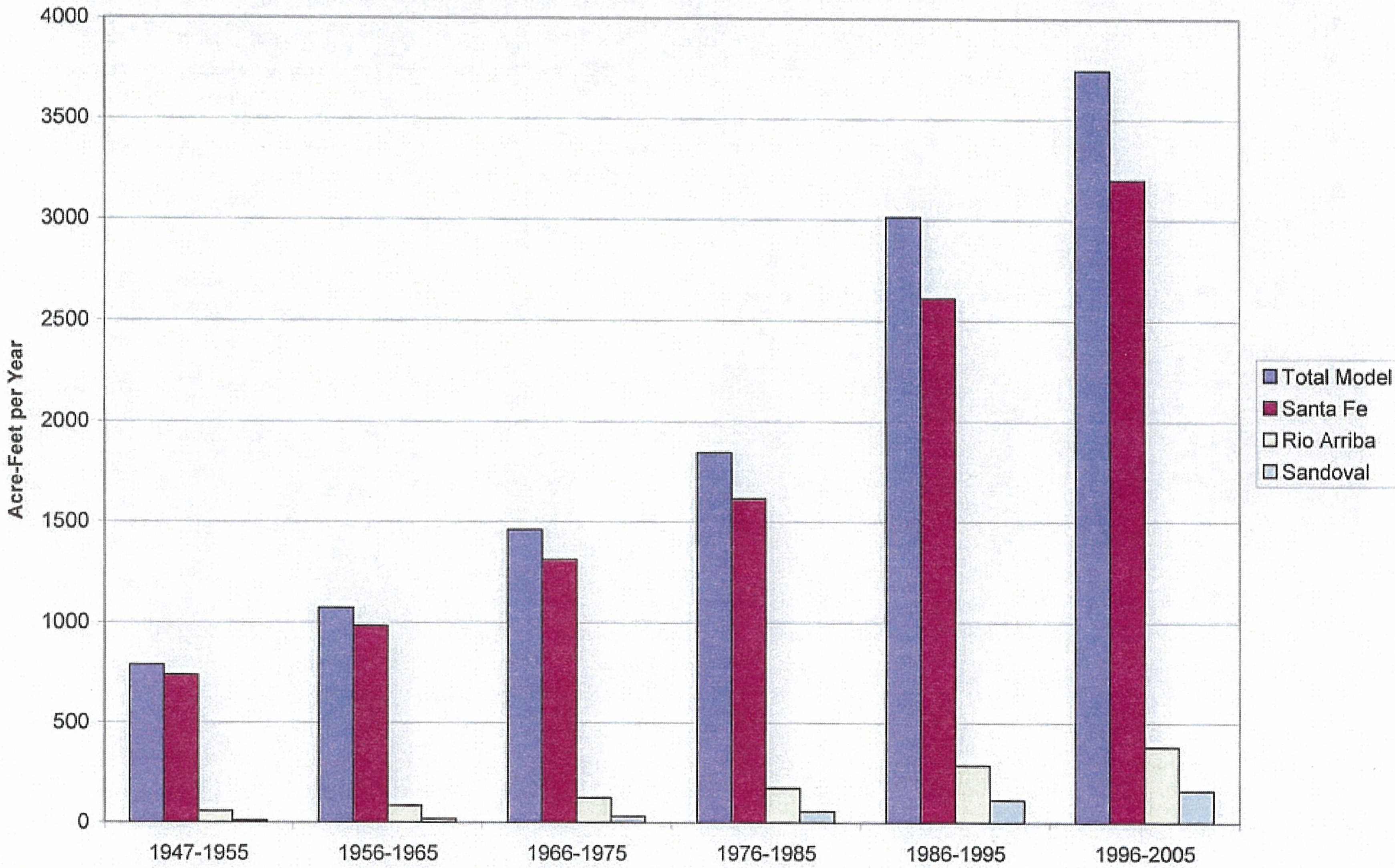
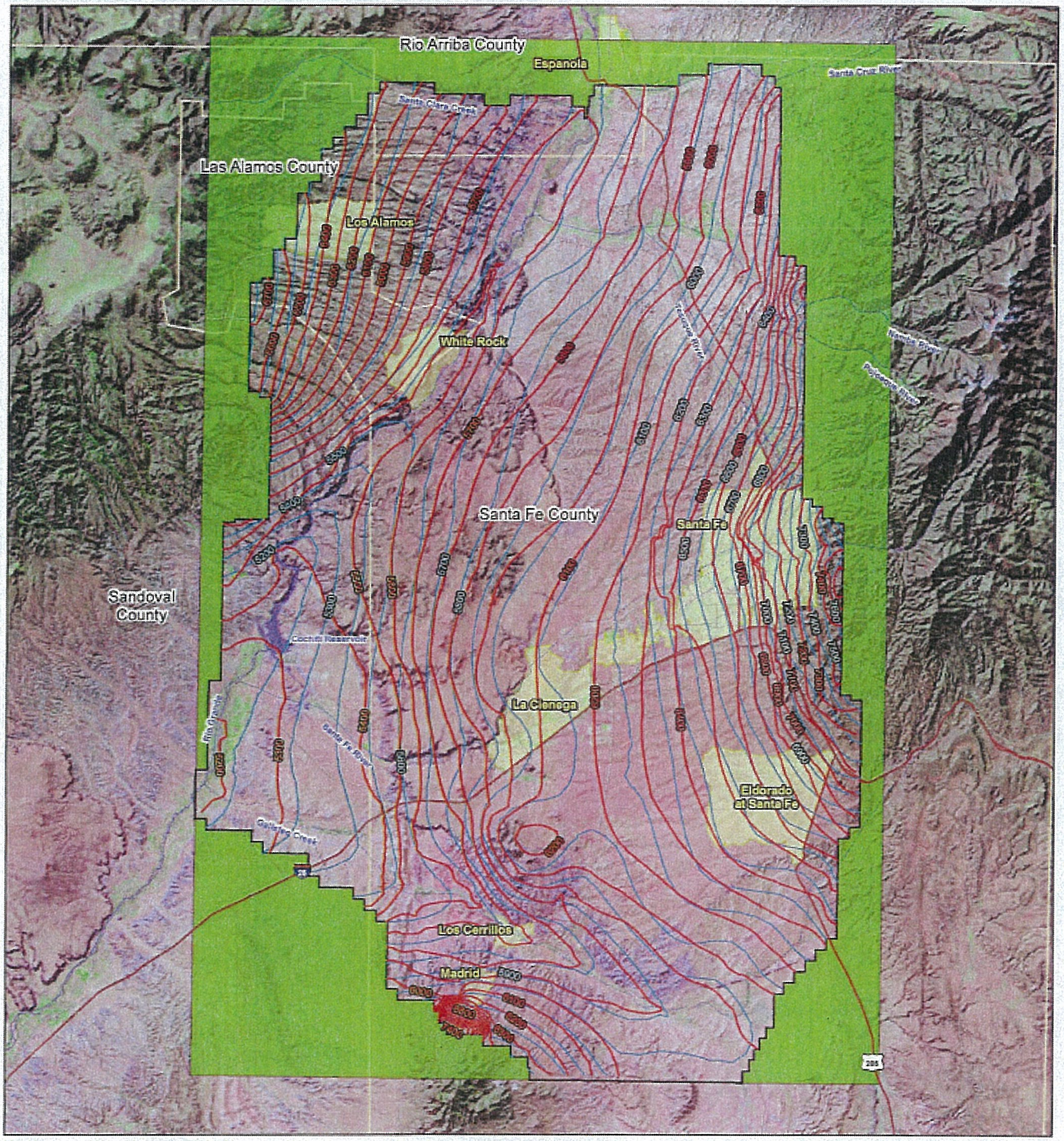


Figure 6-11.
Domestic Usage by Time Interval

FILE:T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_8-1.mxd 08/22/2006



Legend
- Simulate Steady-State Water Table Elevation, ft msl
- Pre-Development Water Table Elevation, ft msl
- Model boundary with inactive areas shaded

NORTH

1 inch equals 6 miles

Miles 6 3 0 6

UTM NAD 83 Zone 13, Meters

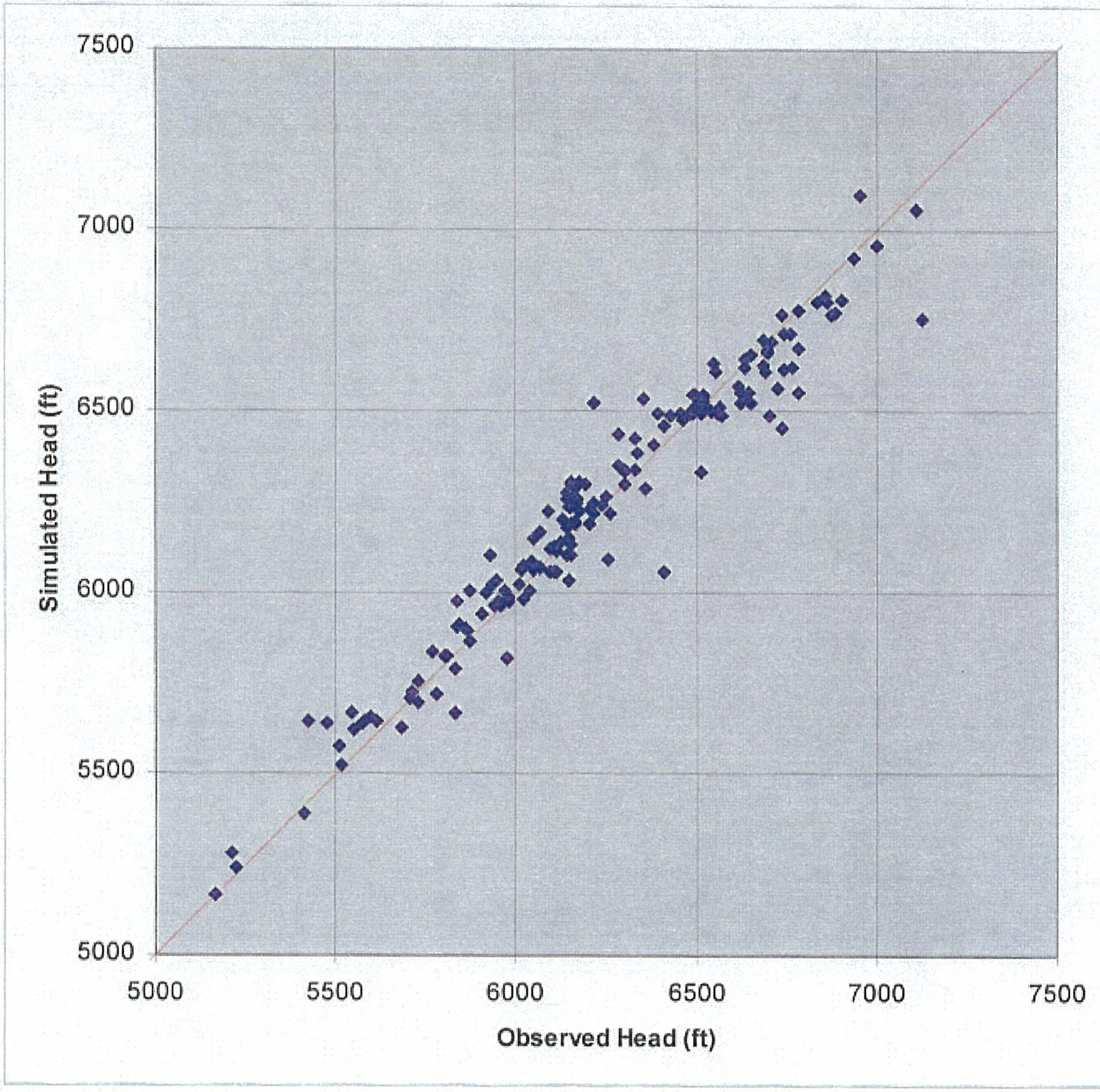
Scale 1:400,000

Figure 8-1. Simulated Steady-State Unconfined Head Surface and Pre-Development Head Surface

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

INTERA

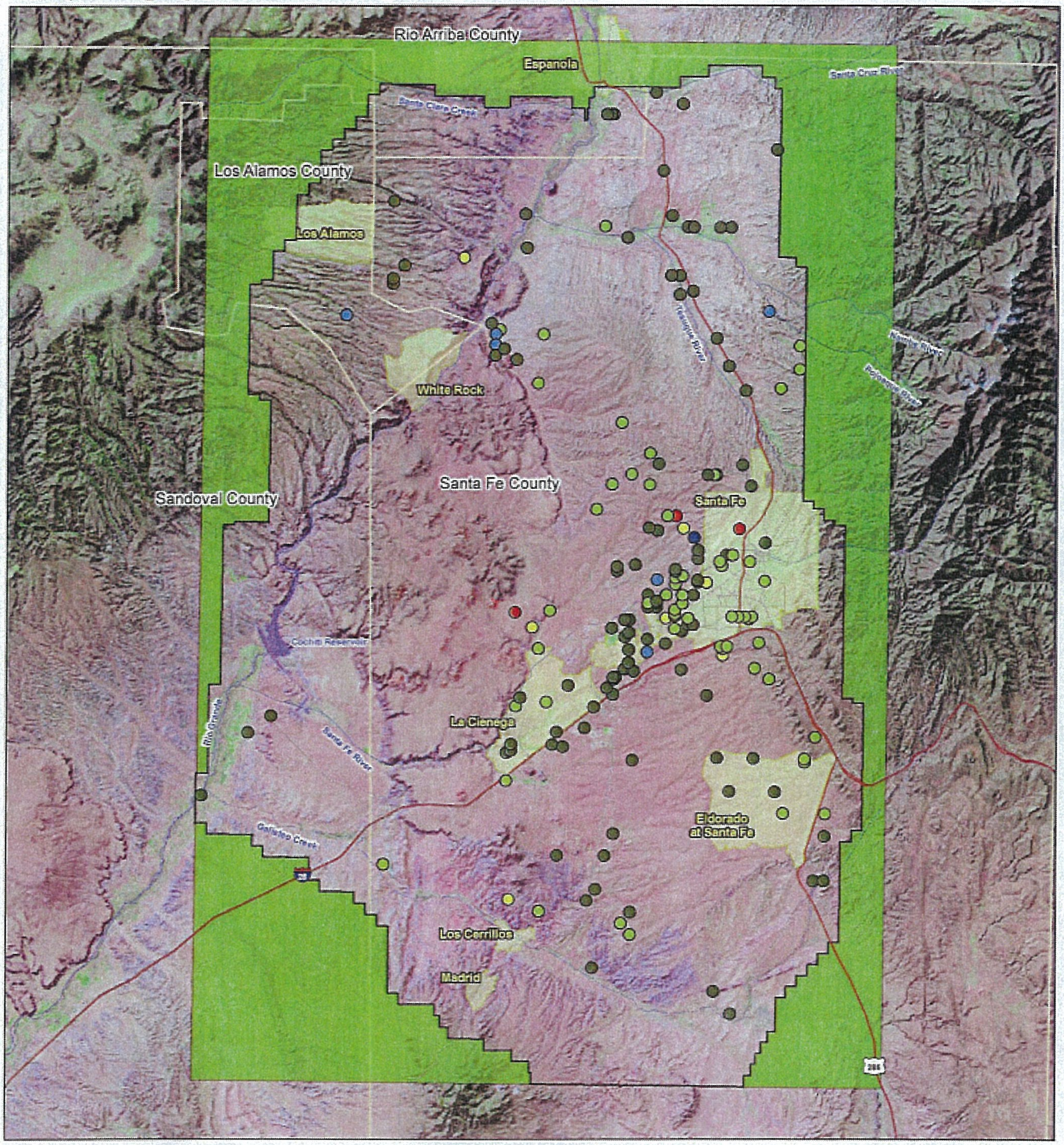
FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_8-2.mxd 08/31/2006



INTERA

Figure 8-2.
Head Crossplot of Steady-State Simulated and Measured Heads for the Model Area.

FILE:T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_8-3.mxd 08/31/2006



NORTH

1 inch equals 6 miles

Miles 6 3 0 6

UTM NAD 83 Zone 13, Meters

Scale 1:400,000

Legend

Model boundary with inactive areas shaded

Residual, ft

- -400 - -250
- -250 - -150
- -150 - 0
- 0 - 150
- 150 - 300
- 300 - 450

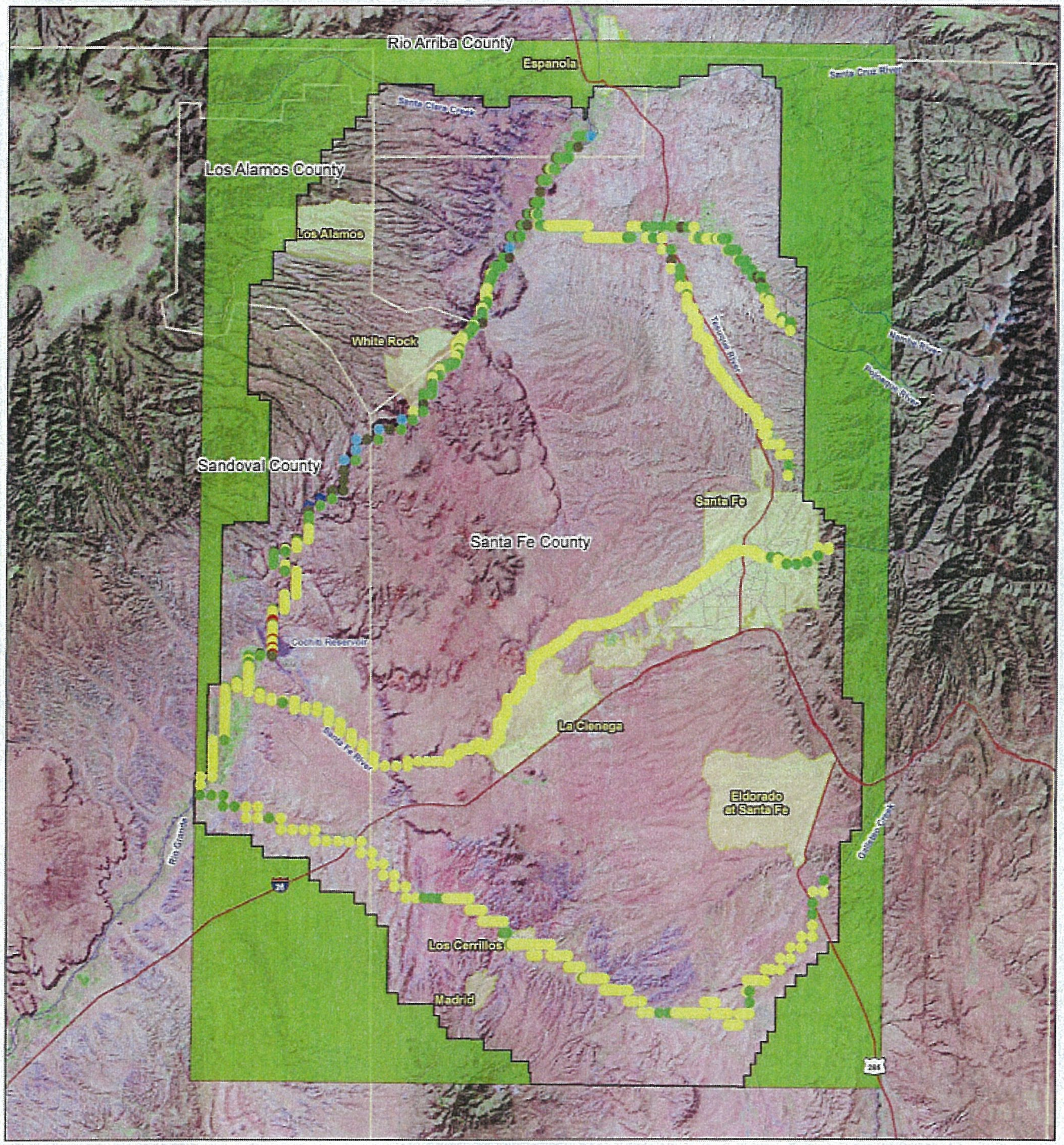
Figure 8-3.
Steady-State
Head Residuals

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

SANTA FE COUNTY

FILE:T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_8-4.mxd 08/09/2006



NORTH

1 inch equals 6 miles

6 3 0 6

Miles

UTM NAD 83 Zone 13, Meters

Scale 1:400,000

Legend

- Model boundary with inactive areas shaded

Gain, ac-ft/yr

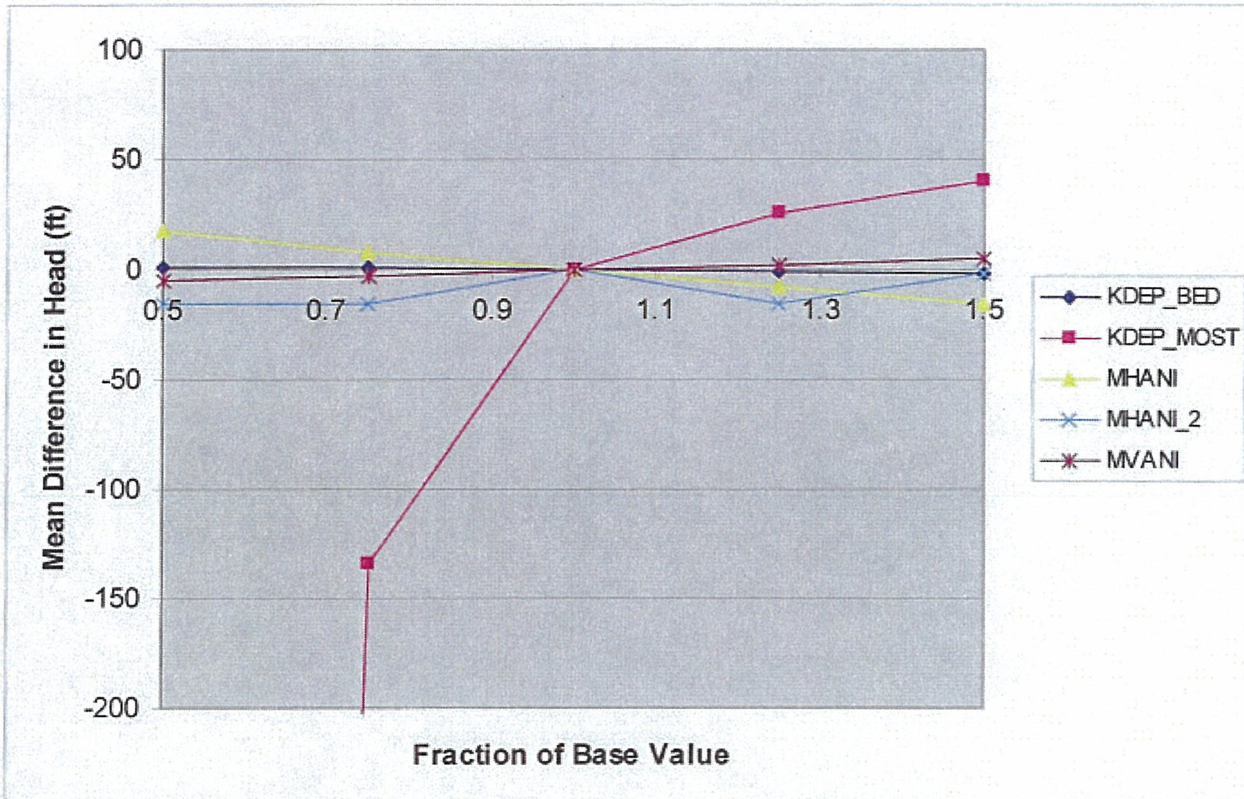
- -200 - -75
- -75 - 50
- 50 - 175
- 175 - 300
- 300 - 425
- 425 - 550

