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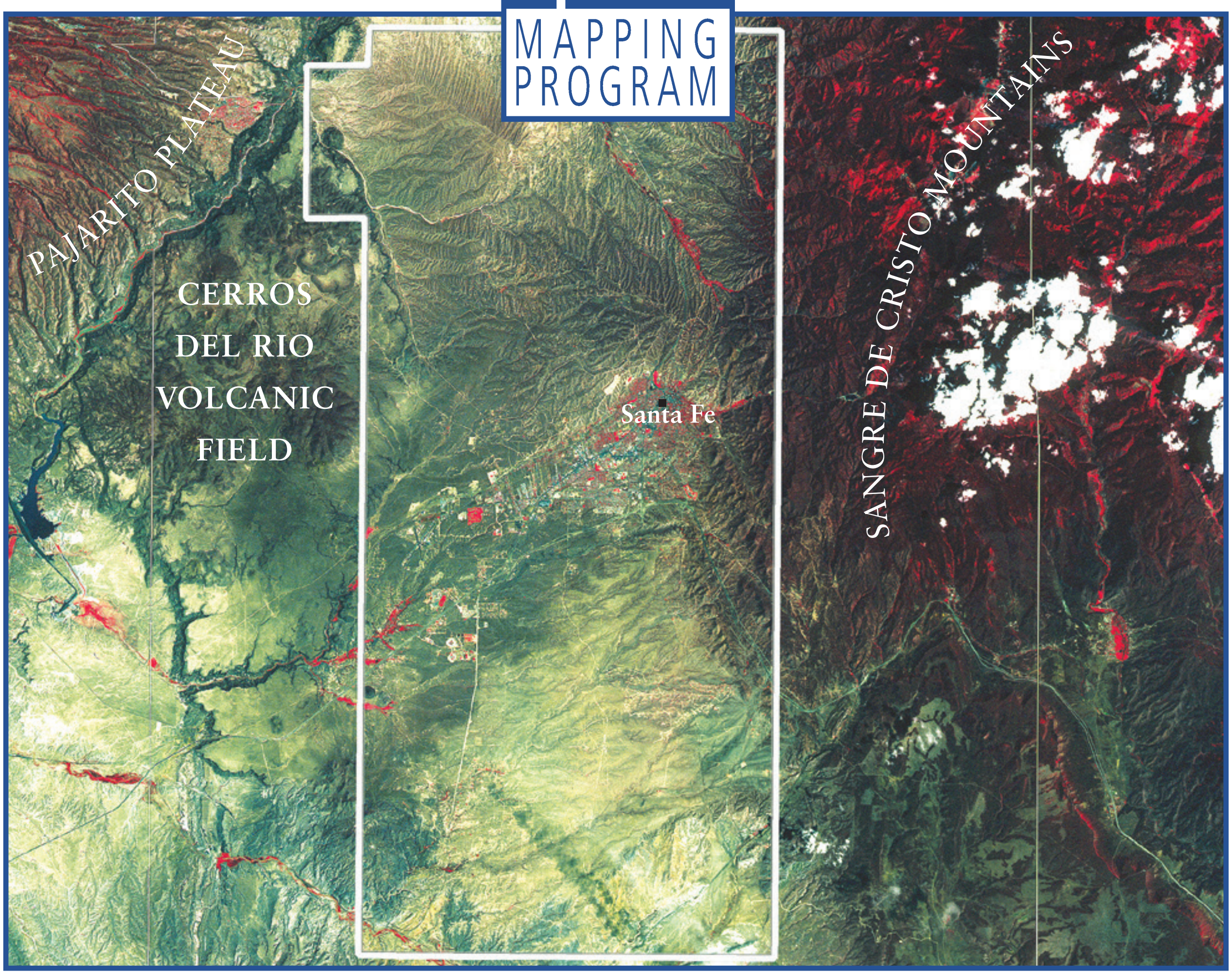
AQUIFER MAPPING PROGRAM



GEOCHEMICAL CHARACTERIZATION OF GROUND WATER IN THE SANTA FE REGION, NEW MEXICO

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EXECUTIVE SUMMARY

Chemistry and isotopic data from ground water and surface water in the southern Española Basin and Santa Fe embayment were compiled from existing sources, and supplemented with data obtained from new sampling events in 2005. Existing records from the City and County of Santa Fe, the New Mexico Office of the State Engineer (NMOSE), the New Mexico Environment Department (NMED), the U.S. Geological Survey (USGS), the Metropolitan Water Board, and libraries of private consultants provide baseline chemistry data spanning 50 years and over 300 locations. In 2005, ground water from 50 new sample locations was analyzed for major and minor ion and trace element chemistry (38 elements), oxygen-18 and deuterium, and field measurements of specific conductance, dissolved oxygen, pH and temperature. The data are derived from wells, streams and springs, including municipal, commercial, and private domestic wells, and the NMOSE multi-level piezometers. The large size and mixed origin of the data set present data quality challenges. Quality control filters provide a high degree of confidence in the precision of the data, but temporal inconsistencies are inherent in the data set.

Data analysis included mapping the spatial distribution of chemical parameters in relation to streams, hydrogeologic and structural features, geologic formations and hydrologic boundaries. Statistical correlation methods were applied to quantify chemical relationships. The approach is useful in evaluating basin-scale hydrologic processes, such as recharge sources, geologic controls on ground water flow, aquifer compartments, ground water flow patterns, areas of ground water mixing, and the degree to which ground water is stratified chemically and with respect to age.

A variety of ground water types occurs, with the most common being calcium-bicarbonate, sodium-bicarbonate, and mixed calcium-sodium water. Calcium-depleted, sodium-rich waters dominate the basin west of the Barrancos structure zone, near the Buckman well field, the Las Dos and Jacona fault systems, and in shallow discharge zones at La Cienega. Sodium-rich waters are dominant in deep ground water from the Tesuque and Espinaso Formations. Bicarbonate waters enriched with chloride and sulfate are associated with mountain-front bedrock aquifers, which also possess relatively elevated bromide and dissolved ion content. Concentrations of these chemical parameters decrease west from the mountain front. Ground water in the vicinity of the Santa Fe River and Arroyo Hondo has the lowest concentration of TDS and major ions, reflecting the influence of channel infiltration and recharge. Elevated chloride and chloride-to-bromide ratios in shallow wells beneath urban areas of Santa Fe are consistent with anthropogenic sources. Changes in the distribution of some chemical ions (barium and magnesium) across the San Isidro fault are consistent with hydrologic data that suggest the fault is an impediment to horizontal ground water movement. An area of elevated arsenic, with concentrations ranging from 7 to 54 µg/L, occurs west of Santa Fe in warm, sodium-rich waters. Elevated arsenic concentrations conjunct with basement structures including the northern axis of the basin syncline, the Santa Fe flexure, and a graben formed west of El Dorado in the Santa Fe platform by a southern extension

of the San Isidro Crossing fault. Concentrations of arsenic exceeding 10 µg/L are independent of well depth and are observed across the upper 1700 feet of saturated aquifer.

Stable isotope ($^{2}H/H$ and $^{18}O/^{16}O$) data identify the occurrence of paleo ground water at depths below about 400 feet below the water table in the Buckman well field, in wells at Horcado Ranch and Las Dos, and in multi-level piezometers in the western half of the basin.

Geochemical, hydrologic, geologic and geophysical data are used to refine a conceptual model of ground water flow, evaluate sources of water and aquifer compartmentalization, and delineate aquifer domains. The ground water domains are based on hydrologic attributes such as aquifer thickness, permeability of aquifer material, and magnitude and direction of horizontal and vertical hydraulic gradient; spatial distribution of geochemical and physical parameters in ground water; and geologic features such as faults, stratigraphic contacts, bedrock basement structure, and subsurface distribution of Oligocene volcanic rocks, which appear to influence both flow and geochemical characteristics of the aquifer. Six aquifer domains are defined: the mountain block, the mountain front, the Barrancos structure, the Santa Fe platform, the Santa Fe flexure, and the central basin. The ground water domains exhibit unique flow and chemical characteristics.

INTRODUCTION

Background

The Santa Fe area in the southern Española Basin of central New Mexico has been the focus of several multi-year hydrogeologic studies by the New Mexico Office of the State Engineer (NMOSE), the New Mexico Bureau of Geology and Mineral Resources (NMBGMR), the U. S. Geological Survey (USGS) and other agencies to improve understanding of the water resources in the basin. Ground water from basin-fill deposits provides domestic drinking water for most of the area's population. Declines in water levels, well production, and perennial stream and spring flow, combined with a steadily increasing demand, have stimulated an effort to gain new information about the region's basin-fill and bedrock aquifers. This document describes the results of a geochemical study of ground water in the southern Española Basin in Santa Fe County based on a large, geographically broad data set that combines existing data with new sample collection from water wells.

Previous Work

Previous water quality studies in Santa Fe County have largely been reconnaissance in nature, relying on conductivity as a gross measure of general water quality (Lewis and West, 1995; Lewis, 1994), or have been limited in geographic extent (Longmire, 1985). Anderholm (1994) conducted the first study of recharge in the Santa Fe area based on the chloride and stable-isotope composition of potential recharge and ground water, and developed a meteoric water line from local precipitation that is used in this report to frame interpretations of oxygen-18 and deuterium data. Manning et al. (2005, 2006) provided the first basin-scale evaluation of recharge and residence time of ground water near Santa Fe based on a limited number of samples. Many professional consultants and researchers for state agencies have worked in the area over the past 50 years and the multitude of unpublished professional reports produced as a result of this work provided much of the data for this study.