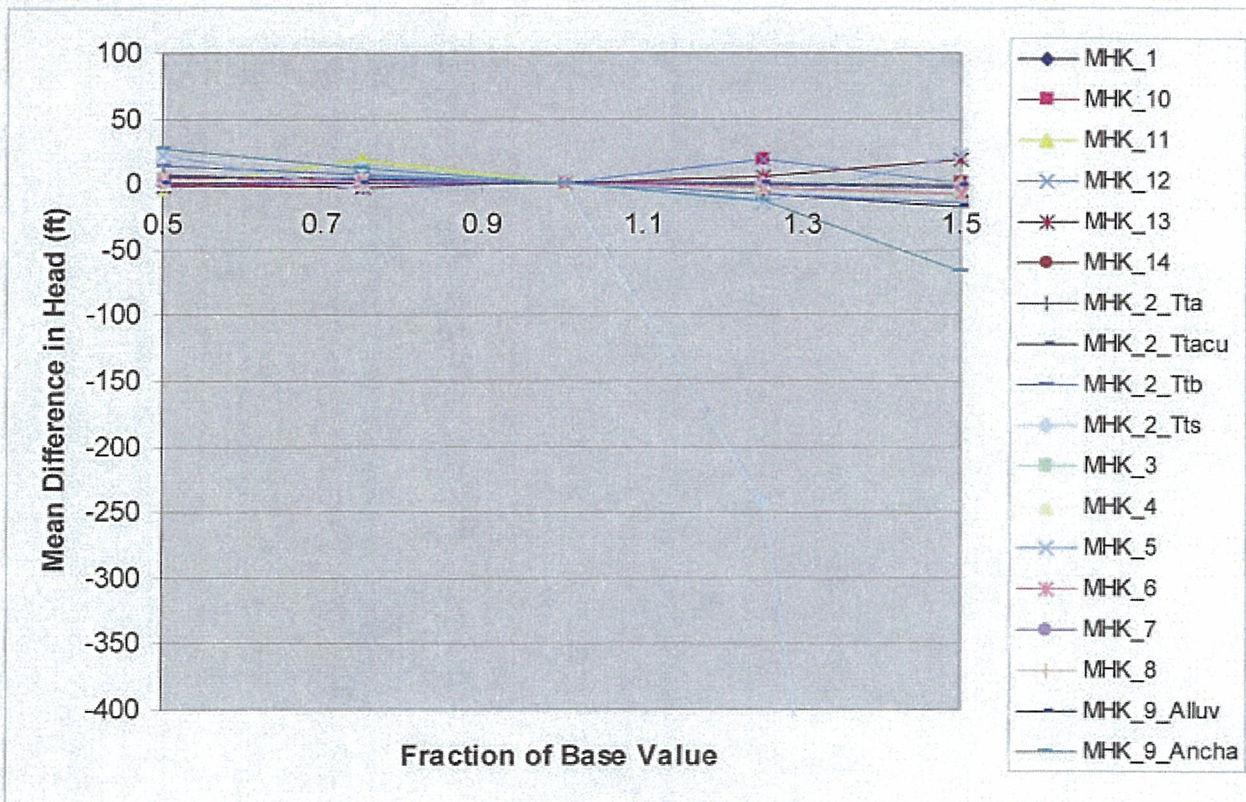
Figure 8-4.
Steady-State Model Stream Gain/Loss (Positive Value Denotes Gaining Stream)