Previous investigations in the Albuquerque ground water basin (Plummer et al., 2004) and other Southwest arid alluvial basins (for example, Robertson, 1991; Thomas et al., 1996) have demonstrated the worth of using chemical and isotopic information from ground water to decipher complex, basin-scale hydrologic processes. Specifically, the distribution of major-, minor-, and trace-element chemistry can help delineate the spatial extent of waters of similar composition and flow history. Physical parameters such as temperature and dissolved oxygen concentration can help differentiate between recent recharge and ground water with deeper circulation, and presumably older residence times. Stable isotopes of oxygen and hydrogen can be used to identify different sources of water recharged under distinct climatic conditions. Using these chemical and isotopic constituents in combination with other hydrologic and geologic information can provide an accurate conceptual model of the movement of ground water through a complex aquifer system.

Purpose and Scope

This study compiles select chemical and isotopic data for ground water and surface water from existing sources and supplements the historical data set with the collection of additional water samples and analyses. Specific objectives of this study are to: (1) characterize the chemical composition of ground water in the various aquifers found in and contiguous to the southern Española Basin; (2) identify separate sources of recharge to the basin aquifer system; (3) delineate ground water flow paths, aquifer compartments, and areas of mixing; (4) qualify the degree to which water in the aquifer system is stratified chemically and with respect to age; and (5) characterize the chemical composition of discharge from the aquifer system to streams. This document describes all the data, new and previously existing, used in the study, the methods of data collection and analysis, the geologic and hydrologic setting, and the distribution of the major chemical parameters. A conceptual model of ground water occurrence and movement is developed through integration of geologic, hydrologic and geochemical data depicted in maps and hydrogeologic cross sections.

Description of Study Area

The southern Española Basin (SEB) study area generally includes the area from the base of the Sangre de Cristo Mountains west to the Rio Grande in White Rock Canyon, and from Galisteo Creek north to the Rio Pojoaque. The study area encompasses the major portion of eight 7.5-minute quadrangles (Figure 1), covers 440 square miles, and includes the City of Santa Fe, the surrounding villages of Tesuque, Agua Fria, El Dorado, and La Cienega, all or part of the Pueblos of Tesuque, Nambe, Pojoaque, and San Ildefonso, and numerous rural developments in Santa Fe County. Important geographic features, described in more detail below, include the Caja del Rio Plateau to the northwest, the Jacona and Santa Fe Uplands north and northwest of Santa Fe, and the Santa Fe embayment south of the city.

A number of streams and arroyos drain the western slope of the Sangre de Cristo Mountains, flow west across the study area, and eventually discharge into the Rio Grande (Figures 2 and 3). The Rio Grande, the main drainage in the Española Basin, flows south from the San Juan Mountains of southern Colorado through the basins of the Rio Grande rift (Figure 2). Ground water and streams in the study area generally discharge to the Rio Grande. The Santa Fe River, a tributary to the Rio Grande, is an important third-order stream in the study area. Several second- and lower-order streams and arroyos carry surface runoff and/or baseflow to the Santa Fe River, including (from north to south) Arroyo Calabasas, Arroyo de los Chamisos, Arroyo Hondo, Cienega Creek, and Bonanza Creek. The Cañada Ancha carries surface runoff through Buckman and into the Rio Grande from the Santa Fe and Jacona Uplands and part of the Caja del Rio Plateau (the landform associated with the Cerros del Rio volcanic field). The Rio Pojoaque and the Rio Tesuque drain the northern margin of the study area and Galisteo Creek and its tributaries, Gallina Arroyo and San Marcos Arroyo, drain the southern margin of the study area.

Project Personnel and Funding

Project Personnel

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METHODOLOGY

Compilation of Existing Data

The chemical data used in this investigation include both historical data – compiled from existing public and private databases, libraries and compilations – as well as new data collected by the NMBGMR for this study. Element chemistry data for 280 ground water and surface water sites were compiled from the Jemez y Sangre Water Planning Council database, the USGS National Water Information System (NWIS) database, New Mexico Environment Department (NMED) Petroleum Storage Tank, Solid Waste, and Drinking Water Bureaus, City of Santa Fe, County of Santa Fe, historical Metropolitan Water Board reports, and libraries of private consultants and water users. Stable isotope data totalling 103 ground water and surface water locations were compiled from Anderholm (1994) and from samples collected by the NMOSE in 2004.

The compiled chemistry data were reviewed and filtered for data quality and data gaps. This filtering was necessary because historical compilation resulted in a large and mixed geochemistry data set, with many locations having incomplete element analyses or, in some cases, having multiple sample events. Significant data quality and data management issues were associated with the historical portion of the data compilation. Historical data were compiled from original reports and laboratory sheets as well as previous compilations by other researchers. Data originating directly from technical reports and records of the analyzing laboratory met the highest data quality standards. Caution was used with data originating from tabular or electronic database compilations generated by intermediate parties or agencies where the potential existed for introduced error. Where either the spatial or chemical accuracy of the data could not be verified, the data were either omitted from the compilation or marked as being inadequate for use in final interpretations. Spatial reliability required a verifiable map location or geographical coordinates and chemical reliability was screened using ion balance criteria or statistical outlier analysis.

New Data Collection

Additional ground water samples were collected from 50 well sites across the basin between March and June 2005. Four additional samples from the Las Campanas well (Figure 4, NMOSE piezometer H) and a private well in the Santa Fe highlands were collected in 2006. The new sample sites were selected primarily on the basis of location in an attempt to extend the existing data set and attain the best possible coverage across the basin, in representative hydrostratigraphic units, and with depth in the Tesuque aquifer system. A priority was placed on sampling wells with discrete sampling intervals corresponding to a range of aquifer depths, most importantly the multilevel, triple-completion piezometers under administration of the NMOSE.

The full data set for major element chemistry (Figure 4) contains 242 sample sites consisting of 236 ground water wells and 6 surface water sites. The full data set for stable isotope chemistry (Figure 5) contains 154 sample locations consisting of 142 ground water wells and 12 surface water sites. Well depths range from 35 to 2495 feet with a median of 510 feet.

Surface water sites with major element chemistry (Figure 4) include the Santa Fe River, San Marcos Creek, Bonanza Creek, Sunrise Spring, Las Lagunitas, and the effluent stream from the City of Santa Fe wastewater treatment plant in the channel of the Santa Fe River. Surface water sites with stable isotope chemistry (Figure 5) include the Rio Grande at Otowi Bridge, the Santa Fe River, Rio Tesuque, Little Tesuque Creek, Tesuque Creek, Rio Chupadero, Pojoaque River, and Arroyo Hondo. Some shallow well sites located immediately up-gradient of perennial surface water features are used as a proxy for ground water discharge – for example, EB-342 reflects discharge into San Marcos Arroyo and EB-315 reflects discharge into ponds and springs near La Cienega Creek (Figures 4 and 5).

Ground water sites and data are summarized in Appendix A. Surface water sites and data are summarized in Appendix B. Each entry is associated with a unique site identification number of the form "EB-###", which identifies a unique location in the Española Basin water database. The database is accessed from the attached CD-ROM.

Sample Collection Methods and Laboratory Analysis

Ground water samples collected between March and June 2005 originated from a variety of sites, including in-service domestic, commercial, and utility wells with permanently installed submersible pumps and monitoring wells with portable sample pumps. Wells were normally purged of up to three casing volumes before sampling, except for the deep completion monitoring wells, which were purged of at least one casing volume. Samples were collected in appropriate containers following stabilization of the field parameters water temperature, pH, specific conductance, and dissolved oxygen. The containers were rinsed three times with water before filling. Samples for ion and element chemistry were not filtered and acidified in the field, but were cooled and transported to the NMBG&MR water quality laboratory for analysis within 24-36 hours of sample collection, processed in the lab through a 0.45-micron filter and analyzed using various instruments.

Major anions were measured by ion chromatograph. Major cations were measured by flame AA (atomic absorption) for samples collected in 2005, and by ICP-OES (optical emission spectrometry) for samples collected in 2006. Trace metals were measured using an inductively coupled plasma instrument with a mass spectrometer detector (ICP-MS). Titration alkalinity was determined within 36 hours of sample collection in the field. Stable isotope samples were collected in 30 ml Qorpak bottles with inverted cone lids and analyzed by accelerator mass spectrometry at the New Mexico Tech, Department of Earth and Environmental Sciences, stable isotope laboratory. One duplicate field sample was collected for every 20 standard samples to provide replicate analyses for ion, trace and stable isotope chemistry. An ion balance was performed on major and minor ion concentrations and results were within plus or minus 5 percent relative difference. Analytical variability for $\delta^{18}O$ and $\delta^{2}H$ was evaluated by determining standard deviations of duplicate analyses for water samples collected from the same well. For the 50 samples analyzed in 2005, the standard deviation was 0.06 per mil for $\delta^{18}O$ (based on a sample size of 10) and 0.24 per mil for $\delta^{2}H$ (based on a sample size of 8).

Data Interpretation

The nature and distribution of chemical and isotopic constituents are illustrated and interpreted through the use of Piper and Schoeller plots, Stiff diagrams, scatter plots, concentration contour maps and correlation statistics. Chemical data are evaluated by formation and aquifer of origin. The distribution of chemical constituents is interpreted in the context of the geologic formations, geologic structures and hydrologic features that form the framework of the basin's surface water and ground water systems.