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_8-5a.mxd 07/31/2006

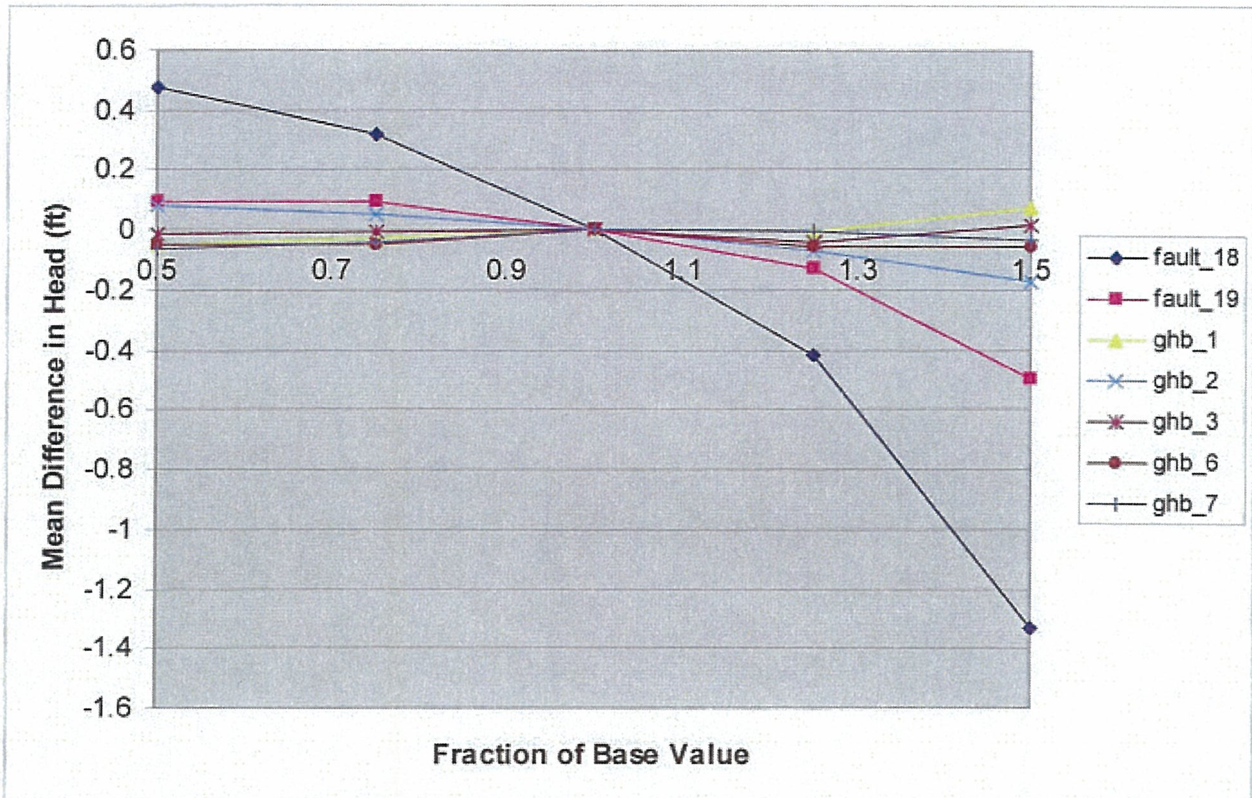


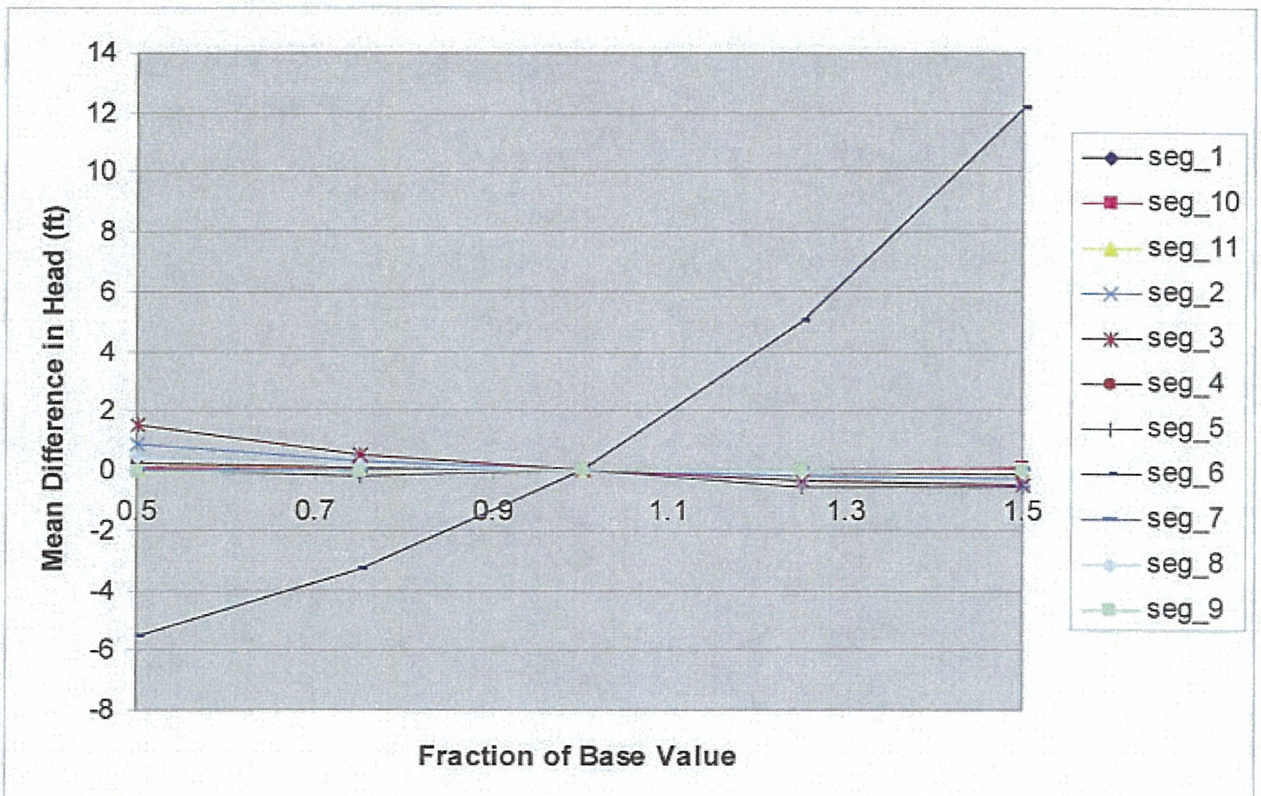


INTERA

Figure 8-5a.
Steady-State Sensitivity Results for Target Wells

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_8-5b.mxd 07/31/2006

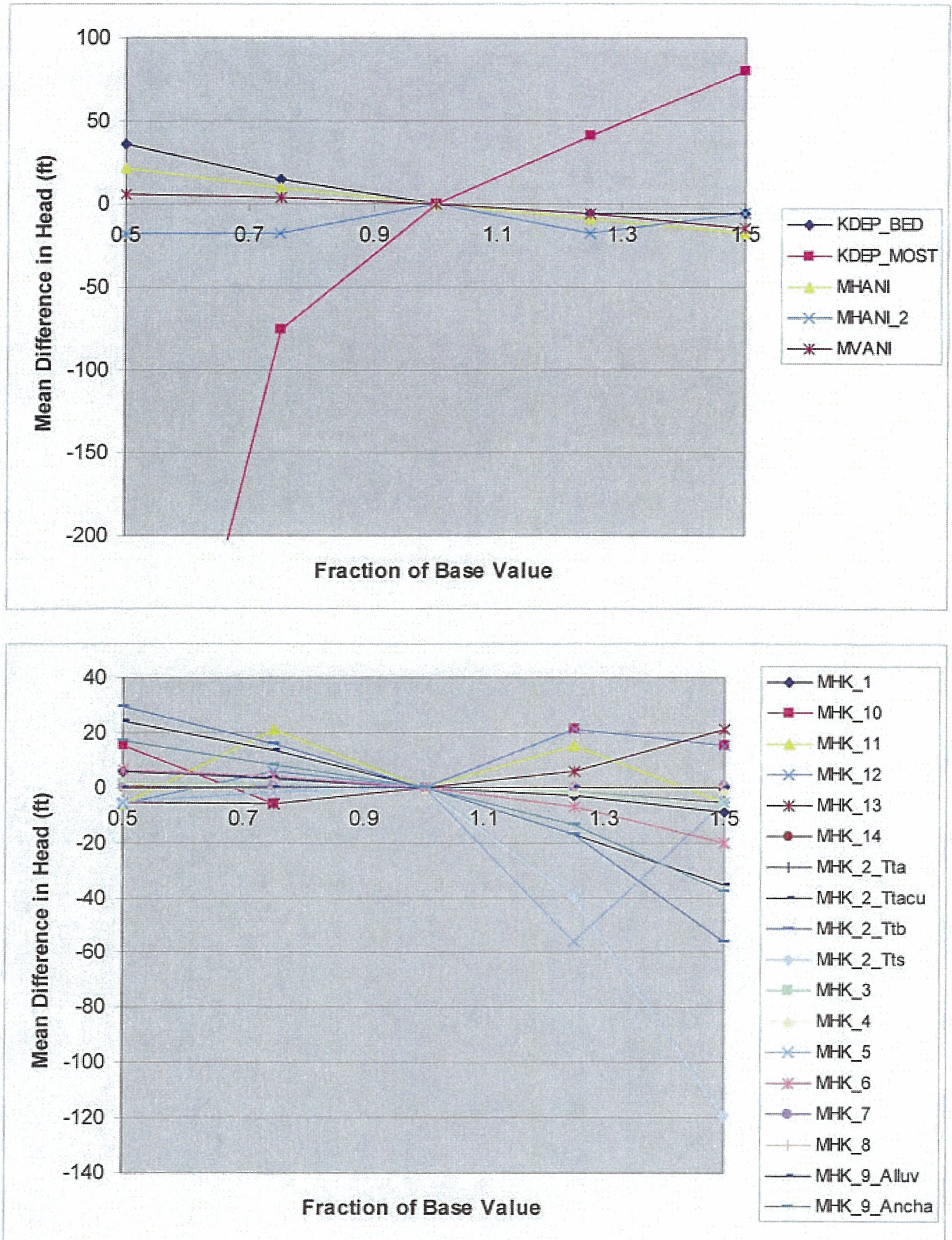




INTERA

Figure 8-5b.
Steady-State Sensitivity Results for Target Wells

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_8-6a.mxd 07/31/2006

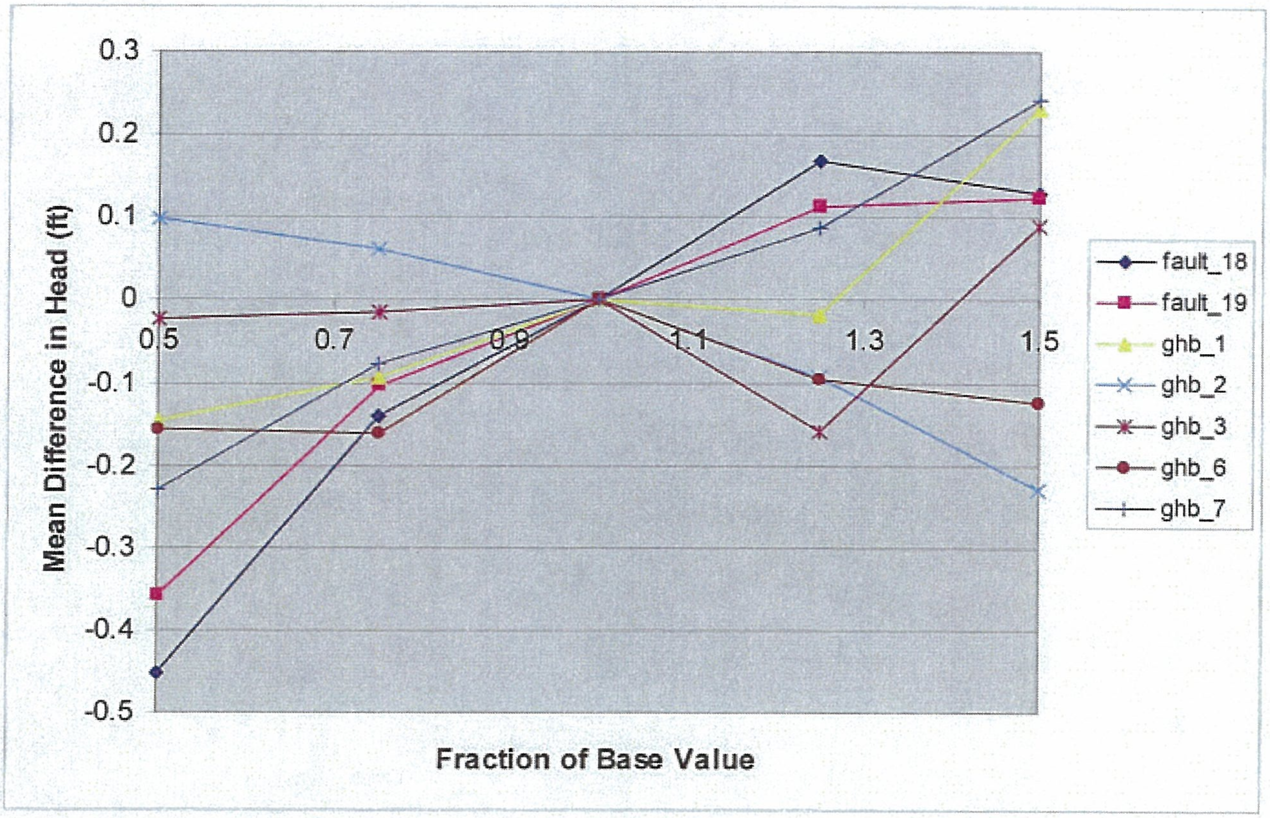


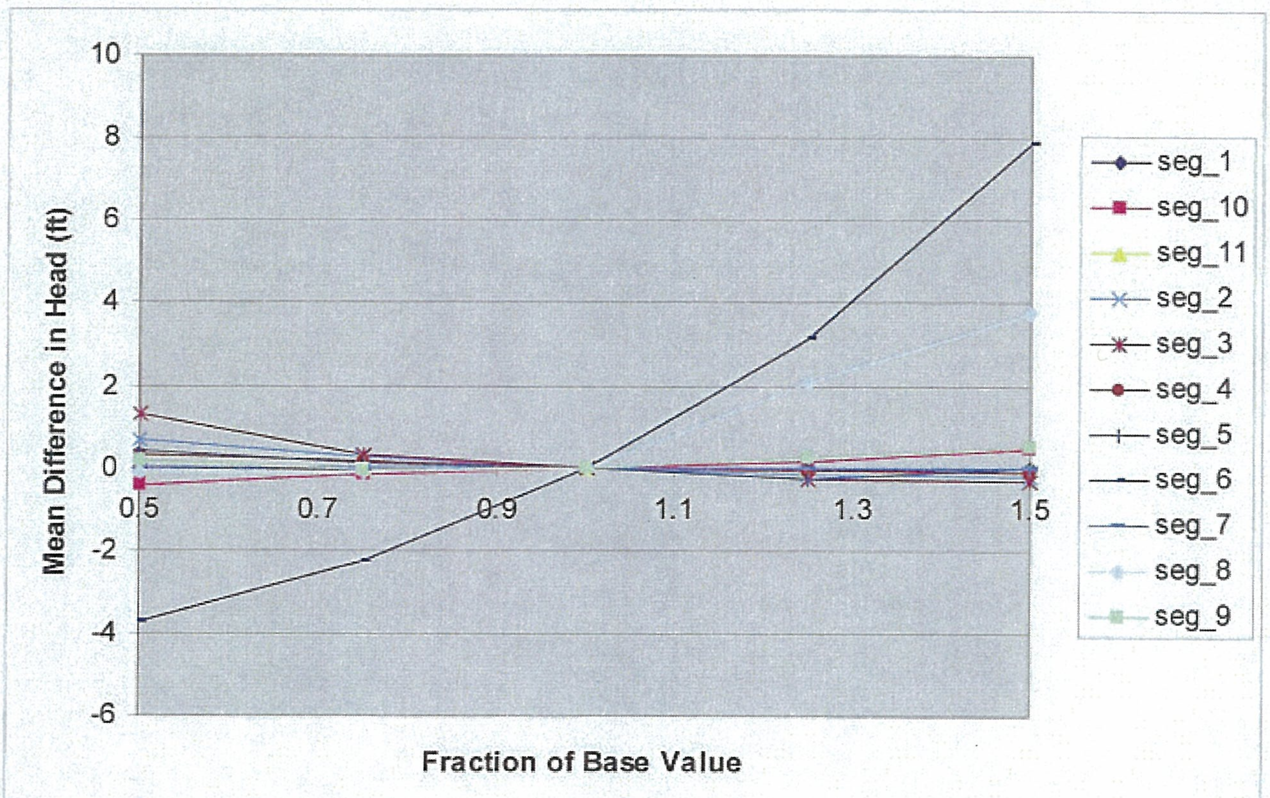
INTERA

Figure 8-6a.
Steady-State Sensitivity Results for All Active Grid Blocks

SANTA FE COUNTY

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_8-6b.mxd 07/31/2006



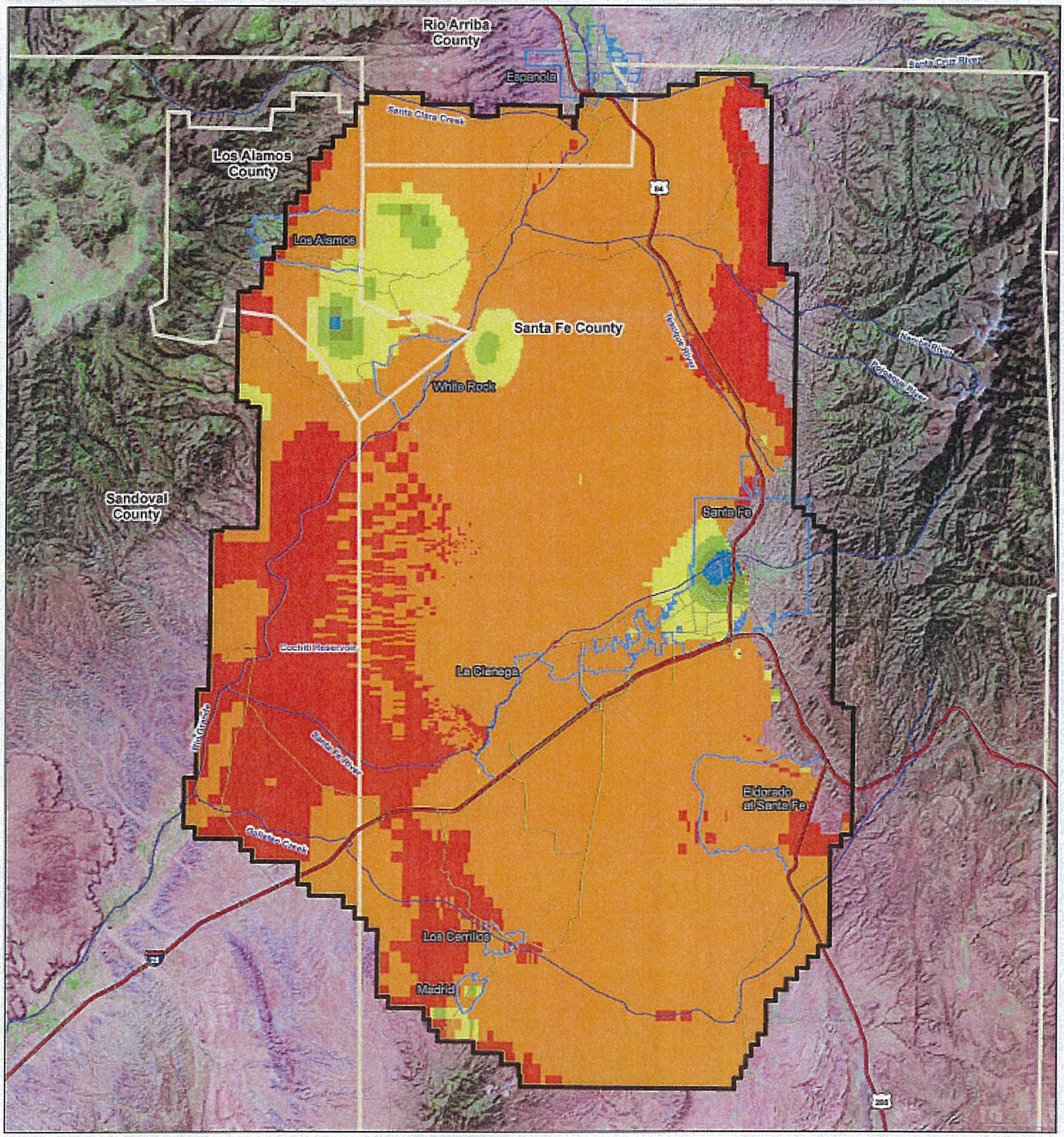


INTERA

Figure 8-6b.
Steady-State Sensitivity Results for All Active Grid Blocks

SANTA FE COUNTY

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_9-1.mxd 08/10/2006



NORTH

1 inch equals 6 miles

6 3 0 6

Miles

UTM NAD 83 Zone 13, Meters

Scale 1:400,000

INTERA

Legend

Active Model Boundary

Drawdown (ft)

- -60 - -40
- -40 - -20
- -20 - 0
- 0 - 20
- 20-40
- 40-60
- 60-80
- 80-100
- 100-120
- 120-140

Figure 9-1.
Simulated Total Drawdown from 1947 to 2004 in the Model Area

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

SANTA FE COUNTY

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_9-2.mxd 08/31/20

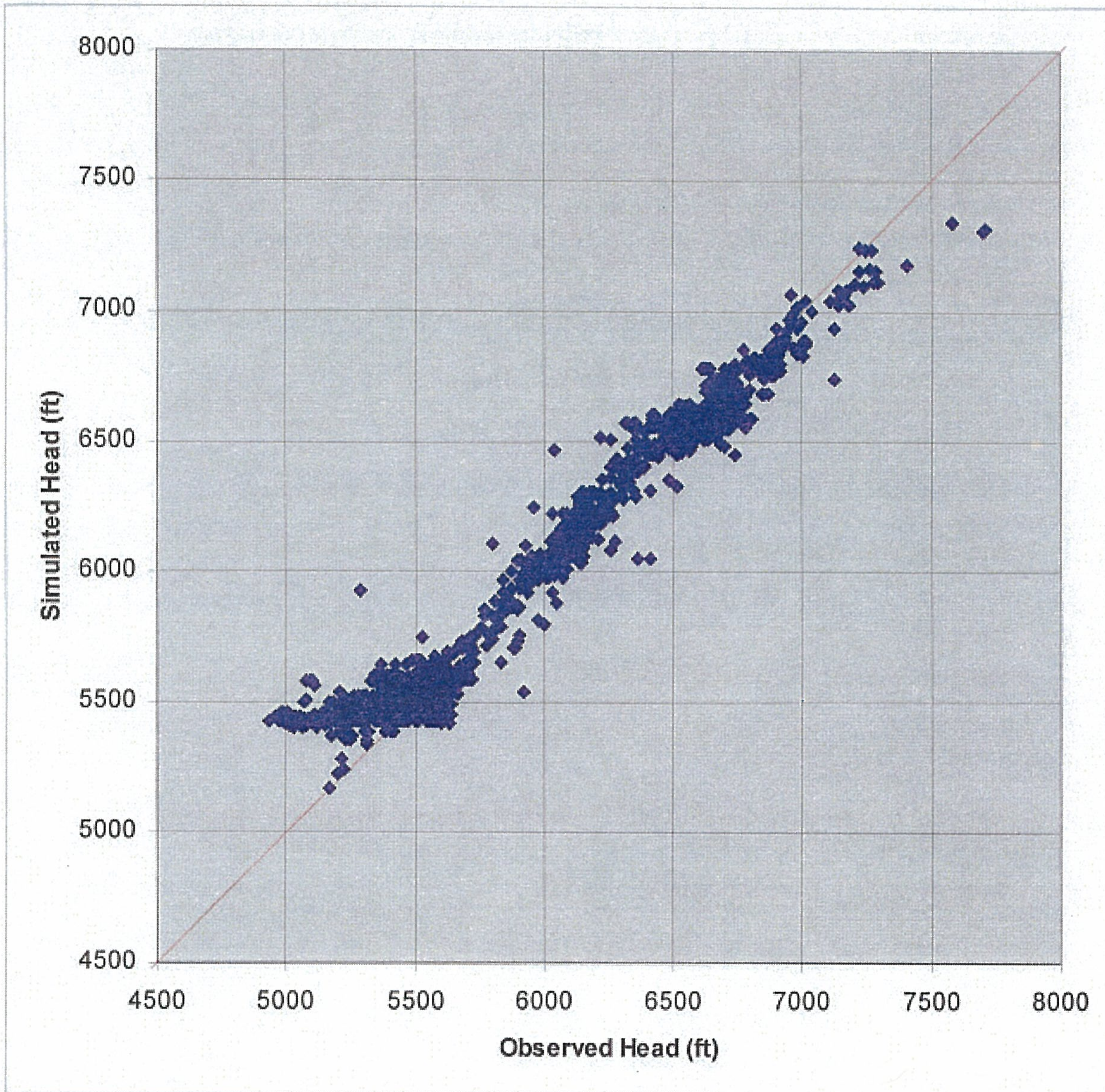
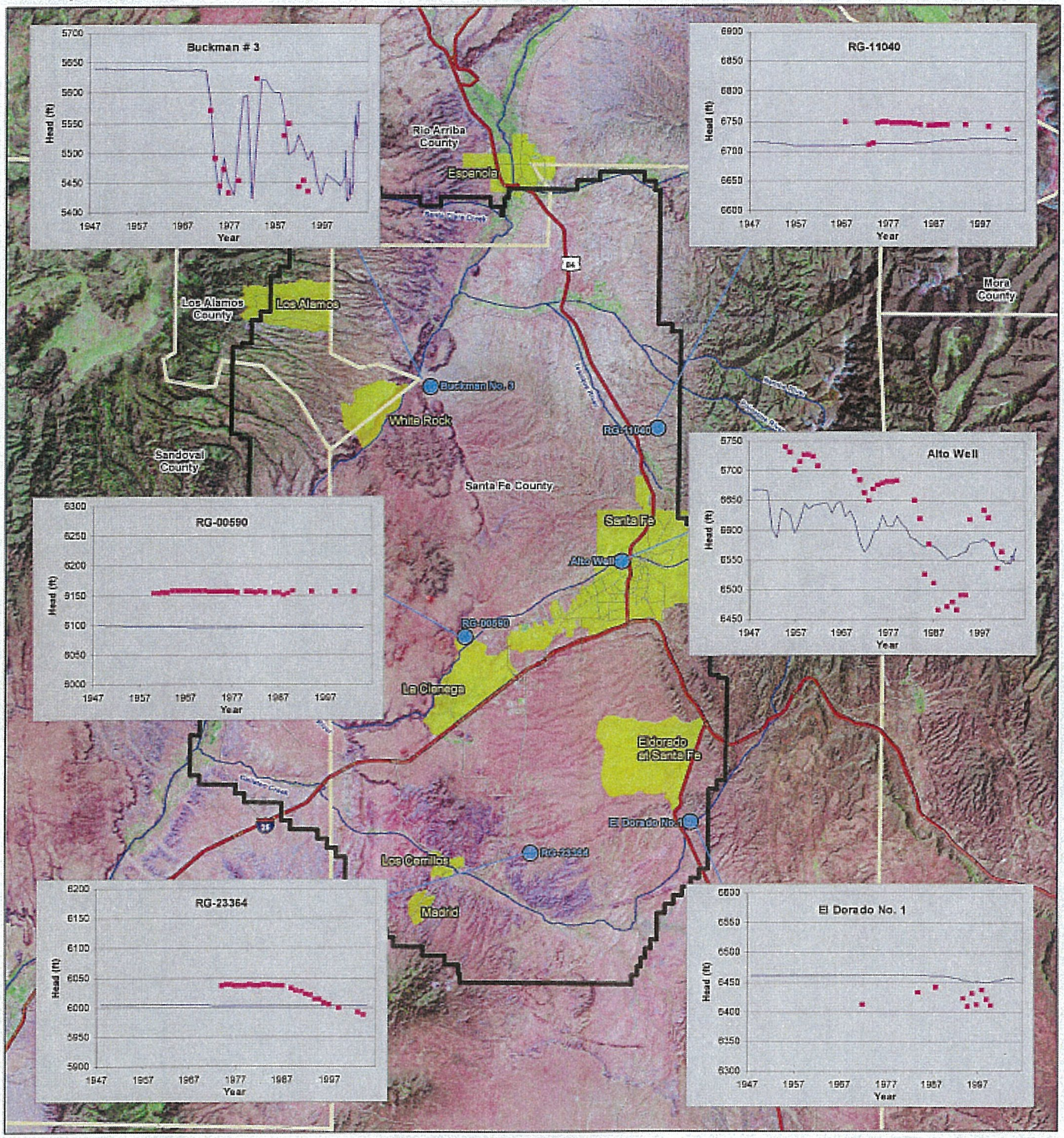


Figure 9-2.
Head Crossplot of Transient Simulated and Measured Heads for the Model Area

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_9-3.mxd 06/10/2006



NORTH

1 inch equals 8 miles

8 4 0 8

Miles

UTM NAD 83 Zone 13, Meters

Scale 1:500,000

Legend

- Active Model Boundary
- Selected Well

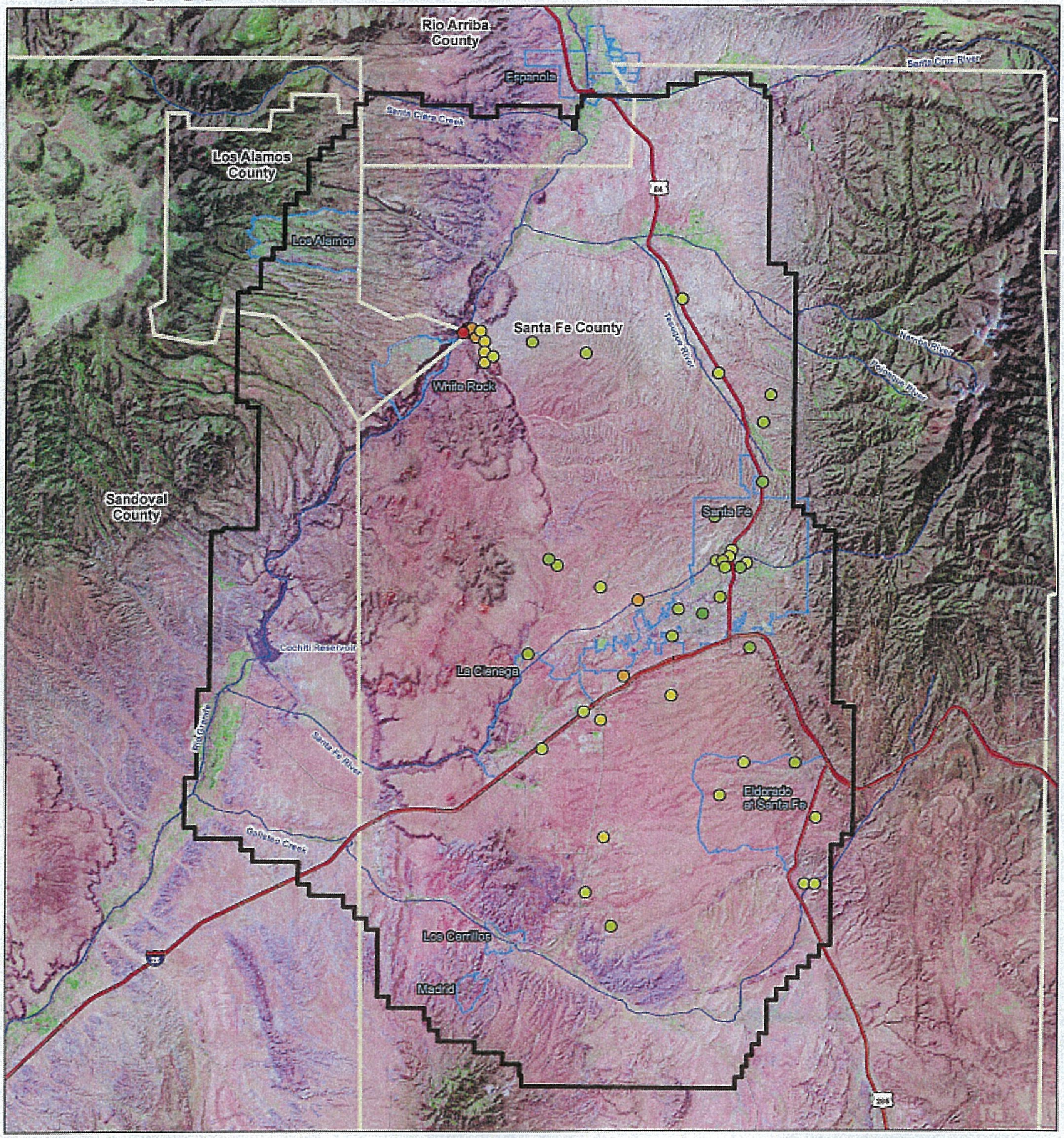
Figure 9-3.
Select Transient Hydrographs Comparing Simulated to Observed Heads

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

SANTA FE COUNTY

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_9-4.mxd 08/10/2006



NORTH

1 inch equals 6 miles

6 3 0 6

Miles

UTM NAD 83 Zone 13, Meters

Scale 1:400,000

INTERA

Legend

Active Model Boundary

Residual (ft)

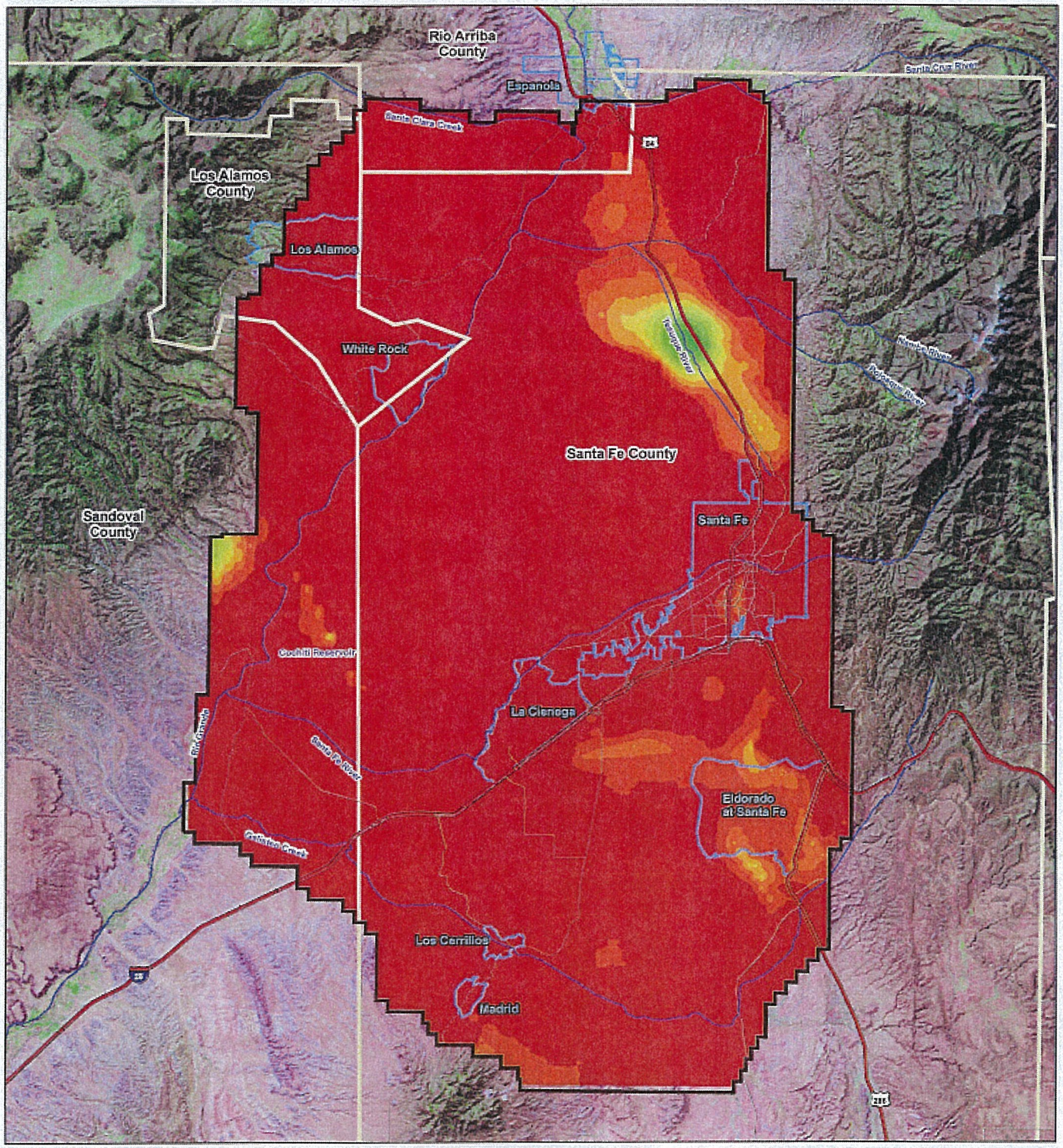
- -240 - -180
- -180 - -120
- -120 - -60
- -60 - 0
- 0 - 60
- 60 - 120
- 120 - 180
- 180 - 240
- 240 - 300
- 300 - 360

Figure 9-4.
Transient Mean
Head Residuals

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

SANTA FE COUNTY

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_10-1.mxd 08/14/2006



NORTH
1 inch equals 6 miles
6 3 0 6
Miles
UTM NAD 83 Zone 13, Meters
Scale 1:400,000

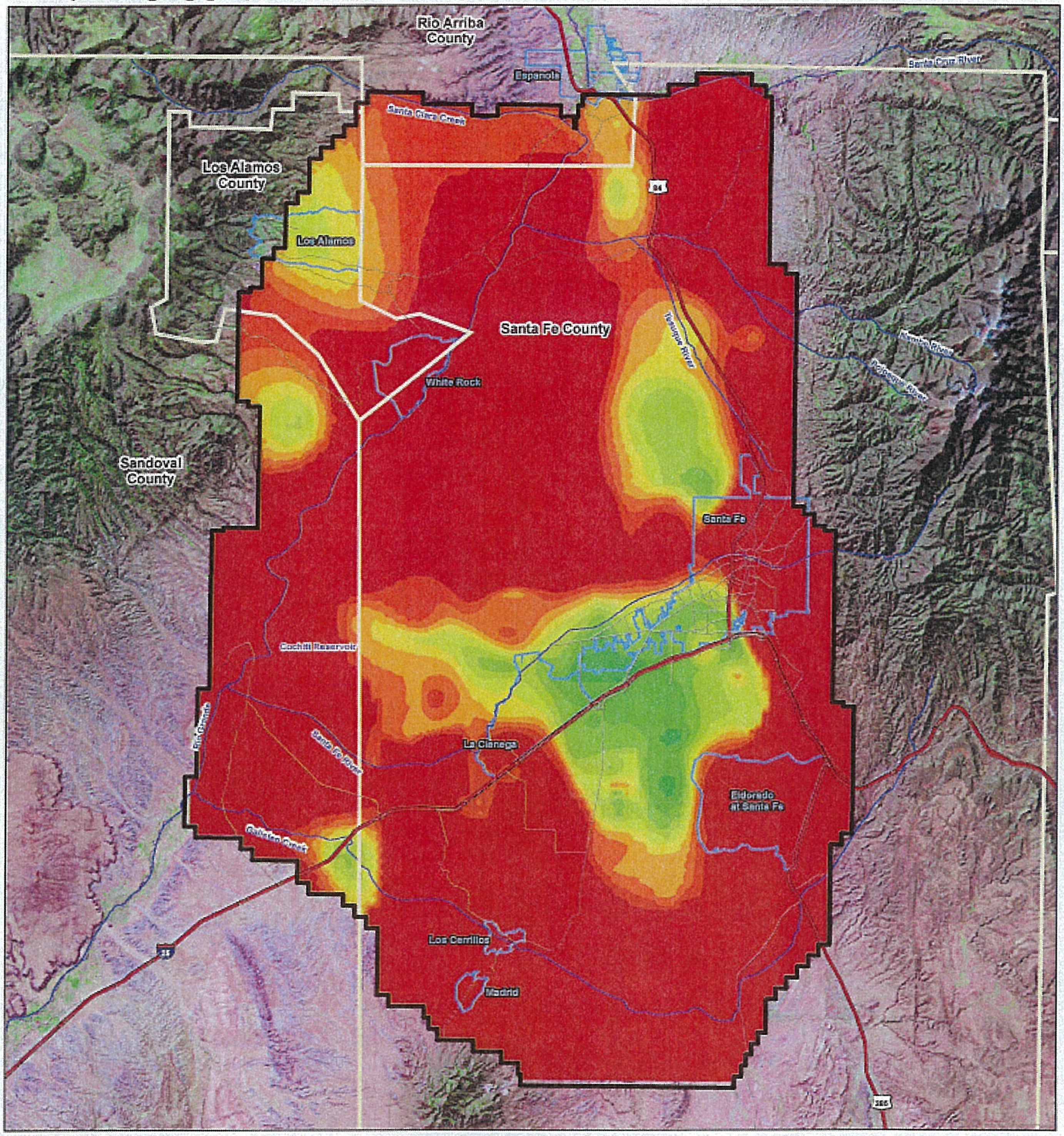
Legend
Active Model Boundary

Figure 10-1.
Ancha Aquifer Thickness

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_10-2.mxd 08/14/2006



NORTH

1 inch equals 6 miles

Miles 6 3 0 6

UTM NAD 83 Zone 13, Meters

Scale 1:400,000

Legend

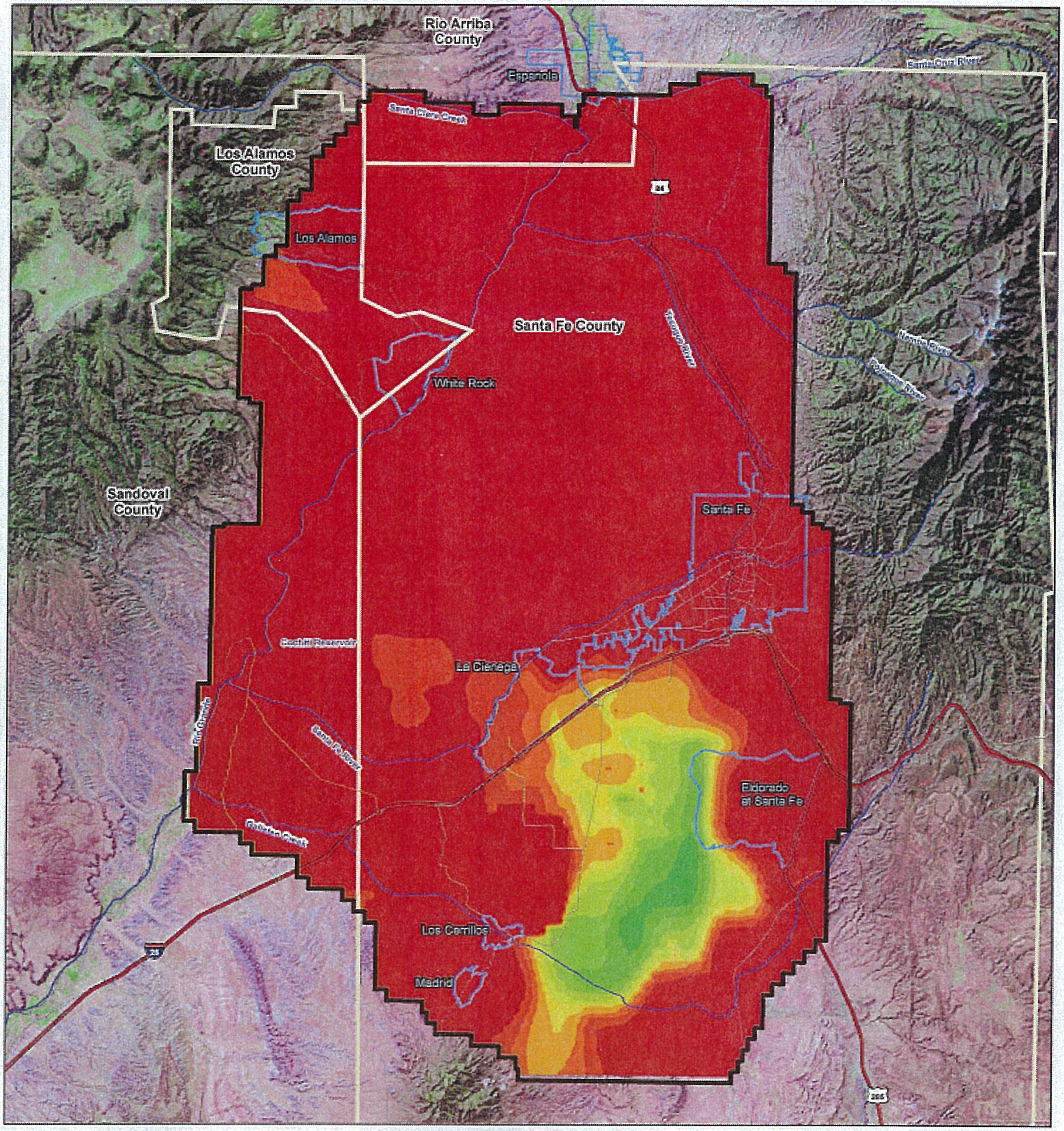
Active Model Boundary

Figure 10-2.
Espinaso Aquifer Thickness

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_10-3.mxd 08/14/2006



NORTH

1 inch equals 6 miles

Miles 6 3 0 6

UTM NAD 83 Zone 13, Meters

Scale 1:400,000

Legend

Active Model Boundary

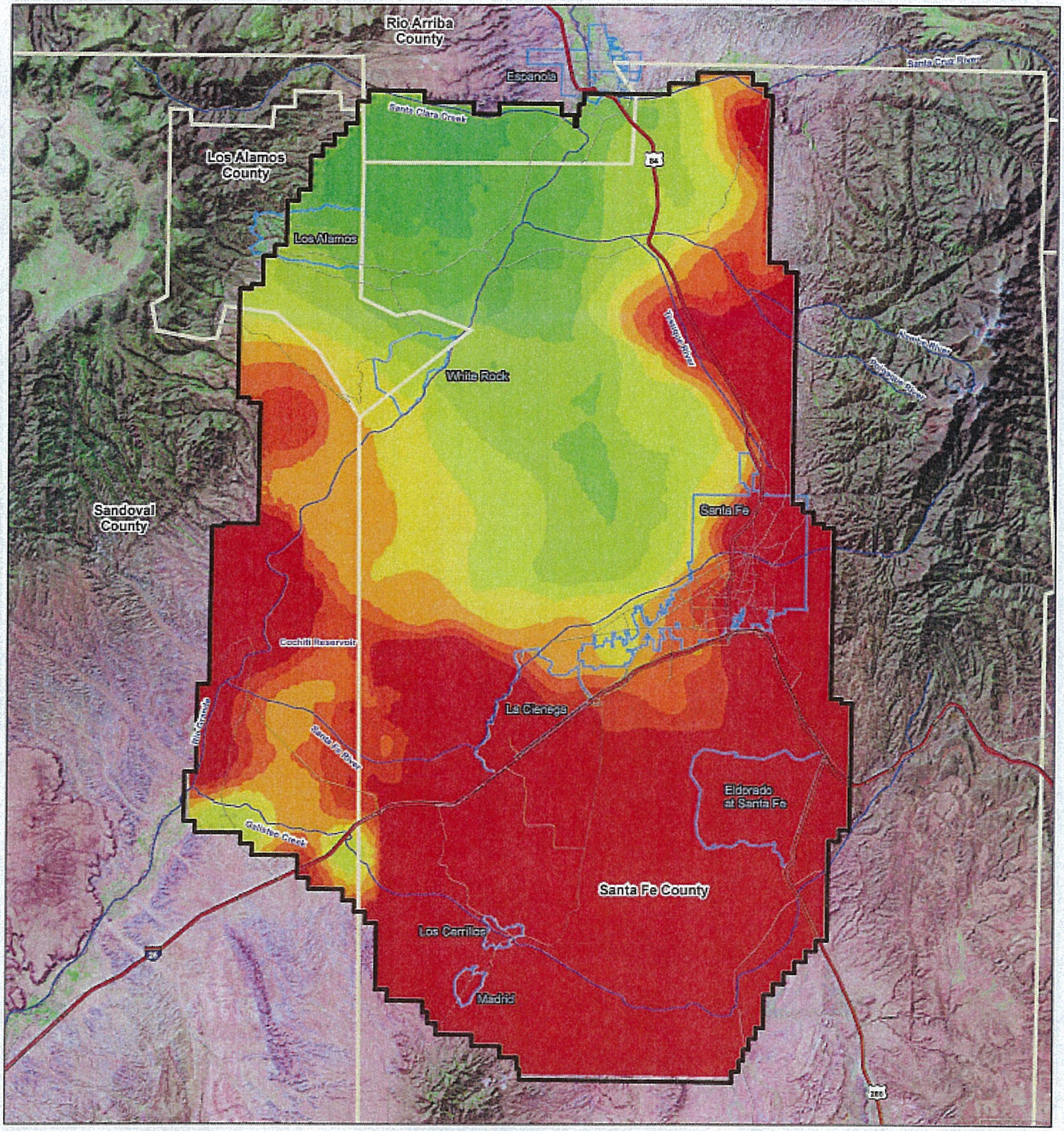
Figure 10-3.
Galisteo Aquifer Thickness

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

SANTA FE COUNTY

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_10-4.mxd 08/14/2006



NORTH

1 inch equals 6 miles

Miles 6 3 0 6

UTM NAD 83 Zone 13, Meters

Scale 1:400,000

Legend

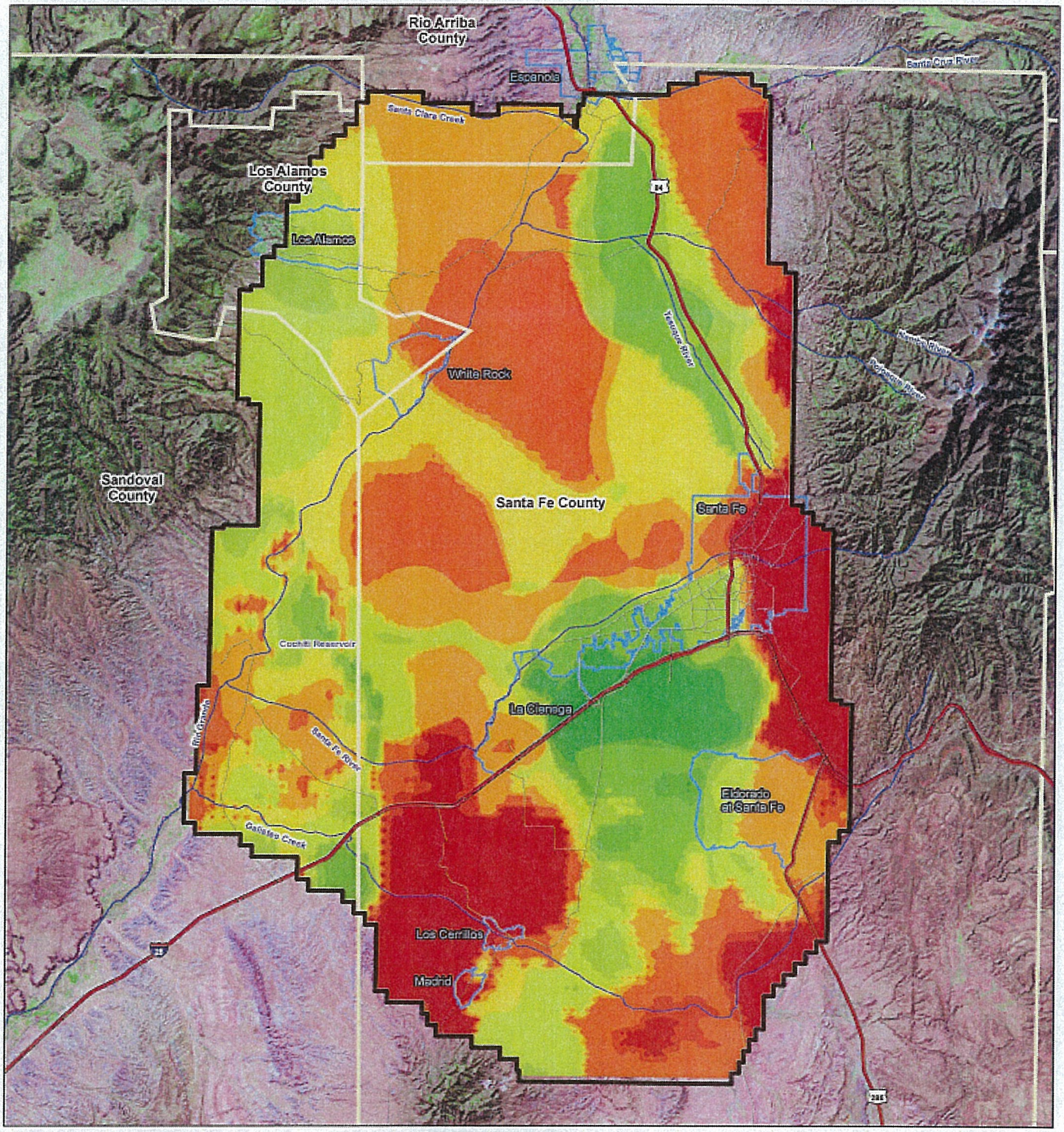
Active Model Boundary

Figure 10-4.
Tesuque Aquifer Thickness

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_10-5.mxd 08/14/2006



NORTH

1 inch equals 6 miles

6 3 0 6

Miles

UTM NAD 83 Zone 13, Meters

Scale 1:400,000

Legend

Active Model Boundary

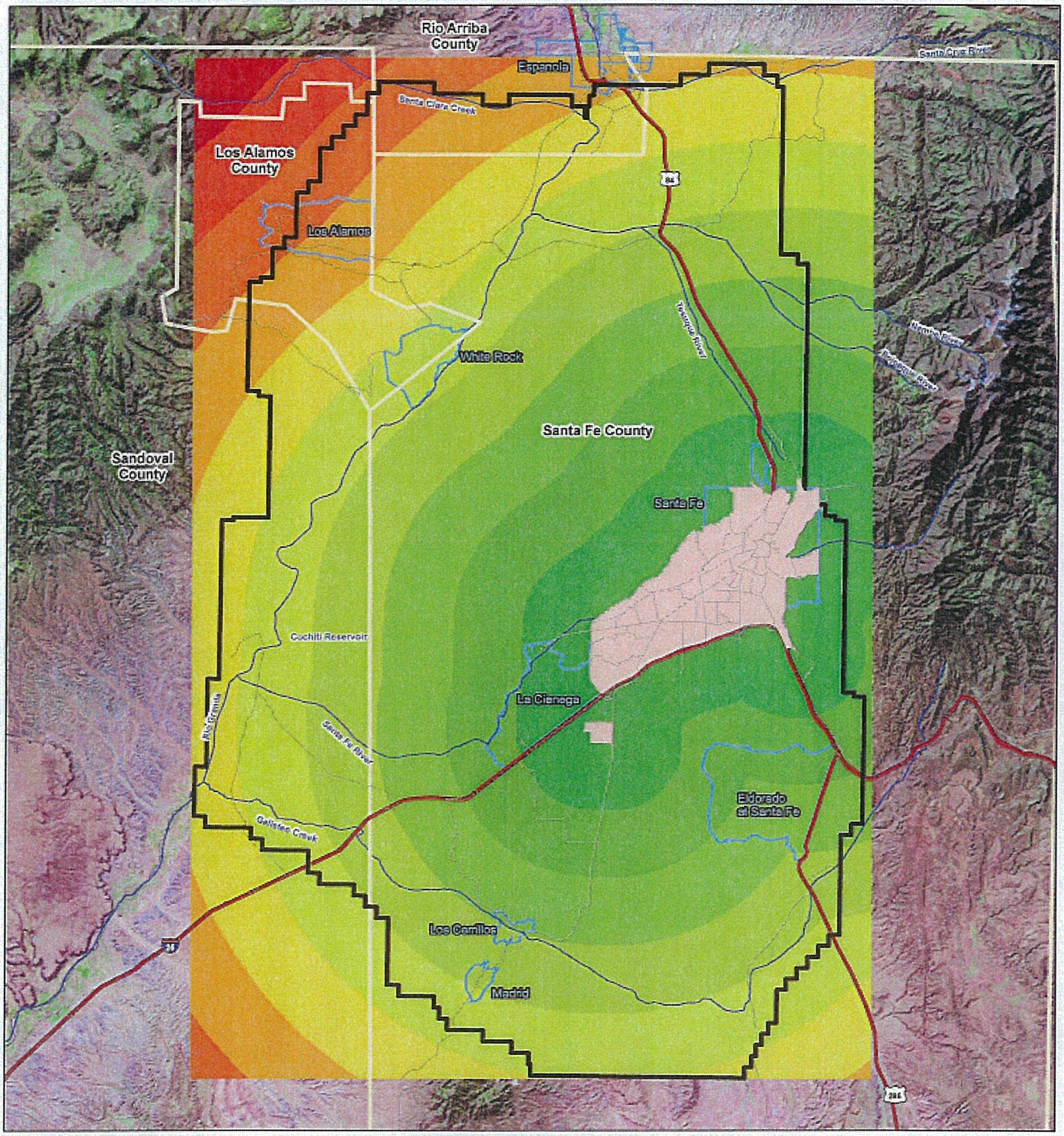
Figure 10-5.
Normalized, Depth-Weighted Composite Aquifer Transmissivity