PHYSICAL, GEOLOGIC AND HYDROLOGIC SETTING

The Española Basin, one of a series of interconnected basins in the Rio Grande rift, extends roughly 25 miles north-to-south by 37 miles east-to-west. The Española Basin adjoins the San Luis Basin to the north and the Santo Domingo Basin to the south (Figure 2). The northern boundary with the San Luis Basin is generally considered to extend from the Precambrian-cored Picuris Mountains northwest to Precambrian exposures near Ojo Caliente. The Sangre de Cristo Mountains, a Precambrian uplift, forms the east boundary of the basin. The southwestern boundary adjoining the Santo Domingo Basin is defined by the Cerrillos uplift and the La Bajada fault (Minor 2006); the surface expressions of these geologic features are the Cerrillos Hills and the La Bajada escarpment. The west boundary of the modern basin corresponds in part with the Pajarito fault near Los Alamos, which lies at the base of the Jemez Mountains and the western edge of the Pajarito Plateau. The western margin of the basin wraps around the northern Jemez Mountains to include the Abiquiu embayment (Figure 2).

The southern part of the Espanola Basin extends into the Santa Fe embayment, a west-sloping topographic low nestled between the southernmost Sangre de Cristo Mountains on the east and the Cerrillos Hills and Caja del Rio Plateau on the west. The Santa Fe uplands, immediately north of the Santa Fe River, constitute the northern margin of the embayment. The north rim of the Rio Galisteo valley defines the south boundary of the Santa Fe embayment. Under the Santa Fe embayment (a topographic feature) are two structural domains, the Santa Fe platform and the Santa Fe flexure, which are discussed in the next section.

This study focuses on the southern Española Basin (SEB) and the Santa Fe embayment. Accordingly, it covers the area between the Sangre de Cristo Mountains and White Rock Canyon of the Rio Grande, and from Galisteo Creek north through the Santa Fe uplands to the southern boundary of tribal lands in the Tesuque and Pojoaque valleys (Figure 3).

Stratigraphic Setting

Sedimentary basin-fill and interbedded volcanic rocks that filled the Rio Grande rift during and after its formation are called the Santa Fe Group, following Spiegel and Baldwin (1963, p. 39). In the Santa Fe area, the Oligocene-Miocene Tesuque Formation forms the bulk of the Santa Fe Group and consists of several hundred to several thousand feet of pinkish-tan, arkosic, silty sandstone and sandstone, with minor conglomerate, siltstone and claystone (Spiegel and Baldwin 1963; Read et al. 2000; Koning and Maldonaldo 2001; Koning et al. 2004; Koning et al. 2007a; Biehler et al. 1991). Distribution of the Tesuque Formation is shown on the generalized geologic map of Figure 6. Preserved Tesuque Formation strata were deposited between 30 and 5 million years ago in alluvial slope and adjoining basin-floor depositional environments while the Rio Grande rift was forming (Koning 2003; Koning et al. 2007a; Koning et al. 2007b; Cavazza 1986; Smith 2000; Kuhle and Smith 2001; Smith 2004). The Tesuque Formation has been subdivided into five primary map units (called lithosomes) on the basis of sedimentologic criteria that correspond to depositional facies of contributing drainage systems (Koning 2003; Koning et al. 2004; Koning and Johnson 2006; Koning et al. 2007a; Koning et al. 2007b; Cavazza 1986). Recognition and mapping of these units are based on physical criteria such as texture, composition, and other sediment characteristics (Figure 7 and Table 1). Some characteristics, such as gross grain size, relate to hydrologic properties that may contrast between the lithosomes.

Lithosome E. Lithosome E lies on the southeast side of the embayment and consists of volcaniclastic sediment (mostly clayey-silty sand) eroded from the Cerrillos uplift to the south-southwest. Lithosome E interfingers to the east-northeast with two fluvial units, lithosome S and lithosome A, derived from the southern Sangre de Cristo Mountains.

Lithosome S. Lithosome S was deposited by a west-flowing, ancestral Santa Fe River sourced in the present-day Pecos River drainage. Being the largest drainage exiting the Sangre de Cristo Mountains, the ancestral Santa Fe River probably formed an alluvial fan near Santa Fe (D. Koning, written communication, 2008). Lithosome S is relatively coarse (mostly a pebbly sand) along the fan axis near the present course of the Santa Fe River, but becomes increasingly finer-grained to the north, west, and south. Near the Santa Fe airport, lithosome S exhibits a thick interval of clay and sandy clay (possibly as much as 500 ft-thick) probably deposited in shallow lakes or ponds on the floodplain of the ancestral Santa Fe River.

Lithosome A. Lithosome S grades north and south into alluvial-slope deposits derived from the western flanks of the Sangre de Cristo Mountains. Called lithosome A, these alluvial-slope deposits consist of silty arkosic sand and minor pebbly sand channel-fills, where the clasts are predominately granitic. Over time the alluvial slope streams began to carry and deposit coarser material (Koning 2003; Koning and Maldonaldo 2001; Koning et al. 2005; Koning et al. 2007). These upper coarse deposits are referred to as the Cuarteles Member of the Tesuque Formation by Koning et al. (2005) and Koning and Aby (2005). Lithosome A grades eastward into fine-grained basin-floor deposits of lithosome B. Table 1 gives more detail on the characteristics of these lithosomes.