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

SANTA FE COUNTY

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_10-6.mxd 07/31/2006



NORTH

1 inch equals 6 miles

Scale 1:400,000

Miles 6 3 0 6

UTM NAD 83 Zone 13, Meters

Legend

- 2004 Population >= 300/sq mi
- Active Model Boundary

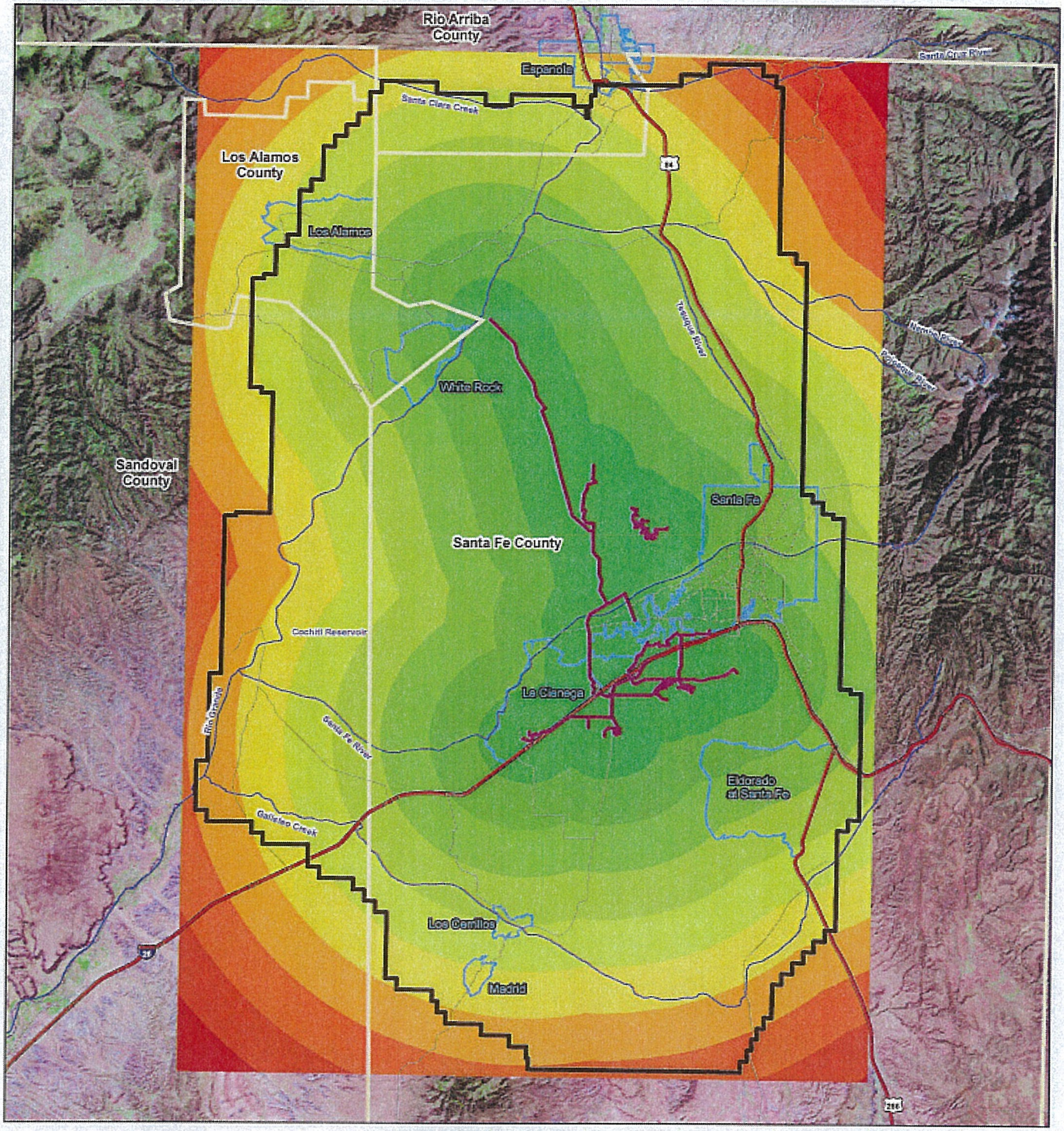
Normalized Distance to Populated Areas

- 0 - 10
- 10 - 20
- 20 - 30
- 30 - 40
- 40 - 50
- 50 - 60
- 60 - 70
- 70 - 80
- 80 - 90
- 90 - 100

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

Figure 10-6.
Normalized Suitability Score for Proximity to Populated Areas

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Map_10-7.mxd 07/31/2006



NORTH
1 inch equals 6 miles

6 3 0 6
Miles

UTM NAD 83 Zone 13, Meters
Scale 1:400,000

Legend

- Water Service Areas
- Active Model Boundary

Normalized Distance to Water Service Areas

0 - 10	50 - 60
10 - 20	60 - 70
20 - 30	70 - 80
30 - 40	80 - 90
40 - 50	90 - 100

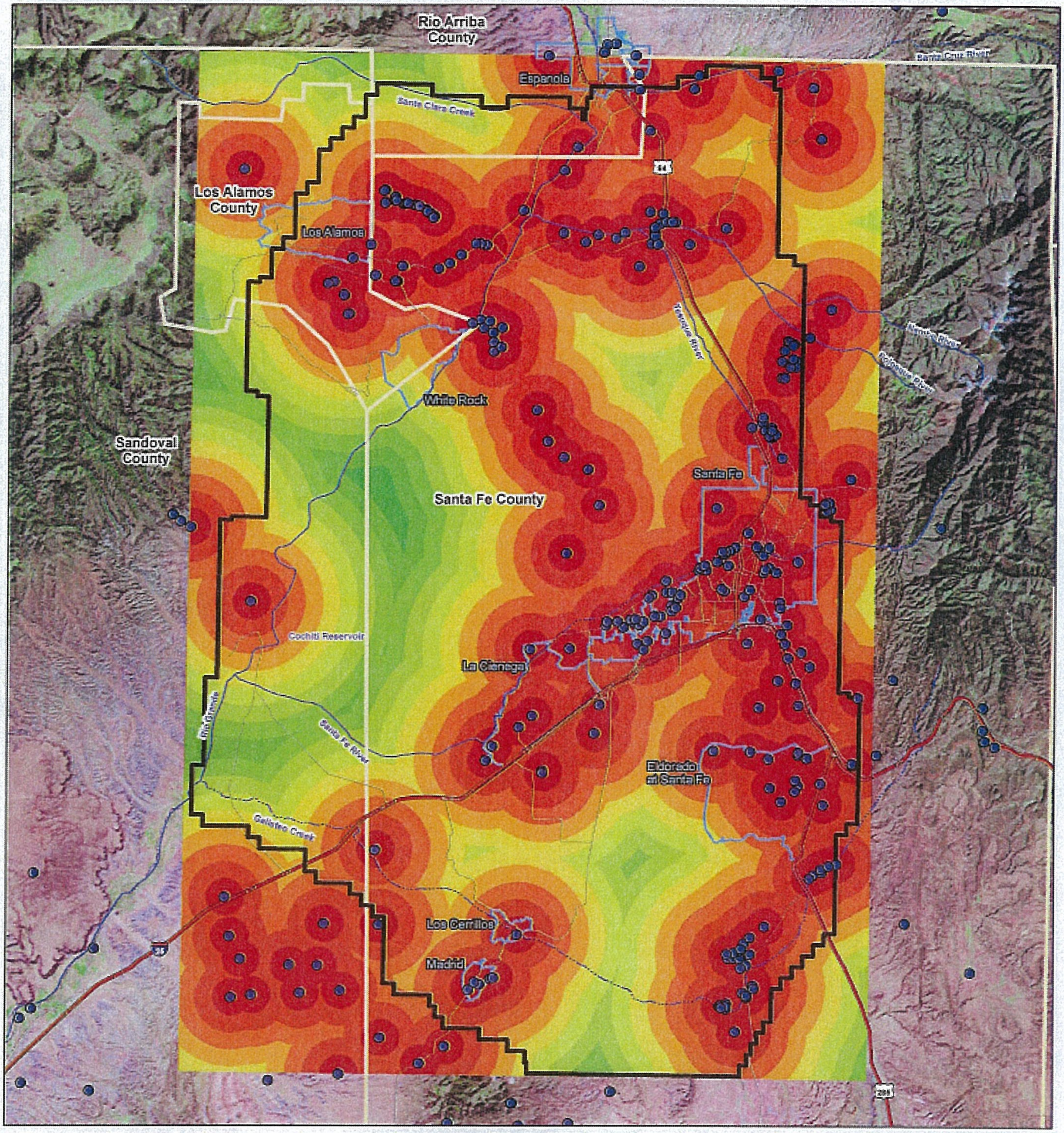
Figure 10-7.
Normalized Suitability Score for Proximity to Existing and Proposed Infrastructure

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

SANTA FE COUNTY

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_10-8.mxd 07/31/2006



NORTH

1 inch equals 6 miles

Miles 6 3 0 6

UTM NAD 83 Zone 13, Meters

Scale 1:400,000

Legend

- Well
- Active Model Boundary

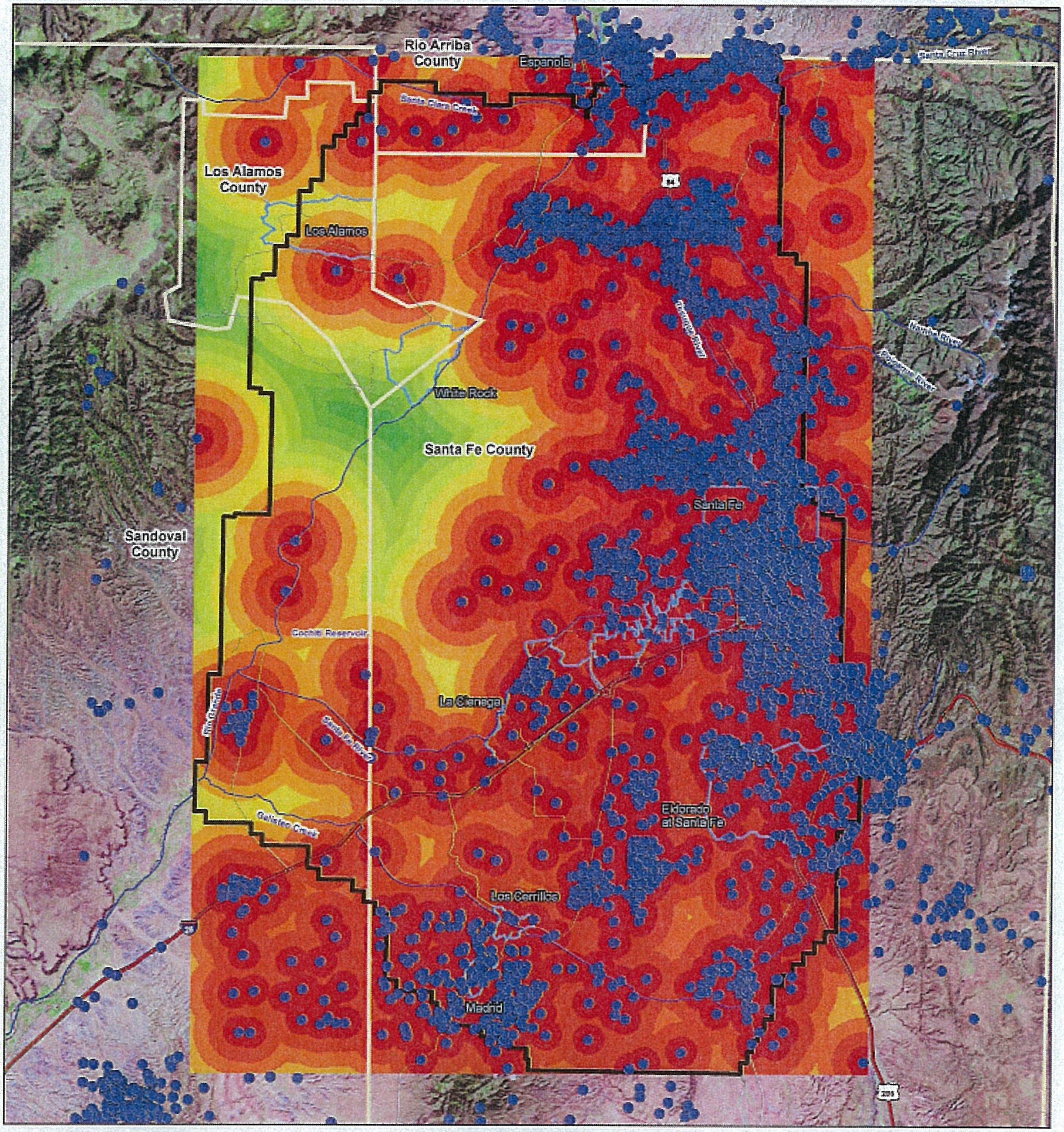
Normalized Distance to Wells

0 - 10	50 - 60
10 - 20	60 - 70
20 - 30	70 - 80
30 - 40	80 - 90
40 - 50	90 - 100

Figure 10-8.
Normalized Suitability Score for Proximity to Existing Supply Wells and Large Water-Right Holders

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_10-9.mxd 07/31/2006



NORTH

1 inch equals 6 miles

Miles 6 3 0 6

UTM NAD 83 Zone 13, Meters
Scale 1:400,000

Legend

- Domestic Well
- Active Model Boundary

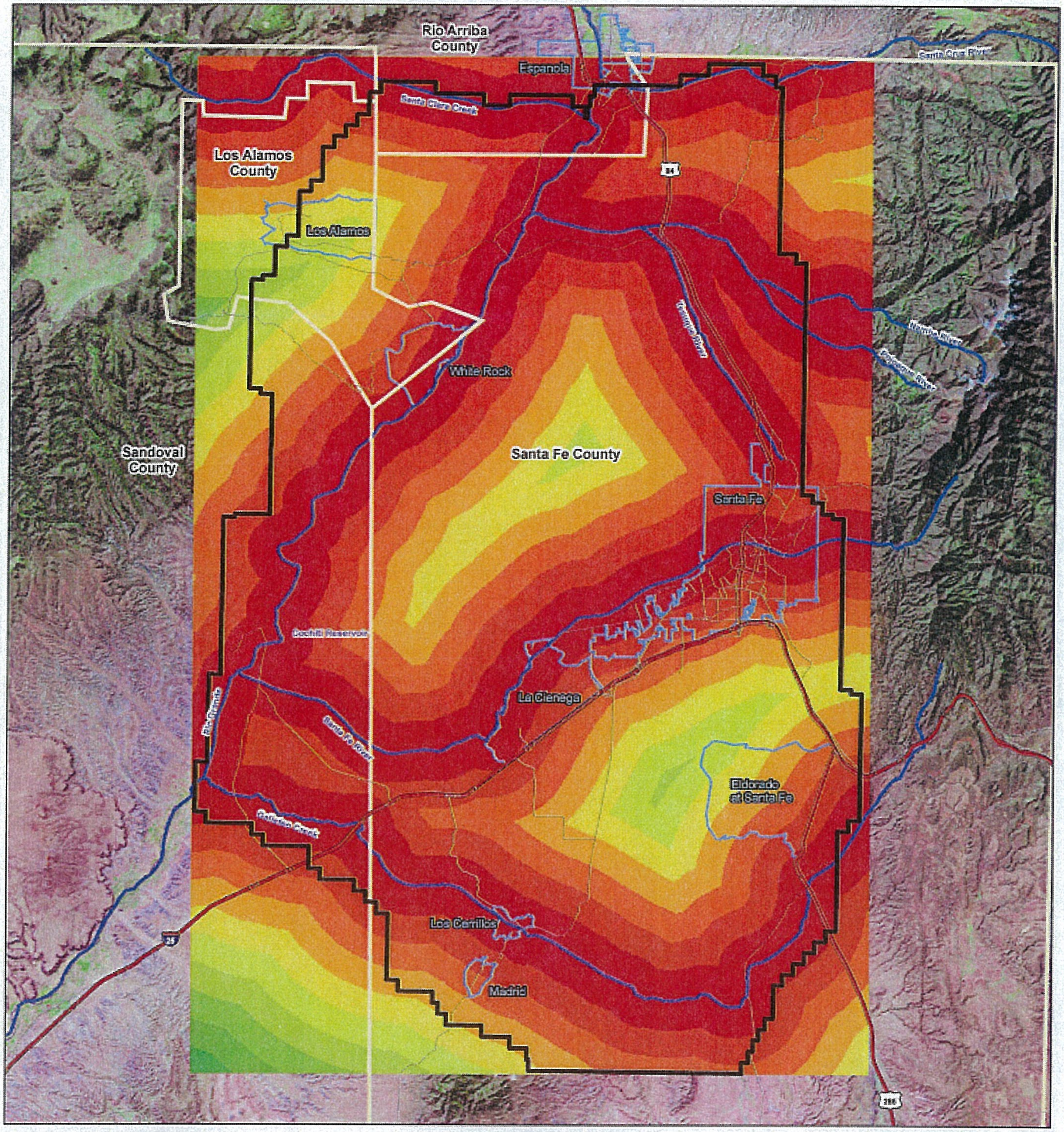
Normalized Distance to Domestic Wells

0 - 10	50 - 60
10 - 20	60 - 70
20 - 30	70 - 80
30 - 40	80 - 90
40 - 50	90 - 100

Figure 10-9.
Normalized Suitability Score for Proximity to Existing Domestic Wells

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_10-10.mxd 07/31/2006



NORTH

1 inch equals 6 miles

Miles 6 3 0 6

UTM NAD 83 Zone 13, Meters

Scale 1:400,000

Legend

Stream

Active Model Boundary

Normalized Distance to Streams

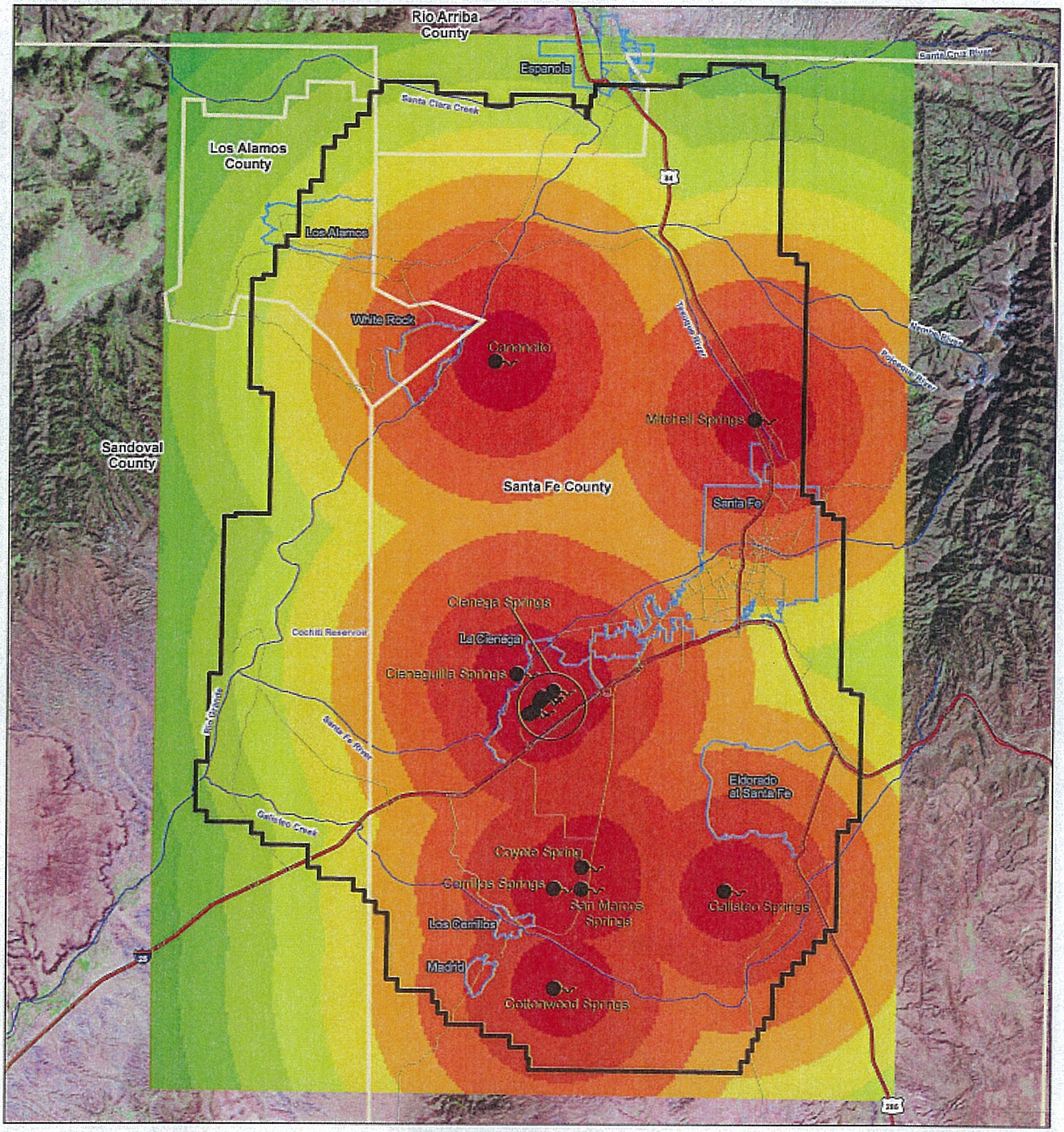
0 - 10	50 - 60
10 - 20	60 - 70
20 - 30	70 - 80
30 - 40	80 - 90
40 - 50	90 - 100

Figure 10-10.
Normalized Suitability Score for Proximity to Streams

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

INTERA

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_10-11.mxd 07/31/2006



NORTH

1 inch equals 6 miles

6 3 0 6

Miles

UTM NAD 83 Zone 13, Meters

Scale 1:400,000

Legend

Modeled Spring

Active Model Boundary

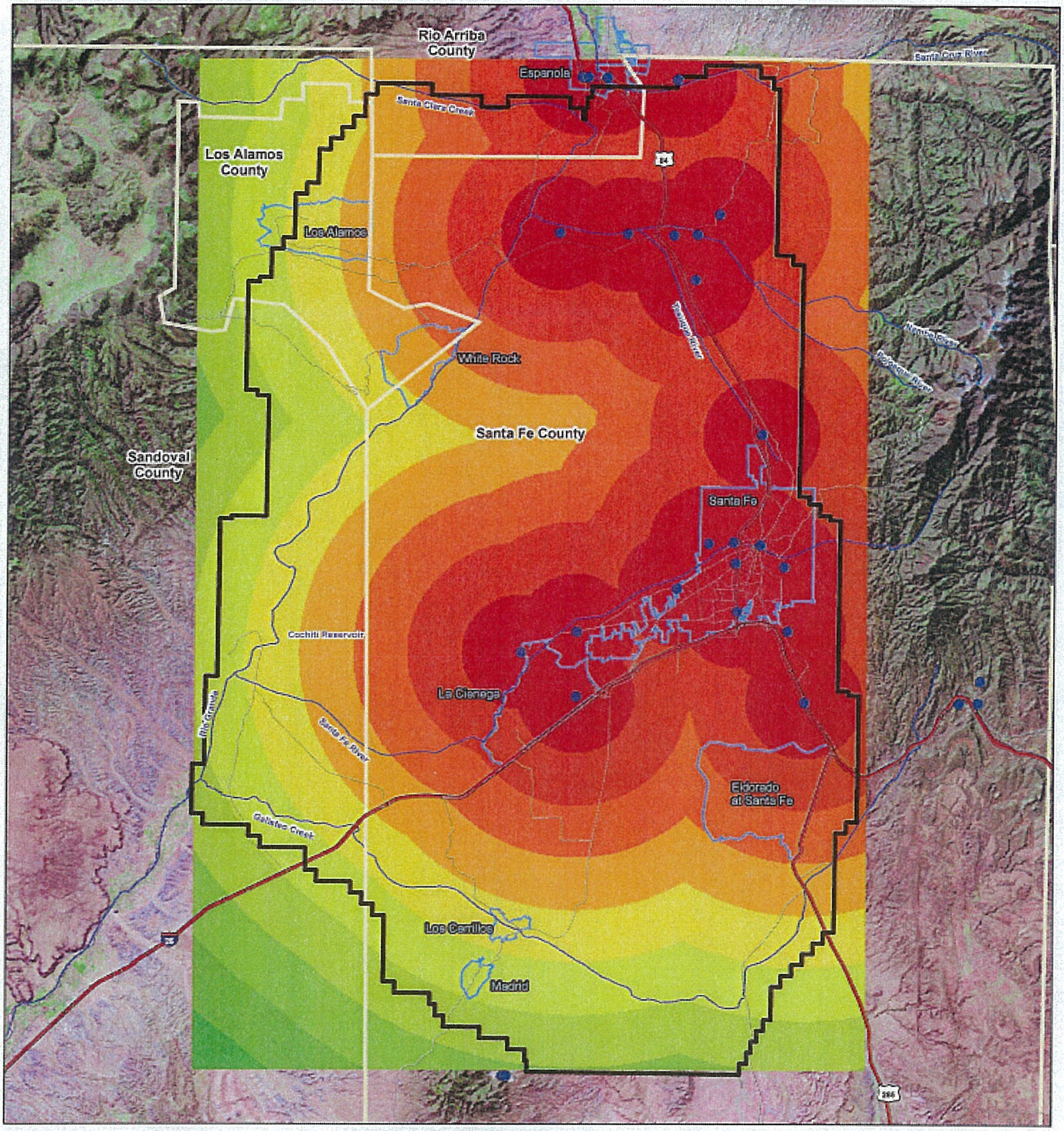
Normalized Distance to Modeled Springs

0 - 10	50 - 60
10 - 20	60 - 70
20 - 30	70 - 80
30 - 40	80 - 90
40 - 50	90 - 100

Figure 10-11. Normalized Suitability Score for Proximity to Springs

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_10-12.mxd 08/01/2006



NORTH

1 inch equals 6 miles

6 3 0 6

Miles

UTM NAD 83 Zone 13, Meters

Scale 1:400,000

Legend

- Groundwater Contamination
- Active Model Boundary

Normalized Distance to Groundwater Contamination

0 - 10	50 - 60
10 - 20	60 - 70
20 - 30	70 - 80
30 - 40	80 - 90
40 - 50	90 - 100

Figure 10-12.
Normalized Suitability Score for Proximity to Areas of Known Ground Water Contamination

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

SANTA FE COUNTY

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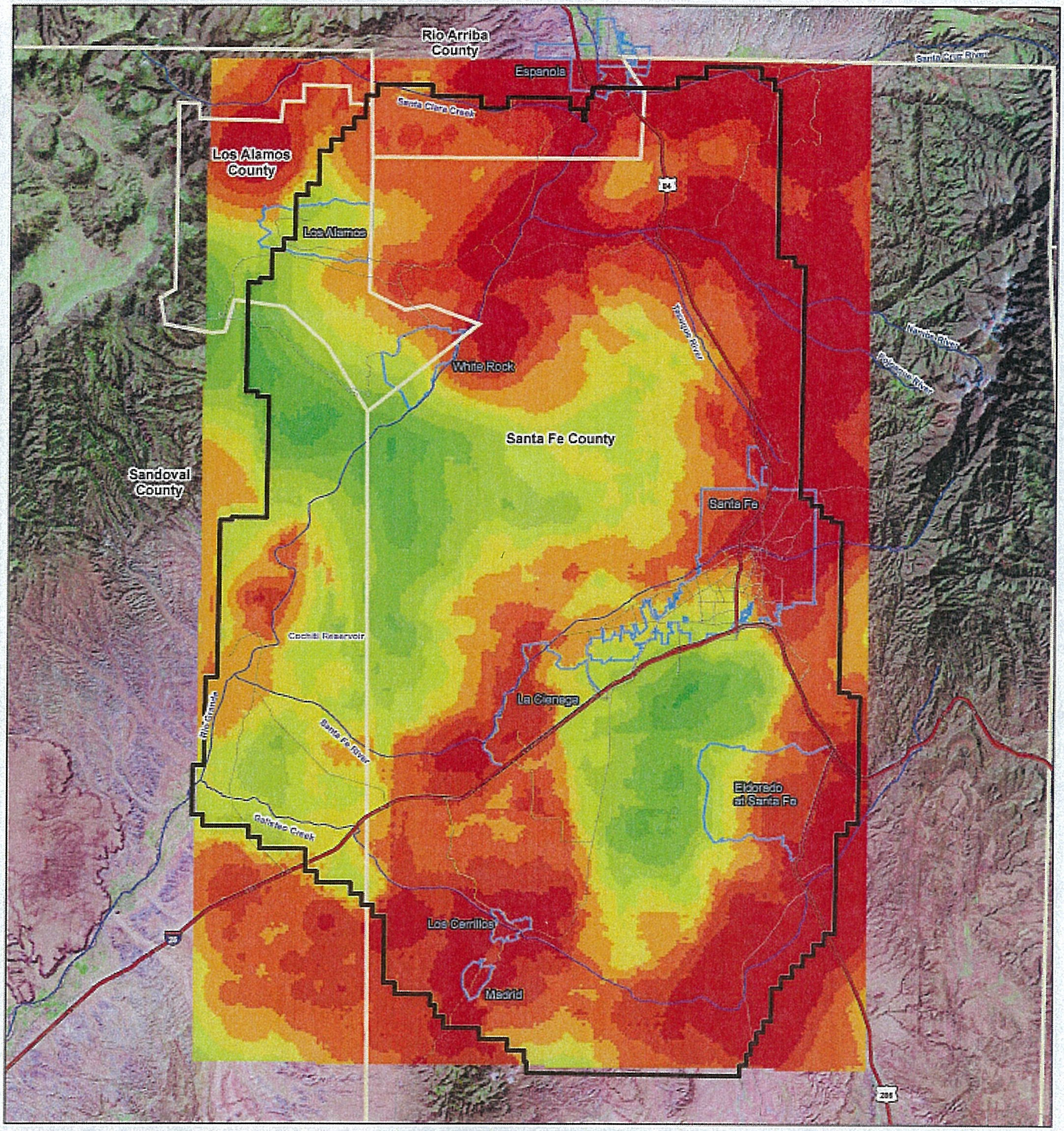


NORTH

1 inch equals 6 miles

6 3 0 6

Miles

UTM NAD 83 Zone 13, Meters
Scale 1:400,000

Legend

Active Model Boundary

Normalized Sum of Decision Analysis Layers

0 - 55	75 - 80
55 - 60	80 - 85
60 - 65	85 - 90
65 - 70	90 - 95
70 - 75	95 - 100

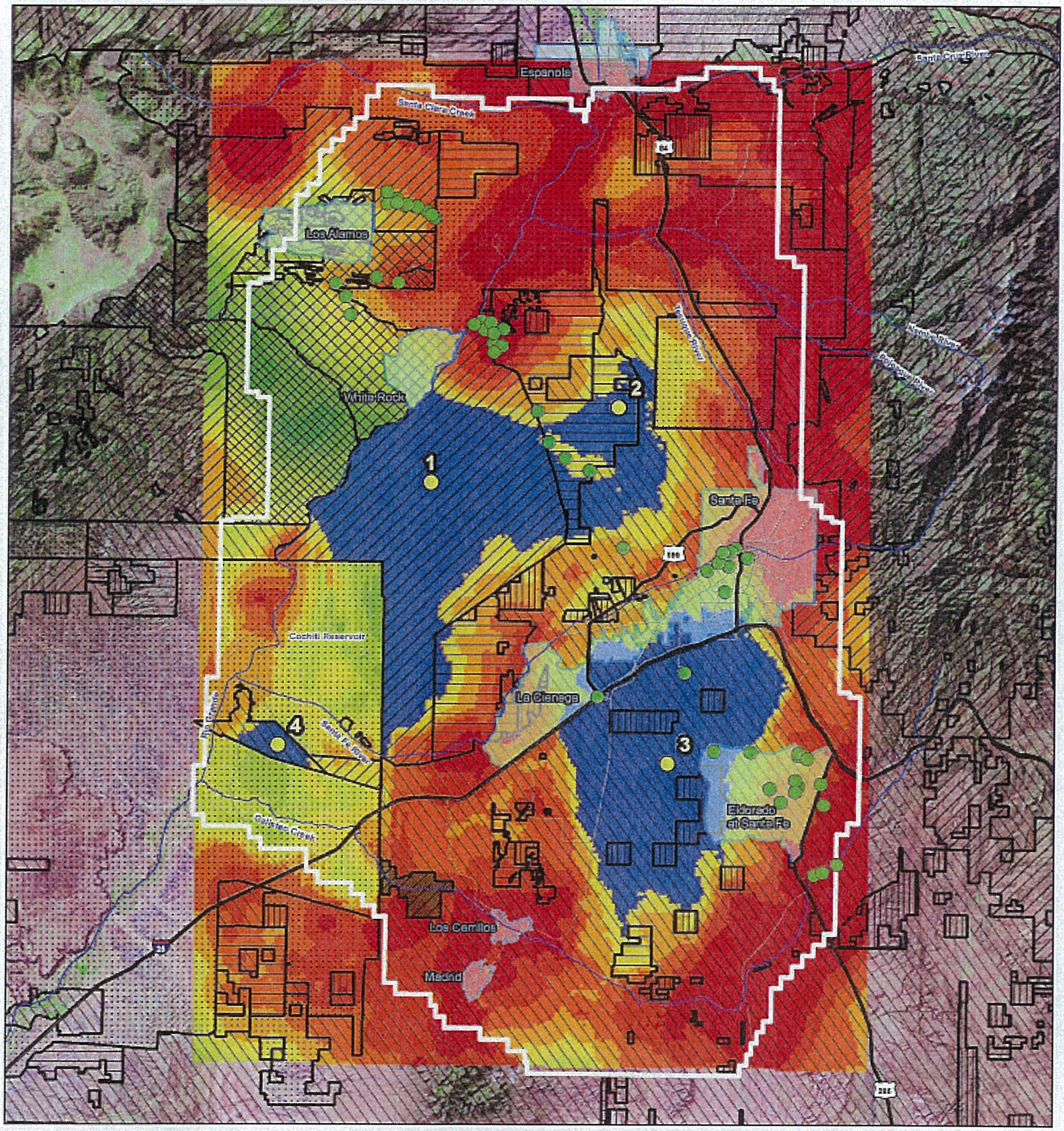
Figure 10-13.
Composite Site Suitability Score
Based on the Suitability Criteria

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

SANTA FE COUNTY

FILE: T:\Projects\SFC-001_Santa_Fe_County\GIS\MapDocuments\May_06\Final\Fig_10-14.mxd 08/31/2006



NORTH

1 inch equals 6 miles

6 3 0 6

Miles

UTM NAD 83 Zone 13, Meters

Scale 1:400,000

Legend

- Proposed Well
- Existing Major Supply Well
- Active Model Boundary

Selected Areas

- Score >= 75

Land Ownership

- BLM
- DOD
- DOE
- Forest Service
- Tribal
- National Park Service
- Private
- State

Figure 10-14.
Potential Well Sites Chosen Based on Composite Site Suitability and Property Ownership

INTERA

Sources:
New Mexico county boundaries, roads, streams, and cities: New Mexico Resource Geographic Information System
Landsat: University of Maryland Global Land Cover Facility
DEM: USGS

SANTA FE COUNTY

Table 3-1 Model Evaluation Summary

Model Reference	Code	No Layers	Calibration Period		Predictive Period	Discretization		Recharge Implementation	Surface Water Implementation	Kx/Kv Anisotropy
			Steady-State	Transient		Horizontal	Vertical			
Hearne (1980)	Trescott & Larson (1976)	21	1946	1947-1980	1980-2080	1 to 4.5 mile	650 to 950 ft	Specified Lateral flux, no areal recharge	Combination of drain and specified flux	250-500
McAda & Wasiolek (1988)	MODFLOW	4	1946	1947-1982	1983-2020	1 mile	800 to 1800 ft	Specified lateral flux, stream flux, areal flux	Combination of head dependant and specified flux boundaries	100
Frenzel (1995)	MODFLOW	8	1946	1947-1992	1993-2012	1 mile	200 to 1400 ft	lateral flux, stream flux, areal flux	Combination of head dependant and specified flux boundaries	50
Core (1996)	MODFLOW	4	N/A	N/A	Superposition	1 mile	800 to 1800 ft	lateral flux, stream flux, areal flux	Same as McAda except for La Cienega. Changed from specified flux to drains boundaries.	100
Barroll & Logan (1998)	MODFLOW	3	N/A	N/A	40 & 100 yrs	660 to 5280 ft	200 to 600 ft	Unknown	General head boundaries	100-1000
Keating et al., (2000)	FEHM	9 HSU's	Pre-1945	1945-1995	NA	Unknown	Unknown	Specified areal flux	Constant head boundaries for gaining reaches	Unknown
Shoemaker (2001)	Modified MODFLOW	4	Pre-1947	1947-1998	1999-2100	800 ft	100 to 1350 ft	Mountain front redistribution (Wasiolek, 1995)	MODFLOW RIV2 package, Head dependent, flow limited	1 to 100
CDM (2002)	MODFLOW96	9	1946	1947-2000	2000 – 2060	500 to 3000 ft	100 to 1400 ft	See Frenzel (1995)	Stream package except for Sante Fe River (specified flux)	10-1000

Table 4-1 Oil-Exploration Wells Used to Develop the Hydrogeologic Conceptual Model

Name	API Number	Township	Range	Section
Bar-S-Bar Ranch Fee #1	30-049-20001	12N	10E	23
Ramsey White Lakes #1	30-049-20002	11N	11E	28
Eastern Sandia Horton #1	30-049-20003	11N	07E	32
Eastland Oil McKee #1	30-049-20004	13N	09E	8
Transocean McKee #1	30-049-20005	13N	09E	4
Whigham Davis-Pinon #1	30-049-20006	14N	10E	21
Whigham Davis-Pinon #2	30-049-20007	14N	10E	21
Pelto McKee #1	30-049-20008	13N	09E	5
Pelto Ortiz #1	30-049-20009	14N	08E	26
Pelto State #1	30-049-20010	14N	08E	36
Colorado Plateau Ferrill #1	30-049-20015	13N	09E	7
Black Oil Ferrill #2	30-049-20016	13N	09E	5
John Gianardi #1	30-049-20017	15N	08E	22
Eastern Sandia Horton #2	30-049-20018	11N	07E	32
Black Oil McKee #1	30-049-20020	13N	09E	5
Black Oil Ferrill #1	30-049-20022	13N	08E	1
Chace Oil Pinon Unit #1	30-049-20024	14N	08E	31
Chace Oil Pinon Unit #2	30-049-20025	14N	08E	26
Yates La Mesa #2	30-049-20028	17N	08E	24
Black Oil Ferrill Hazel #3	30-049-20031	13N	08E	1
Black Oil Cash #1	30-049-20033	13N	09E	5
Black Oil Ferrill #5	30-049-20036	13N	08E	1
Black Oil Ferrill #6	30-049-20037	13N	08W	1
Yates La Mesa #3	30-049-20038	15N	08E	13
Blackstone Neville #2	30-049-20040	11N	11E	9
English Fullerton Dobson #1	30-049-20041	12N	10E	16
no log-not used	30-049-20042	12N	10E	16
Black Federal #1	30-049-20043	14N	11E	23
Castle Wigzell Kelly-Federal	30-049-20044	20N	09E	11

Table 4-2 Stratigraphic Column for the Geologic Model

Era	Period	Group, Formation, or Member	Description
Cenozoic	Quaternary	Alluvium, and Ancha Fm.	Sands and gravels
	Tertiary	Cerros del Rios	Lava flows from monogenetic volcanic field
		Rio Grande Axial Gravels	Gravel, sands, and volcaniclastics
		Tesuque Fm.	Silts, sands, gravels
		Espinaso Fm.	Tuff, agglomerate, and volcaniclastic sandstone
		Undifferentiated Intrusives	Crystalline sills, dykes, and laccoliths
		Galisteo Fm.	Muds, sands, silts, and gravels
Mesozoic	Cretaceous	Mesa Verde Group (includes Menefee Shale and Point Lookout Sandstone)	Bedded sandstones, mudstones and shales
		Mancos Fm. (includes Niobrara Shale and Dakota Sandstone)	Fossiliferous limestones, shales and sandstones
	Jurassic	Morrison Fm.	Mudstone interbedded with lenticular sandstones
		Entrada Sandstone	Arenite sandstone
	Triassic	Chinle Fm. (undifferentiated)	Mudstone interbedded with sandstone and limestone
Paleozoic	Permian	Undifferentiated Permian sediments	Mudstones, sandstones, limestones, and conglomerates
		Sandia/Sangre de Cristo Fm.	Mudstone
	Pennsylvanian	Madera Fm.	Limestone
	Precambrian	Undifferentiated	Crystalline rocks

Note:
Fm. = Formation

Table 4-3 Summary Statistics for Hydraulic Conductivity Estimates for Study Area HSUs

Unit	Count	Median K (ft/d)	Mean K (ft/d)	Geometric Mean K (ft/d)	Standard Deviation log K	Min K (ft/d)	Max K (ft/d)
Alluvium	2	38.9	38.9	29.6	0.47	13.7	64.0
Ancha	24	53.0	102.4	42.1	0.68	3.6	340
Axial Gravels*	0					1*	100*
Cerros Del Rio*	0					0.02*	5*
Espinaso	11	0.060	1.188	0.126	1.01	0.0062	6.8
Galisteo	7	1.80	5.06	2.14	0.63	0.35	18
Intrusive	4	0.16	1.43	0.24	0.97	0.042	5.35
Madera	1	0.24	0.24	0.24	--	0.24	0.24
Mancos	2	0.10	0.10	0.068	0.57	0.027	0.17
Mesa Verde	9	0.13	1.14	0.16	1.00	0.012	5.35
Morrison	3	0.063	0.20	0.036	1.32	0.0013	0.55
Permian	2	58.8	58.8	58.8	0.017	57.2	60.5
Precambrian	45	0.46	3.67	0.30	1.23	0.0002	32
Tesuque	165	1.1	6.08	1.07	0.81	0.0055	146
Lithosome A	18	0.082	0.18	0.0696	18	0.0055	0.91
Lithosome ACU	2	17.5	17.5	17.5	2	17	18
Lithosome B	12	1.05	1.11	0.852	12	0.16	2.4
Lithosome S	127	1.2	5.2	1.36	127	0.034	94
Triassic	1	0.053	0.053	0.053	--	0.053	0.053

Notes:
*Minimum and maximum taken from summary of previous modeling efforts.
ft/d = Feet per day.

Table 4-4 Storage Values Used in the Shomaker (1999) El Dorado Model

Period	Group, Formation, or Member	Specific Yield	Confined Storage
Quaternary	Alluvium	0.2	0.0001
Tertiary	Ancha Formation	0.05-0.2	0.0001–0.0002
	Tesuque Fm.	0.01-0.2	0.0001–0.0027
	Espinaso Fm.	0.01-0.2	0.0001–0.0027
	Undifferentiated Intrusives	0.01	0.0001–0.001
	Galisteo Fm.	0.01-0.05	0.0001–0.0027
Cretaceous	Mesa Verde Group	0.01	0.0001–0.001
	Mancos Formation	0.01	0.0001–0.001
	Dakota Sandstone	0.01	0.0001–0.001
Jurassic	Morrison Formation	0.01	0.0001–0.0027
Triassic	Chinle Formation (undifferentiated)	0.01	0.0001–0.0027
Permian	San Andres Formation	0.01	0.0001–0.0027
	Glorieta Sandstone	0.01	0.0001–0.0027
Pennsylvanian	Madera Group	0.01	0.0001–0.0027
Precambrian	Undifferentiated	0.01	0.0001–0.0027

Table 4-5 Literature Estimates of Mountain-Front and Related Tributary Recharge

Basin	Mountain Front (ac-ft/yr)	Tributary (ac-ft/yr)	Reference
South Galisteo Creek	3,200	0	DE&S 2000
South Galisteo Creek	3,600	NR	Kernodle (1995); McAda &Barroll (2002)
North Galisteo Creek	0	3,563	Shomaker et al. (2001)
North Galisteo Creek	0	770	DE&S 2000
Santa Fe River	4,000	NR	McAda and Barroll (2002)
Santa Fe River	6,637	4,693	Shomaker et al. (2001)
Santa Fe River	5,050	8,500	DE&S 2000
Santa Fe River	4,170	NR	Wasiolek (1995) 12% mtn precip
Santa Fe River	7,643	4,709	McAda and Wasiolek (1988)
Little Tesuque	1,790	NR	Wasiolek (1995) 19% mtn precip
Tesuque	1,530	NR	Wasiolek (1995) 11% mtn precip
Tesuque	2,460	2,500	DE&S 2000
Rio en Medio	1,710	NR	Wasiolek (1995) 15% mtn precip
Pojoaque-Nambe	5,520	NR	Wasiolek (1995) 12% mtn precip
Pojoaque-Nambe	4,500	4,200	DE&S 2000
Santa Cruz	3,760	510	DE&S 2000
Santa Cruz	Unknown	1,884	Keating et al. (2002)
Santa Clara	3,760	510	DE&S 2000
Los Alamos	3,820	400	DE&S 2000
Los Alamos Canyon 93	6.5 in/yr	NR	Gray (1997)
Los Alamos Canyon 94	4 in/yr	NR	Gray (1997)
Los Alamos Canyon 95	7.3 in/yr	NR	Gray (1997)
Pajarito Plateau	4,296–5,523	NR	Griggs (1964)
Pajarito Plateau	4,509	NR	McLinn et al. (1996)
Pajarito Plateau[1]	8,592	NR	Kwicklis et al. (2004)
Otowi Bridge to Cochiti[1]	18,155	NR	Spiegel and Baldwin (1963)
Otowi Bridge to Cochiti[1]	10,228	NR	U.S. Department of Justice (1996)
Jemez Mountains	7,305	NR	Frenzel (1995)

Notes:
mtn precip = Mountain precipitation.
NR =
[1] Estimate includes diffuse recharge.