Ancha Formation. Tilted and faulted beds of the Tesuque Formation are beveled by a Pliocene erosional surface. This unconformity is overlain by a sand and gravel blanket of Pliocene-Pleistocene Ancha Formation (Spiegel and Baldwin 1963), which is somewhat coarser and less consolidated than underlying Tesuque sediments. When redefining the Ancha Formation, Koning et al. (2002) documented a predominance of silty and clayey sand in the southwestern Santa Fe embayment and an increasing proportion of gravel beds eastward towards the Sangre de Cristo Mountains. The Ancha Formation can locally reach thicknesses of 250 to 300 feet near the center of the Santa Fe embayment, but elsewhere is observed to be 200 to 250 feet thick or less. Saturated portions of the Tesuque and Ancha Formations (Figure 6) comprise the Tesuque aquifer system (also known as the Santa Fe Group aquifer), which is the primary aquifer in the Española Basin, and the focus of this study.

Aquifer test data compiled for various stratigraphic units indicate statistical correlation between hydrologic properties and some lithostratigraphic units (Koning and Johnson 2006). Furthermore, evaluation of geochemical data as a function of Tesuque Formation lithosome and other formations indicates that there is some correlation between dissolved ion content and geologic unit. The Precambrian crystalline rocks, the Espinaso Formation, certain lithosomes within the Tesuque Formation, and the Ancha Formation generally possess unique ion contents and concentrations relative to adjacent formations and units. Exceptions exist, however, as the distribution of geochemical facies and regional ground water flow patterns are complexly controlled by multiple factors.

Structural Setting and Thickness Variations in Santa Fe Group Strata

The southern Española Basin was created by crustal extension and subsidence associated with formation of the Rio Grande rift. Important geologic and hydrogeologic features in the southern Española Basin are illustrated in Figure 3 and a generalized geologic map is shown in Figure 6. Interpretations of aeromagnetic (Grauch and Bankey 2003), seismic (Black 1984) and gravity (Cordell 1979; Biehler et al. 1991; Ferguson et al. 1995) data define the general structure under the Santa Fe embayment as a north-plunging syncline. West of the Santa Fe uplands the syncline loses its definition as its west limb wraps around the north end of the Cerrillos uplift. North of the Santa Fe River, the basin geometry is that of a west-tilted half graben (Biehler et al. 1991). The west-sloping front of the Sangre de Cristo Mountains is a surface expression of the half-graben (to the north) and the east limb of the syncline (to the south).

The Sangre de Cristo Mountains, which form the eastern boundary of the basin, range in elevation from 7,000 to more than 13,000 feet and serve as the major recharge source for the Tesuque aquifer system in the southern Española Basin. This mountain block consists of Proterozoic granites and associated crystalline rocks, locally overlain by thin Pennsylvanian sedimentary strata, which possess secondary, fracture permeability that is locally enhanced by faulting.

Under the Santa Fe embayment is a prominent north-down, arcuate flexure (monocline) of strata called the Rancho Viejo hinge zone, across which the thickness of Santa Fe Group strata changes (Figure 3). Less subsidence has occurred south of this flexure and the Santa Fe Group is relatively thin here, compared to the north, where the thickness increases rapidly to 2000 feet beneath south Santa Fe and to an estimated 7000 ft or more at Buckman. These observations have lead to the name "Santa Fe platform" for the structurally high region at the southern end of the Santa Fe embayment. The bedrock floor of the Santa Fe platform has been deformed by folding and local faulting. Geologic mapping north of Galisteo Creek identifies three unnamed, north-northwest-striking faults and the northeast-striking Tijeras-Cañoncito fault that collectively deform the southern edge of the Santa Fe embayment between the Cerrillos Hills and Lamy (Lisenbee 1999; Read and Koning, 2004, section E-E'). Locations of these faults in the subsurface are inferred from gravity and aeromagnetic data of Grauch and Hudson (2007). One of the northwest-striking faults appears to connect with the San Isidro Crossing fault to the north, based on aeromagnetic data (Figure 3). These faults produce west-tilted fault blocks of lower Tertiary and older strata, with relative offsets up to 1,000 feet, that plunge northward with the east limb of the embayment syncline.

The southwestern boundary of the Española Basin, formed by the La Bajada fault and Cerrillos uplift (Minor 2006), is structurally complex. The Cerrillos uplift is a north-trending structural high that may have formed, in part, by footwall uplift along the La Bajada fault (Koning et al. 2006; Hudson et al. 2006). This structural feature consists of Mesozoic sedimentary rocks and the Eocene-age Galisteo Formation, which together host Eocene-Oligocene-age intrusions, and the overlying Eocene(?)-Oligocene-age Espinaso Formation. The uplift is primarily a buried structure defined by geophysical data and overlain by Tertiary lavas associated with the Cerros del Rio volcanic field (Minor 2006). Topographic expression of the uplift occurs at its southern end where the Cerrillos Hills and Ortiz Mountains are formed by resistant Eocene-Oligocene intrusive rocks.