Table 4-6 Literature Estimates of Areal Recharge Estimates including Arroyo Rates

Location / Area	Recharge Rate (in/yr)	Source	Estimate Method
Santa Fe Group	0.28	Wilson & Assoc (1978)	Unknown
Tesuque Fm., uplands	0.2	McAda & Wasiolek (1988)	Model calibration
Tesuque Fm., floodplains areas	0.4	McAda & Wasiolek (1988)	Model calibration
Ancha Fm. outcrop	0.5	McAda & Wasiolek (1988)	Model calibration
Volcanic outcrops	0.05	McAda & Wasiolek (1988)	Model calibration
Pajarito Plateau volcanics	0.15	McAda & Wasiolek (1988)	Model calibration
Pajarito Plateau volcanics	0.02	Frenzel (1995)	Model calibration
Areal & mountain front	10% of precipitation	Shomaker et al. (2001)	Model calibration
Upland areas	0.15 – 0.25	Shomaker et al. (2001)	Model calibration
Lowland areas	0.0	Shomaker et al. (2001)	Model calibration
Los Cerrillos Hills	0.5 & 1.0	Shomaker et al. (2001)	Model calibration
Mesa (inter-arroyo)	0	Anderholm (1994)	Chloride mass balance
Arroyo channel	0.09–.07[1]	Anderholm (1994)	Chloride mass balance
Arroyo margin	0.05–.19	Anderholm (1994)	Chloride mass balance

Notes:
Fm. = Formation.
[1] Minimum estimates.

Table 4-7 Estimates of Stream Gain, Loss, and ET for the Study Area

Stream Segment	Reference	Gain (ac-ft/yr)	Loss (ac-ft/yr)	ET (ac-ft/yr)	Time	Notes
Rio Grande						
Rio Grande	McAda & Wasiolek (1989)	28,500	n/a	5,144	PreD	assumes ET 5 ft/yr
Rio Grande	McAda & Wasiolek (1989)	26,900	n/a	n/a	Modern	
Rio Grande	Spiegel and Baldwin (1963)	28,285	n/a	n/a	1960s	1 cfs/mile where 1 cfs = 724.5 ac-ft/yr
Rio – Upper	Spiegel and Baldwin (1963)	4,148	n/a	n/a	1960s	Calculated based on 1 cfs/mile rule of thumb
Rio - Middle	Spiegel and Baldwin (1963)	19,989	n/a	n/a	1960s	Calculated based on 1 cfs/mile rule of thumb
Rio - Lower	Spiegel and Baldwin (1963)	4148	n/a	n/a	1960s	Calculated based on 1 cfs/mile rule of thumb
Santa Fe River						
Santa Fe River	Grant (1998) DBS&A (1990)	4,706	3,083–8,145	n/a	Modern	
Santa Fe River	Grant 2001	n/a	n/a	n/a	n/a	2 perennial reaches: Santa Fe Lake to bridge at Alaeda/Camin Cabra and between the WTP and La Bajada
Santa Fe River	Frenzel (1996)	Unknown	5,434	n/a	PreD	
Santa Fe River	Frenzel (1996)	Unknown	6,593	n/a	1993	Loss counts sewage treatment Q of 4999 ac-ft/yr
Santa Fe River	DE&S (2000)	2,170	8,500	1,180		based on CDM study
Santa Fe River	McAda & Wasiolek (1989)	4,700	5,434	n/a	PreD	
Santa Fe River	McAda & Wasiolek (1989)	4,700	4,260–5,028	n/a	Modern	Loss counts sewage treatment Q of
Santa Fe - Upper	McAda & Wasiolek (1989)	n/a	5434	n/a	PreD	
	McAda & Wasiolek (1989)	n/a	1,594–3,623	n/a	Modern	
	Grant 2001	5,701	n/a	n/a	PreD	Based on 1917 hydrographic survey of diversions; baseflow/runoff allocation unknown.
	DBS&A (2002)	n/a	780	n/a	Modern	Based on 2.1 miles – St. Francis Dr. to Osage Well 0.8 cfs/mile; Assumes 2 months flow for 13 river miles
Santa Fe - WTP	McAda & Wasiolek (1989)	n/a	2,304–3,434	n/a	Modern	modern WTP discharges 9 cfs, 6520 ac-ft/yr

Table 4-7, continued

Stream Segment	Reference	Gain (ac-ft/yr)	Loss (ac-ft/yr)	ET (ac-ft/yr)	Time	Notes
Santa Fe River (continued)						
Santa Fe - Lower	McAda & Wasiolek (1989)	4,700	n/a	n/a	Mod &PreD	Constant rate discharge assumes to be at lower segment of SFR
Santa Fe – Lower	Thomas and Constantz (1998)	NR	145–1,347	1–6% of loss	Jun-97	
Santa Fe - Lower	Grant 2001	2,173.5	2,173.5	n/a	Present	3 cfs gain and then loss between WTP and La Bajada Gage in low flow; net = 0 cfs
Tesuque						
Tesuque	Grant (1998) DBS&A (1990)	883	1,500–4,995	n/a	Modern	
Tesuque	DE&S (2000)	1,400	2,500	1,280	Modern	Based on Frenzel 95
Pojoaque						
Pojoaque - Nambe	Grant (1998) DBS&A (1990)	4,315	2,700–5,502	n/a	Modern	
Pojoaque	McAda & Wasiolek (1989)	5,300	5,900	3,200	PreD	
Pojoaque	McAda & Wasiolek (1989)	5,100	n/a	n/a	Modern	
Pojoaque	DE&S (2000)	4,000	4,200	2,850	Modern	Based on Frenzel 95
Galisteo						
Galisteo Creek		335	n/a	n/a		Streams in San Marcos Arroyo into Galisteo, not entire creek
Upper Galisteo	Grant (1998) DBS&A (1990)	Unknown	1,000–1,158	n/a	Modern	
Upper Galisteo	DE&S (2000)	0	770	130	Modern	water balance calculation
Lower Galisteo	Grant (1998) DBS&A (1990)	Unknown	5,000	n/a	Modern	
Lower Galisteo	DE&S (2000)	890	0	2,570	Modern	water balance calculation

Table 4-7, continued

Stream Segment	Reference	Gain (ac-ft/yr)	Loss (ac-ft/yr)	ET (ac-ft/yr)	Time	Notes
Combined Estimates						
Santa Fe and Galisteo	Shomaker et al. (2001) Model	4,904	8,256	6,521	PreD	Gain counts springs; Loss is applied areal recharge
Rio, Pojoaque/Nb/ Tes.	Frenzel	23,691	942	n/a	PreD	
Rio, Pojoaque/Nb/ Tes.	Frenzel	22,677	942	n/a	1993	
La Cienega, Cienega Creek, Lower Santa Fe River	Spiegel and Baldwin (1963)	4,059	n/a	n/a	1960s	6.5 cfs used as flow target in Core (1996)

Notes:
*Minimum and maximum taken from summary of previous modeling efforts.
cfs = Cubic feet per second.
ft/d = Feet per day.
n/a = Not applicable.
Nb = Nambe.
PreD = Predevelopment.
Tes = Tesuque.
WTP = Water treatment plant.

Table 4-8 Spring Flow Measurements for Springs in the Model Domain

Spring	Reference	Gain (ac-ft/yr)	Time of Measurement
Cieneguilla	Shomaker et al. (2001)	581	3/19/53
Cerrillos Reservoir Spring	Shomaker et al. (2001)	338	1/6/65
Mitchell Ditch	White and Kues (1992)	242	11/2/51
Cienega Spring	Shomaker et al. (2001)	80	10/10/51
Unnamed spring at 16N.8E.28.332	Shomaker et al. (2001)	80	5/31/73
Unnamed spring at 16N.8E.32.232	Shomaker et al. (2001)	32	5/30/73
Cañoncito Spring	White and Kues (1992)	16	2/13/52
Unnamed spring at 16N.8E.28.321	Shomaker et al. (2001)	16	5/31/73
Unnamed spring at 16N.8E.32.224	Shomaker et al. (2001)	8	7/4/51
Coyote Spring	Shomaker et al. (2001)	8	7/31/73
San Marcos Spring	Shomaker et al. (2001)	8	7/16/73
Unnamed spring at 16N.8E.28.323	Shomaker et al. (2001)	5	5/14/53
Cottonwood Spring	White and Kues (1992)	4	11/13/75
Galisteo Spring	Shomaker et al. (2001)	3	7/23/73

Table 4-9 Steady-State Flow Balance for Previous Models in the Study Area

Flow Balance Component	McAda & Wasiolek (1989) ac-ft/yr	McAda & Wasiolek (1989) (% of total flow)	Frenzel (1995) ac-ft/yr	Frenzel (1995) (% of total flow)
Areal Recharge	7,700	14.4%	3,477	6.5%
Mountain Front Recharge	41,400	77.4%	22,458	42.0%
Stream Loss	1,400	2.6%	6,375	11.9%
Boundary Flows	3,000	5.6%	9,273	17.4%
Total Inflow	53,500	100.0%	41,583	100.0%
Stream/Spring Gains/ET	38,500	72.2%	23,690	57.0%
Rio Grande	28,500	53.5%	11,845	28.5%
Boundary	14,800	27.8%	17,894	43.0%
Total Outflow	53,300	100.0%	41,584	100.0%

Table 5-1 Conceptual Ground Water Flow Balance for the Model Region

Flow Component	Flow Estimate (AFY)	Flow Percent
Areal Recharge	7,000	16%
Mountain Front Recharge	30,000	67%
Stream Loss	5,000	11%
Subsurface Boundary Flows	3,000	7%
Net Inflow	45,000	100%
Stream/Spring Gains(ET)	33,000	73%
Rio Grande	24,000	53%
ET	11,000	24%
Subsurface Boundary Flows	1,000	2%
Net Outflow	45,000	100%

Table 6-1 Initial Hydraulic Parameter Inputs by HSU

Unit	$K_{surface}$ (ft/d)	Depth Decay Constant (λ)	Specific Yield (S_y)	Specific Storage (S_s) (ft^{-1})
Ancha & Alluvium	77.4	0.0012	0.2	10^{-6}
Axial Gravels	30	0.0012	0.2	10^{-6}
Cerros Del Rio	0.5	0.0012	0.05	10^{-6}
Espinaso	0.295	0.0012	0.15	10^{-6}
Galisteo	6.03	0.0012	0.15	10^{-6}
Intrusive	0.24	0.0012	0.01	10^{-6}
Madera	0.3	0.0012	0.03	10^{-6}
Mancos	0.1	0.0012	0.01	10^{-6}
Mesa Verde	2	0.0012	0.01	10^{-6}
Morrison	0.3	0.0012	0.01	10^{-6}
Permian	0.5	0.0012	0.01	10^{-6}
Precambrian	0.1	0.0012	0.01	10^{-6}
Tesuque Lithosome A	1.14	0.0012	0.2	10^{-6}
Tesuque Lithosome ACU	32.5	0.0012	0.2	10^{-6}
Tesuque Lithosome B	7.35	0.0012	0.2	10^{-6}
Tesuque Lithosome S	7.75	0.0012	0.2	10^{-6}
Triassic	0.1	0.0012	0.01	10^{-6}

Table 6-2 Precipitation Gages Used to Compute Mountain-Front and Areal Recharge

Model Region	Precipitation Station Number	Precipitation Station Name	Period of Record	Station Average Precipitation (in)	Area Average Precipitation (in)
East	9113	Truchas	1948–1962	10.4	14.8
	6676	Pecos Nat'l Mon	1948–2004	16.4	
	8072	Santa Fe (east)	1940–1971	13.4	
	3586	Glorieta	1949–2003	15.1	
West	5084	Los Alamos	1948–2003	18.2	15.8
	743	Bandalier Nat'l Mon	1948–1976	15.2	
	1982	Cochiti Dam	1975–2003	11.9	
Areal	8078	Santa Fe (west)	1948–1958	8.7	11.3
	8085	Santa Fe (west)	1972–2000	13.6	
	3031	Española	1948–2003	9.3	
	8518	Stanley 2 NNE	1955–2004	12.6	

Notes:
Nat'l Mon = National monument.
NNE = North, northeast.

Table 6-3 Annual Recharge Coefficients for Mountain-Front and Areal Recharge

Year	West Boundary	East Boundary	Areal Recharge
1946	1.000	1.000	1.000
1947	1.000	1.000	1.000
1948	1.031	0.970	0.926
1949	1.256	0.902	0.985
1950	0.650	0.647	0.664
1951	0.943	0.769	0.740
1952	1.418	0.926	0.755
1953	0.968	0.770	0.687
1954	0.866	0.924	0.713
1955	0.698	0.879	0.687
1956	0.374	0.450	0.341
1957	1.566	1.370	1.296
1958	1.068	0.935	0.793
1959	1.339	0.981	1.107
1960	1.161	1.071	0.878
1961	1.142	1.071	0.897
1962	0.888	0.686	0.750
1963	1.013	0.999	0.951
1964	0.699	0.949	0.621
1965	1.538	1.374	1.129
1966	0.921	0.917	0.477
1967	1.251	1.221	0.922
1968	1.138	0.845	0.650
1969	1.542	1.373	1.249
1970	0.839	0.954	0.808
1971	1.163	1.093	0.845
1972	1.116	1.169	1.062
1973	1.001	1.117	0.873
1974	1.084	1.085	1.077
1975	0.943	1.059	1.018
1976	0.651	0.738	0.828
1977	0.886	1.195	0.976
1978	1.098	1.020	1.105
1979	0.810	1.126	1.205
1980	0.599	0.939	0.840
1981	0.872	1.268	1.042
1982	1.096	1.257	1.108

Table 6-3, continued

Year	West Boundary	East Boundary	Areal Recharge
1983	0.886	1.136	0.966
1984	1.057	1.266	1.399
1985	1.403	1.483	1.689
1986	1.402	1.415	1.543
1987	1.099	0.856	0.927
1988	1.253	1.328	1.315
1989	0.829	0.902	0.819
1990	1.092	1.286	1.219
1991	1.378	1.584	1.533
1992	0.967	1.009	1.074
1993	1.041	1.086	1.120
1994	1.096	1.428	1.538
1995	0.824	0.754	0.883
1996	0.980	1.216	1.305
1997	1.389	1.205	1.554
1998	0.854	1.282	1.088
1999	0.819	1.100	0.748
2000	0.855	1.084	1.037
2001	0.736	0.938	0.509

Table 6-4 Monthly Recharge Coefficients for Mountain-Front and Areal Recharge

Month	West Boundary	East Boundary	Aerial Recharge
Jan	0.048	0.036	0.038
Feb	0.043	0.033	0.029
Mar	0.063	0.048	0.059
Apr	0.060	0.049	0.054
May	0.076	0.069	0.083
Jun	0.081	0.092	0.105
Jul	0.143	0.181	0.140
Aug	0.172	0.203	0.177
Sep	0.107	0.112	0.109
Oct	0.096	0.085	0.098
Nov	0.062	0.051	0.061
Dec	0.049	0.040	0.047

Table 6-5 Information for Municipal Wells Used in the Model

Alias	SEO file #	T	R	S	q	q	q	X-coord (NMC SP83 ft)	Y-coord (NMC SP83 ft)	Ground El. (ft)	Depth of well (ft)	Top of screen	Bottom of Screen
EUI_1	18528	15N	09E	3	4	3	1	1723004.33	1657203.1	6550	719	350	700
EUI_2	18529	15N	09E	1	3	3	2	1731592.73	1657148.1	6670	350	0	350
EUI_3	18543	15N	10E	5	3	4	3	1742777.76	1656427.1	6910	324	113	320
EUI_4	18550	15N	10E	5	3	4	1	1742777.76	1657087.1	6935	374	76	365
EUI_5	18515	15N	10E	8	2	1	2	1744754.32	1655777.1	6990	192		
EUI_6	18571	15N	10E	18	1	3	3	1736213.22	1648514.9	6745	260	220	260
EUI_7	18595	15N	10E	19	2	1	1	1738858.26	1645328.8	6755	250	102	250
EUI_8	18531	15N	10E	21	1	2	4	1748697.63	1644641.8	6850	312	165	278
EUI_9	18556	14N	10E	4	1	3	1	1746721.58	1627914.4	6420	300	45	114
EUI_10	18524	14N	10E	4	1	2	4	1748701.53	1628574.4	6441	94	64	94
EUI_11	18523	15N	10E	34	3	3	1	1752029.05	1630548.4	6490	65	45	65
EUI_12	18516	15N	10E	8	2	2	1	1748033.74	1649728.9	6995	197		
EUI_13	18529	15N	10E	17	1	4	1	1742766.57	1649121.9	6880	340	160	290
EUI_14	65707	15N	10E	17	1	1	2	1742106.58	1650442	6850	477	280	477
EUI_15	65707	15N	10E	16	1	1	2	1742106.58	1647801.9	6977	400	280	400
Buckman #1 (new)	20516-S	18N	7E	1	1	2		1667451.45	1759204.94	5510	1093	260	1100
Buckman #2	20516-S-2	18N	7E	1	3	2		1668101.91	1757227.88	5539	1585	240	1585
Buckman #3	20516-S-3	18N	7E	1	3	4		1670274.32	1756212.49	5619	1490	500	1490
Buckman #4	20516-S-4	18N	7E	1	4	4		1670432.53	1753863.46	5646	1220	454	1214
Buckman #5	20516-S-5	19N	7E	36	1	3		1670544.64	1751643.96	5790	1170	246	1068
Buckman #6	20516-S-6	19N	7E	36	3	4		1672196.99	1752739.89	5710	1154	300	1154
Buckman #7	20516-S-7	19N	7E	36	3	2	2	1669441.34	1758862.59	5606	1400	700	1400
Buckman #8	20516-S-8	19N	7E	35	1	3		1665516.98	1758386.45	5514	910	381	900
Buckman #9	20516-S-9	19N	8E	31	3	3	1	1672334.92	1757402.54	5738	1340	300	1320
Buckman #10	20516-S-10	18N	8E	20	4	1	2	1680747.23	1737869.53	6046	2016	500	1980
Buckman #11	20516-S-11	18N	8E	28	3	3	4	1683443.14	1730441.53	6150	2020	450	1980
Buckman #12	20516-S-12	18N	8E	33	4	2	3	1687231.55	1726672.54	6246	1930	400	1900
Buckman #13	20516-S-13	17N	8E	3	2	2	4	1692899.12	1723816.58	6427	2018	400	1980
St Michaels	304	17N	9E	34	4	2	2	1724892.13	1695293.50	6853	795	380	780
Osage	304-S	17N	9E	27	3	1	4	1720652.63	1700220.50	8750	770	210	760
Santa Fe	1117	17N	9E	26	1	3	3	1725689.13	1701399.13	6872	1300	200	725
Agua Fria	1118	17N	9E	27	2	3	2	1723229.13	1702225.13	6798	740	201	740
Ferguson	1116	17N	9E	23	3	2	3	1727231.38	1705718.50	6877	826	175	746
Hickox	1114	17N	9E	26	2	2	2	1730063.76	1703462.89	6965	882	400	840
New Alto St. Well	1113	17N	9E	23	3	2	2	1726111.00	1704946.25	6861	725	226	720
Torreon Well No.2	1115	17N	9E	22	4	4	1	1724318.13	1704672.00	6828	1230	410	1210
Northwest Well	68302	17N	9E	10	4	3	1	1722791.50	1715000.75	7120	2000	500	1980
LA-1		19N	7E	13	1	1		1668227.63	1776913.30	5621	1000	60	865
LA-1B		19N	7E	13	1	1		1668392.63	1776913.46	5628	2200	326	1694
LA-2		19N	7E	14	2	2	2	1667074.78	1777214.92	5648	882	105	865
LA-3		19N	7E	14	2	3	1	1666005.83	1777213.95	5672	910	105	865
LA-4		19N	7E	22	1	1	4	1657453.24	1771241.15	5975	2019	754	1964
LA-5		19N	7E	15	4	3	4	1660002.09	1772557.70	5838	1000	440	1740
LA-6		19N	7E	14	3	1		1662636.05	1774581.29	5770	2030	420	1778
Guaje - 1	486-S-5	19N	7E	4	3	4		1656210.10	1783577.54	5979	2020	282	1980
Guaje - 2	486-S-3	19N	7E	4	3	1	1	1654401.83	1785092.88	6058	2000	281	1960
Guaje - 3	486-S-2	19N	7E	4	1	3		1651685.68	1786203.91	6139	1997	441	1785
Guaje - 4	486-5	19N	7E	5	2	3	1	1649134.95	1786405.76	6238	2000	426	1925
Guaje - 5	486	19N	7E	5	1	1	2	1647243.61	1788022.90	6317	2000	700	1510
Guaje - 6	486-S-6	19N	7E	6	2			1645023.12	1786808.88	6438	2000	570	2000
Guaje - 1A	486-S-4	19N	7E	4	3	2	3	1655387.30	1784283.86	6018	2000	272	1513
Guaje - 2A	486-S-3							1651974.00	1786166.00	6140	2000		
Guaje - 3A	486-S-2							1649662.00	1786585.00	6212	2000		
Guaje - 4A	486-5							1647318.00	1787113.00	6299	2000		
Guaje - 5A	486							1644877.00	1789636.00	6414	2000		
Pajarito - 1	487	19N	7E	20	3	4	1	1647906.17	1768103.21	6497	2500	945	2479
Pajarito - 2	487-S	19N	6E	36	1	3		1636959.23	1760317.02	6717	2600	1004	2280
Pajarito - 3	487-S-2	19N	7E	19	3	2	1	1642803.78	1769415.89	6638	2500	956	2532
Pajarito - 4	487-S-3	19N	6E	25	1	3		1635725.28	1764664.64	6920	2920	1260	2854
Pajarito - 5	487-S-4	19N	6E	23	4	3		1633254.89	1767799.04	7094	3100	1440	3072
Owoti Well #1	485-S-6	19N	07E	20	2	1		1649128.66	1771727.71	6396	2609	1017	2477
Owoti Well #4	485-S-7	19N	06E	13	3	4		1637443.29	1773498.02	6625	2806	1115	2596

Table 6-6 Domestic Usage by County (ac-ft/yr)

Year	Santa Fe	Rio Arriba	Sandoval	Total Model
1950	737.5	57.1	10.0	786.6
1960	983.4	84.5	17.8	1071.6
1970	1311.2	125.0	31.7	1459.9
1980	1615.0	173.9	56.2	1845.1
1990	2610.9	288.5	114.3	3013.8
2000	3199.3	381.9	161.9	3743.1

Notes:

1. Ratio of model domain county population to total county population from 2000 assumed constant in time.
2. 1950, 196 & 1970 values estimated using an exponential fit to 1980–2000 data.
3. Los Alamos County has no domestic pumping; all municipal supply.

Table 6-7 Domestic Pumping Rate Allocation

Year	1950	1960	1970	1980	1990	2000
Number of Wells	65	234	526	1415	2213	3293
Effective Pumping Per Well (ac-ft/yr)	6.72	2.54	1.54	0.72	0.75	0.63

Note:

1. Pumping rates per well are higher than normal due to portion of DOM wells not in WATERS database.

Table 6-8 Community Wells Used in Model

Name	County	Data Source	depth (ft)	drill date	NMSP_C_83		Average Q		
					X	Y	gpcd	afy	cfd
Acre Estates	Santa Fe	JSAI and OSE Tech Reports	505	1960	1704243	1687455		7.50	894
AGUA FRIA WATER ASSOCIATION	Santa Fe	OSE Tech Reports			1711604	1694854	109	12.21	1456
ASI LA MAR TRAILER PARK	Santa Fe	SFC			1710266	1689101		8.00	954
Bolin (MHP)	Santa Fe	JSAI (table 8)	418	1972	1707343	1683162		51.00	6082
Brunn School	Santa Fe	JSAI (table 8)			1729543	1694062		16.77	2000
CANADA DE LOS ALAMOS MDWCA	Santa Fe	SFC			1756365	1670384			
CANONCITO AT APACHE CANYON	Santa Fe	OSE Tech Reports			1760967	1656769	71	9.56	1140
Casitas de Santa Fe (MHP)	Santa Fe	OSE Tech Reports			1705631	1687455	73	65.42	7802
Cerillos MWDCA	Santa Fe	OSE Tech Reports					57	19.15	2284
CHIMAYO MDWCA	Santa Fe	OSE Tech Reports			1735137	1819218	141	19.20	2290
CHUPADERO MDWCA	Santa Fe	SFC			1739296	1754311			
Cielo Lindo (MHP)	Santa Fe	OSE Tech Reports					52	1.98	236
Country Club Estates	Santa Fe	OSE Tech Reports					162	10.28	1226
COUNTRY CLUB GARDENS MHP	Santa Fe	OSE Tech Reports			1700445	1687683	80	87.69	10458
CUNDIYO MDWCA	Santa Fe	SFC			1745622	1803192			
EL RANCHO MHP	Santa Fe	OSE Tech Reports			1691374	1777926	68	4.35	519
EL VADITO DE LOS CERRILLOS	Santa Fe	OSE Tech Reports			1678218	1612732	74	17.31	2064
Enchantment MHP	Santa Fe	OSE Tech Reports					80	21.73	2592
GALISTEO MDWCA	Santa Fe	OSE Tech Reports			1731690	1598527		23.28	2776
HAILE MHP	Santa Fe	SFC			1712933	1694854		6.00	716
Hammon Community Well	Santa Fe	JSAI (table 8)			1708243	1694062		8.38	1000
HYDE PARK ESTATES WATER USERS	Santa Fe	OSE Tech Reports			1748793	1715825	48	10.08	1202
Jemez Road MHP	Santa Fe	JSAI and OSE Tech Reports			1705543	1686962		48.42	5775
JUNIPER HILLS MHP	Santa Fe	OSE Tech Reports			1705804	1804634	54	4.05	483
JUNIPER HILLS RANCH	Santa Fe	JSAI and OSE Tech Reports			1711558	1685115		32.28	3850
La Cienega	Santa Fe	JSAI (table 8)			1677844	1662262		7.42	885
LA CIENEGA LAKESIDE MHP	Santa Fe	JSAI and OSE Tech Reports			1671802	1657649	77	4.15	495
LA CIENEGA MDWCA	Santa Fe	OSE Tech Reports			1680837	1665025	93	14.27	1702
LA PUEBLA MDWCA	Santa Fe	OSE Tech Reports			1715770	1814786	152	24.20	2886
LA VISTA SUBDIVISION	Santa Fe	OSE Tech Reports			1739573	1687427	214	7.93	946
LAMY DOMESTIC WATER USERS	Santa Fe	SFC			1748491	1629307		17.00	2027
LONE STAR MHP	Santa Fe	JSAI (table 8) and SFC			1707617	1693526		16.14	1925
MADRID VILLAGE WATER COOP	Santa Fe	OSE Tech Reports			1669769	1600787	49	14.03	1673
NM STATE PENITENTARY	Santa Fe	OSE Tech Reports			1697857	1660517	226	284.20	33894
POJOAQUE TERRACES MHP	Santa Fe	OSE Tech Reports			1708560	1782429	77	13.52	1613
RANCHITOS DE GALISTEO	Santa Fe	OSE Tech Reports			1729165	1590237	239	8.60	1026
RANCHO ENCNTADO	Santa Fe	SFC			1737971	1746431			
RIO CHIQUITO WATER SUPPLY	Santa Fe	OSE Tech Reports			1743465	1815412	25	3.36	401
RIO EN MEDIO MDWCA	Santa Fe	OSE Tech Reports			1748673	1762759	48	6.12	730
ROADRUNNER TRAILER LODGE	Santa Fe	OSE Tech Reports			1710266	1689101	72	34.28	4088
Roman Catholic Church	Santa Fe	JSAI (table 8)	512	1979	1730143	1709262		16.50	1968
Rufina Apartments	Santa Fe	OSE Tech Reports					72	4.01	479
SANTA CRUZ MDWCA	Santa Fe	OSE Tech Reports			1703010	1817919	46	16.82	2005

Table 6-9 Irrigation Wells and Their Diversion Amounts

Well Number	TWS	RNG	SEC	Q1	Q2	Q3	Diversion	X	Y
RG 00316							5.966	1688191	1703768
RG 00361	17N	09E	27	1			5.966	1688191	1703768
RG 00590	16N	08E	17	2	2	2	233.100	1680171	1680878
RG 03707 -A	15N	07E	31	4	2		70.000	1645250	1632553
RG 03836	19N	09E	5	3	1	3	17.520	1709212	1784911
RG 04001	18N	10E	6	2	3		6.000	1738689	1755102
RG 05503	20N	08E	28	4	3	4	144.760	1686217	1794818
RG 05840	17N	09E	28	4	2	4	14.418	1719290	1700748
RG 07781	19N	08E	11	3			35.580	1694274	1779705
RG 10160	19N	08E	6	4	2	4	9.990	1676850	1785281
RG 11572	19N	08E	12	3	3	1	30.000	1698491	1778932
RG 13100	18N	10E	30	3	1		6.000	1736115	1732759
RG 13423	18N	09E	25	4	2	4	148.200	1735102	1732427
RG 19134	16N	10E	17	1	4	4	14.000	1743023	1680935
RG 19441							43.200	1683471	1651428
RG 19442							32.400	1683421	1651978
RG 20758	18N	09E	25	4	2	4	16.890	1735102	1732427
RG 21941	18N	09E	25	4	2	4	7.680	1735102	1732427
RG 24383	14N	09E	36	3	3	1	5.360	1730771	1599626
RG 25734	14N	09E	36				34.030	1733060	1601309
RG 26090	19N	09E	10	2	4	1	24.630	1723792	1781658
RG 29242	15N	07E	12	2	4		58.200	1670300	1654277
RG 30341	17N	09E					37.100	1733015	1704768
RG 30918							10.500	1733770	1703928
RG 32545	16N	10E	20	2	2	1	48.000	1745041	1677590
RG 34034							12.018	1720275	1701323
RG 36689	18N	10E	31	3	2	4	6.600	1737732	1727167
RG 37458	18N	09E	25	2	3	4	14.850	1733749	1733739
RG 37538	20N	08E	22				5.960	1689122	1800478
RG 37630	18N	09E	25	2	1	1	43.590	1733074	1735710
RG 37639	19N	08E	12	3	2	2	9.030	1700466	1780267
RG 39656	18N	09E	24	4	3	1	5.000	1733145	1736856
RG 47206	14N	09E	25	3	1	2	14.260	1731400	1606205
RG 48630	16N	10E	6	1	2	4	18.427	1737772	1692807
RG 68705 DCL							9.000	1725070	1704728
RG 69441	16N	09E	25	4	3	4	24.440	1733320	1667718
RG 71316	16N	09E	5	4	2	2	7.380	1713782	1691217
RG 80087	13N	09E	2	1	3	3	117.600	1725437	1596320
RG 83202	17N	09E	28				6.132	1718900	1700138

Table 8-1 Final Calibrated Hydraulic Conductivities as Compared to the Initial Estimates by HSU

Unit	*Final $K_{surface}$* (ft/d)	*Initial $K_{surface}$* (ft/d)	Difference (ft/d)
Cerros	5	0.5	4.5
Tesuque A	1.38	1.14	0.2
Tesuque ACU	9.45	32.5	-23.1
Tesuque B	3.25	7.35	-4.1
Tesuque S	4.21	7.75	-3.5
Espinaso	1.02	0.295	0.7
Madera	0.5	0.3	0.2
Precambrian	0.685	0.1	0.6
Galisteo	0.648	6.03	-5.4
Mancos	1.92	0.1	1.8
Morrison	0.1	0.3	-0.2
Alluvium	4	77.4	-73.4
Ancha	2.44	77.4	-75.0
Triassic	0.1	0.1	0.0
Permian	0.1	0.5	-0.4
Axial Gravel	2	30	-28.0
Intrusive	0.1	0.24	-0.1
Mesa Verde	0.5	2	-1.5

Table 8-2 Head Calibration Statistics for the Steady-State Model

Layer	Count	ME (ft)	MAE (ft)	RMSE (ft)	Range (ft)	RMSE/ Range
1-9	184	7.6	68.0	95.8	1,958	0.049

RMSE = Root mean square error.
ME = Mean error.
MAE = Mean absolute error.

Table 8-3 Stream Gain Loss Targets and Simulated Values

Stream Segment	Reference	Gain (AFY)	Loss (AFY)	Gain (AFY)	Loss (AFY)	Relevant Time
		Target		Simulated		
Rio Grande						
Rio Grande	McAda & Wasiolek (1989)	28500	-	22,846	768	PreD
Rio Grande	Spiegel and Baldwin (1963)	28285	-			1960s
Santa Fe River	Grant (1998) DBS&A (1990)	4706	3083-8145	1,745	973	Modern
Santa Fe River	Frenzel (1996)	Unknown	5434			PreD
Santa Fe River	DE&S (2000)	2170	8500			
Santa Fe River	McAda & Wasiolek (1989)	4700	5434			PreD
Tesuque						
Tesuque	Grant (1998) DBS&A (1990)	883	1500-4995	2,285	190	Modern
Tesuque	DE&S (2000)	1400	2500			Modern
Pojoaque						
Pojoaque, Nambe	McAda & Wasiolek (1989)	5300	5900	6,390	70	PreD
Galisteo						
Galisteo Creek	Shomaker et al. (2001)	335	-	3,721	475	
Upper Galisteo	Grant (1998) DBS&A (1990)	Unknown	1000-1158			Modern
Upper Galisteo	DE&S (2000)	0	770			Modern
Lower Galisteo	Grant (1998) DBS&A (1990)	Unknown	5000			Modern
Lower Galisteo	DE&S (2000)	890	0			Modern
Combined Estimates						
Santa Fe and Galisteo	Shomaker et al. (2001) Model	4904	8256	5,467	1,448	PreD
La Cienega, Cienega Creek, Lower Santa Fe River	Spiegel and Baldwin (1963)	4,059	-	2,280.3	-	1960's

Table 8-4 Water Budget for the Steady-State Model Calculated by Model Layer (ac-ft/yr)

IN						
Layer	**Drains**	**Recharge**	**GHBs**	**Streams**	**Top Flow**	**Bot. Flow**
1	0	38,538	3,217	2,470	0	29,266
2	0	1,501	1,371	0	25,832	20,387
3	0	43	895	0	19,290	8,522
4	0	0	398	0	8,183	3,282
5	0	0	145	0	3,186	811
6	0	0	33	0	797	94
7	0	0	4	0	92	4
8	0	0	0	0	4	0
9	0	0	0	0	0	0
Sum	0	40,082	6,063	2,470	57,384	62,367

OUT						
Layer	**Drains**	**ET**	**GHBs**	**Streams**	**Top Flow**	**Bot. Flow**
1	178	10,711	470	36,400	0	25,832
2	0	0	373	0	29,266	19,290
3	0	0	288	0	20,387	8,183
4	0	0	157	0	8,522	3,186
5	0	0	68	0	3,282	797
6	0	0	18	0	811	92
7	0	0	2	0	94	4
8	0	0	0	0	4	0
9	0	0	0	0	0	0
Sum	178	10,711	1,376	36,400	62,367	57,384

Table 8-5 Water budget for the Steady-State Model (% of total inflow or outflow)

		IN		
Layer	**Drains**	**Recharge**	**GHBs**	**Streams**
1	0.00%	79.27%	6.62%	5.08%
2	0.00%	3.09%	2.82%	0.00%
3	0.00%	0.09%	1.84%	0.00%
4	0.00%	0.00%	0.82%	0.00%
5	0.00%	0.00%	0.30%	0.00%
6	0.00%	0.00%	0.07%	0.00%
7	0.00%	0.00%	0.01%	0.00%
8	0.00%	0.00%	0.00%	0.00%
9	0.00%	0.00%	0.00%	0.00%
Sum	0.00%	82.45%	12.47%	5.08%
		OUT		
Layer	**Drains**	**ET**	**GHBs**	**Streams**
1	0.37%	22.01%	0.97%	74.80%
2	0.00%	0.00%	0.77%	0.00%
3	0.00%	0.00%	0.59%	0.00%
4	0.00%	0.00%	0.32%	0.00%
5	0.00%	0.00%	0.14%	0.00%
6	0.00%	0.00%	0.04%	0.00%
7	0.00%	0.00%	0.00%	0.00%
8	0.00%	0.00%	0.00%	0.00%
9	0.00%	0.00%	0.00%	0.00%
Sum	0.37%	22.01%	2.83%	74.80%

Table 8-6 Ground water Flow Balance (Simulated vs. Conceptual)

Flow Component	Simulated Flow (AFY)	Simulated Flow Percent (%)	Conceptual Flow Estimate (AFY)	Conceptual Flow Percent (%)
Areal Recharge	9,574	20	7,000	16
Mountain Front Recharge	30,510	63	30,000	67
Stream Loss	2,476	5	5,000	11
Subsurface Boundary Flows	6,063	12	3,000	7
Net Inflow	48,800	100	45,000	100
Stream/Spring Gains(ET)	-37,344	77	-33,000	73
Rio Grande	-22,077	45	-24,000	53
ET	-10,711	22	-11,000	24
Subsurface Boundary Flows	-1,376	3	-1,000	2
Net Outflow	-49,432	100	-45,000	100

Table 8-7 Parameter Names and Descriptions

Number	Parameter	Description
1	KDEP_BED	depth decay coefficient in Precambrian and Intrusive units
2	KDEP_MOST	depth decay coefficient in all other units
3	MHANI_2	horizontal anisotropy in the Tesuque
4	MHANI	horizontal anisotropy in all other units
5	MHK_1	horizontal hydraulic conductivity in the Cerros
6	MHK_2_Tta	horizontal hydraulic conductivity in Tesuque Lithosome A
7	MHK_2_Ttacu	horizontal hydraulic conductivity in Tesuque Lithosome ACU
8	MHK_2_Ttb	horizontal hydraulic conductivity in Tesuque Lithosome B
9	MHK_2_Tts	horizontal hydraulic conductivity in Tesuque Lithosome S
10	MHK_3	horizontal hydraulic conductivity in the Espinaso
11	MHK_4	horizontal hydraulic conductivity in the Madera
12	MHK_5	horizontal hydraulic conductivity in the Precambrian
13	MHK_6	horizontal hydraulic conductivity in the Galisteo
14	MHK_7	horizontal hydraulic conductivity in the Mancos
15	MHK_8	horizontal hydraulic conductivity in the Morrison
16	MHK_9_Alluv	horizontal hydraulic conductivity in the Alluvium
17	MHK_9_Ancha	horizontal hydraulic conductivity in the Ancha
18	MHK_10	horizontal hydraulic conductivity in the Triassic
19	MHK_11	horizontal hydraulic conductivity in the Permian
20	MHK_12	horizontal hydraulic conductivity in the Axial Gravel
21	MHK_13	horizontal hydraulic conductivity in the Intrusive
22	MHK_14	horizontal hydraulic conductivity in the Mesa Verde
23	MVANI	vertical anisotopy in all units
24	fault_18	fault conductance at northern portion of Las Barancas fault
25	fault_19	fault conductance at southern portion of Las Barancas fault
26	ghb_1	GHB conductance at Santa Clara Creek
27	ghb_2	GHB conductance at Santa Cruz River
28	ghb_3	GHB conductance at SE model boundary
29	ghb_6	GHB conductance at SW model boundary
30	ghb_7	GHB conductance at W model boundary
31	seg_1	stream conductance in Upper Rio Grande
32	seg_2	stream conductance in Upper Pojaque
33	seg_3	stream conductance in Rio Tesuque
34	seg_4	stream conductance in Lower Pojaque
35	seg_5	stream conductance in Middle Rio Grande
36	seg_6	stream conductance in Upper Sante Fe
37	seg_7	stream conductance in WWTP on Sante Fe
38	seg_8	stream conductance in Lower Sante Fe
39	seg_9	stream conductance in Lower Rio Grande
40	seg_10	stream conductance in Galisteo Creek
41	seg_11	stream conductance in Rio Grande at model exit

Table 9-1 Calibration Statistics for the Transient Model

Layer	Count	ME (ft)	MAE (ft)	RMSE (ft)	Range (ft)	RMSE/ Range
1-9	6,708	10.2	82.0	106.8	2,783	0.038

RMSE=Root Mean Square Error; ME=Mean Error; MAE=Mean Absolute Error

Table 9-2 Transient Model Flow Rates for Select Times in Comparison to the Steady State Model Flow Rates (ac-ft/yr)

IN (AFY)	Steady State	1956	1985	2004
Storage	NA	28,390	8,021	33,634
GHB	6,063	6,114	6,085	6,101
Recharge	40,083	16,059	61,180	22,047
Streams	2,482	3,048	3,003	3,000
Drains	178	118	101	91
Wells	NA	60	208	724
	48,806	53,789	78,600	65,597
OUT (AFY)	**Steady State**	**1956**	**1985**	**2004**
Storage	NA	130	15,709	8,672
ET	10,711	11,684	11,796	11,590
GHB	1,376	1,210	1,436	1,292
Streams	36,412	31,413	36,127	31,110
Drains	357	235	203	183
Wells	NA	8,652	12,861	11,678
	48,855	53,324	78,132	64,523

Table 9-3 Cumulative Flow Summary for the Transient Model from 1947 through 2004 (ac-ft)

Flow Component	Total Volume (ac-ft)
Storage In	762,505
Storage Out	(273,968)
Net Storage	488,537
Recharge In	2,379,026
Streams In	173,269
Streams Out	(1,931,957)
Net Streams	(1,758,688)
Drains In (Springs)	6,175
Drains Out (Springs)	(12,349)
Net Drains	(6,175)
Wells In	10,626
Wells Out	(683,493)
Net Wells	(672,867)
GHB In	353,629
GHB Out	(76,748)
Net GHB	276,881
ET Out	(681,448)
Sum Difference	25,266

Table 10-1 SFCM Results of Simulated Pumping at Each of the Four Potential Locations Identified during the DSS Suitability Analysis

Well	Impact to Springflow	Stream Depletion	Drawdown at Nearest Production Well
1	Negligible	-2 ac-ft/yr @ 40 yrs (Rio Grande)	Negligible
2	Negligible	Negligible	<1 foot @ 40 years (Buckman No. 13)
3	Negligible	-2 ac-ft/yr @ 40 yrs (Santa Fe River, Galisteo Creek)	<1 foot @ 40 years (Eldorado No. 1)
4	Negligible	-30 ac-ft/yr @ 40 yrs (Rio, Grande, Santa Fe River, Galisteo Creek)	Negligible