Strata have been tilted during subsidence of the southern Espanola Basin. In both the half graben and on the east limb of the syncline, bedding in the Tesuque Formation dips westward from the base of the Sangre de Cristo Mountains with magnitudes of 10 to 13 degrees common in stratigraphically lower, eastern strata, and 1 to 8 degrees in stratigraphically higher, western strata (Read and Koning, 2004; D. Koning, written communication, 2007). Bedding flattens near the Canada Ancha, but on the eastern flanks of the Cerrillos Uplift, approximately south of the Santa Fe River, beds dip eastward towards the axis of the syncline under the Santa Fe embayment. The dipping strata of the Tesuque Formation create aquifer anisotropy, such that the greatest hydraulic conductivity occurs in a north-south direction, parallel to bedding. This anisotropy manifests more dramatically in the highest dip domains of older strata along the mountain front, which can reach 30 degrees in places.

The major faults that offset and deform the Tesuque Formation within the southern Española Basin include the San Isidro Crossing fault and the Las Dos and Jacona fault systems (Figures 3 and 6). The deformation zones of these faults, where exposed, typically exhibit clay-rich cores, deformation bands, cataclasite zones, strong cementation and few fractures (Caine et al. 2007; J. Sigda, written communication, 2004), features which have been shown to reduce permeability and create barriers or partial barriers to flow (Rawling et al. 2001; Minor and Hudson 2006). The influence of these faults on regional ground water flow patterns is discussed in more detail in a subsequent section titled "Ground Water Flow System".

The thickness of the Santa Fe Group basin-fill is obtained from estimating the depths of denser and more magnetic Oligocene volcanic rocks, which underlie the Tesuque and Ancha Formations over most of the study area (Grauch and Bankey 2003). Aeromagnetic interpretations indicate the Oligocene volcanic rocks are shallow (less than 250 feet) beneath the Ancha Formation on the Santa Fe platform under the southern end of the Santa Fe embayment (Figure 3). There, the upper surface of the Oligocene volcanic rocks is faulted and irregular, with isolated depressions that can be up to a mile wide and 800 feet deep, likely filled with Santa Fe Group sediments (Grauch and Bankey 2003; Koning and Johnson 2006). The volcanic rocks dip northward into the basin as a broad, asymmetric, plunging syncline, forming the base of the Tesuque Formation. The hinge line of the plunge forms an arcuate margin around the south side of Santa Fe, as the fold drops by 3000 feet in little more than 2 miles near La Cieneguilla and by 2000 feet in less than 2 miles northwest of El Dorado, before flattening as it enters the deepest part of the basin south of Buckman. Santa Fe Group thicknesses range from 2000 to 4000 feet west of Santa Fe to more than 7000 feet south of Buckman (Grauch and Bankey 2003). The upper Oligocene volcanic surface rises abruptly along the front of the Sangre de Cristo Mountains, causing the Tesuque Formation to thin to less than 2000 feet beneath the center of Santa Fe. Two north-south elongated basement highs, topped by Oligocene volcanic rocks, lie northwest of Santa Fe, causing the Santa Fe Group to thin to less than 2000 feet locally (Grauch and Bankey 2003, Fig. 7). The syncline flexure and Oligocene bedrock highs correlate with many geochemical and ground water flow anomalies in the shallow Tesuque aquifer system, which are discussed in later sections.

Surface Water Drainages, the Rio Grande and Tributaries

The Rio Grande is the main surface water drainage in central New Mexico (Figures 2 and 3). A number of streams and arroyos drain the western slope of the Sangre de Cristo Mountains and the southern Española Basin before discharging into the Rio Grande. Eight drainage basins and sub-basins were delineated for this study area (Figure 8) including, from north to south, the Tesuque-Pojoaque, Cañada Ancha, Caja del Rio, the Santa Fe River, Cienega (including Cienega Creek and Arroyo Hondo), Bonanza Creek, north Gallisteo Creek (Gallina and San Marcos Arroyos), and south Gallisteo Creek (mainstem of Gallisteo Creek). Drainage divides were created using a 10-meter digital elevation model (DEM) and flow-direction and watershed rasters generated by ARCINFO 9.2 spatial analyst watershed tools. The Rio Pojoaque and the Rio Tesuque drain the northern margin of the study area. Galisteo Creek and its tributaries, Gallina Arroyo and San Marcos Arroyo, drain the southern margin. The Cañada Ancha drains the Santa Fe uplands and the eastern edge of the Caja del Rio Plateau (the landform associated with the Cerros del Rio volcanic field), carrying runoff through Buckman and into the Rio Grande. The central and western parts of the Caja del Rio Plateau drain directly into the Rio Grande in White Rock Canyon. The Santa Fe River watershed is divided into its three sub-basins: the main stem of Santa Fe River, Cienega Creek and Bonanza Creek.

A water supply study for the Jemez y Sangre water planning council (Duke Engineering & Services 2001) divided the planning region into 10 watersheds and sub-basins and developed surface water budgets for each. The Jemez y Sangre study assumed continuity of surface water and ground water divides, but the two hydrologic boundaries are not always coincident. The congruency of surface and ground water divides is generally true for some sub-basin boundaries, including the southern boundary of the Tesuque watershed and the boundary between the Santa Fe River and Arroyo Hondo. However, the southernmost ground water divide (between the Espanola and Galisteo Basins) does not coincide with the surface water divide between the Bonanza Creek sub-basin of the Santa Fe River drainage and North Galisteo Creek.

Most stream courses are ephemeral. Perennial reaches are confined to portions of the Rio Tesuque, the Santa Fe River, and the lower reaches of Arroyo Hondo and Cienega Creek. Anecdotal evidence and historical observations indicate that the Santa Fe River used to be perennial from its upper watershed through the historic village before channel losses and infiltration into underlying Tesuque Formation diminished flow (Scurlock 1998; Spiegel and Baldwin 1963). Partial ground water barriers created by the San Isidro Crossing fault upstream of Agua Fria and by intrusive igneous and other lower Tertiary (pre-Santa Fe Group) rocks at Cieneguilla caused springs to appear that sustained flow for some distance, but the channel often went dry between these reaches (Scurlock 1998; Spiegel and Baldwin 1963). Flow patterns have changed in the Santa Fe River as a result of construction of upstream reservoirs, well-field depletions, and, beginning in 1984, discharge of treated effluent from the Santa Fe waste water treatment plant (WWTP in Figure 3 and subsequent figures) (Longmire 1985). Today the river is perennial above Nichols Reservoir and below the Santa Fe wastewater treatment plant. Studies have concluded that the modern Santa Fe River is primarily a losing stream downstream of the mountain front (Anderholm 1994; Thomas et al. 2000; DBS&A 2002). The only drainage conveying perennial baseflow to the Santa Fe River is lower Cienega Creek. Several smaller streams and arroyos deliver surface runoff, including Arroyo Calabasas, Arroyo de los Chamisos, Arroyo Hondo, Bonanza Creek, and Alamo Creek.

Several previous investigations addressing the connection between ground water and surface water (Anderholm 1994; Thomas et al. 2000; DBS&A 2002; Moore 2004) have concluded that infiltration through the primary stream and arroyo channels – specifically the Santa Fe River, the Rio Tesuque, and Arroyo Hondo – is a significant source of recharge to the Tesuque aquifer system. Water level and geochemical data suggest that infiltration through smaller drainages, including Cañada Ancha, Arroyo Calabasas, upper Cienega Creek, Gallina Arroyo, Bonanza Creek and San Marcos Arroyo may also locally recharge the shallow aquifer system.

Ground Water Flow System

Hydrostratigraphic Units. The shallow regional aquifer in the greater Santa Fe area occurs primarily within the Santa Fe Group sediments, specifically the Ancha and Tesuque Formations. Depth to ground water in the regional aquifer varies from less than 20 to more than 500 feet (Figure 9). Shallow water levels are encountered beneath drainages at the mountain front, in the canyon of the Santa Fe River below Cieneguilla, and in the lower reaches of Cienega and Bonanza Creeks and Gallina and San Marcos Arroyos. The greatest depth to water occurs below the Santa Fe and Jacona uplands and the Cerros del Rio plateau. The Tesuque Formation has from a few hundred to several thousand feet of saturated thickness in silty-clayey sands, sands, gravels, silts and clays of moderate to low permeability. The overlying Ancha Formation is somewhat coarser, less consolidated, and more permeable. The lower Ancha Formation is saturated throughout much of the Santa Fe embayment from south of the Santa Fe River to roughly Gallina Arroyo, but lies above the water table north of the Santa Fe River and is variably saturated south of Gallina Arroyo. Spiegel and Baldwin (1963) first proposed that differences in permeability between the Ancha and pre-Ancha Formations (Figure 7), together with topography on the "bedrock" surface below the Ancha, control the storage of ground water and accretion of saturated thickness within the Ancha aquifer. A periodic source of recharge is also required to maintain saturation of the Ancha aquifer.

Secondary, low permeability, bedrock aquifers occur in older Tertiary formations, including the Espinaso and Galisteo Formations as well as older Mesozoic and Paleozoic strata. These geologic units are accessible via wells drilled through the Ancha and Tesuque Formations near the perimeter of the Santa Fe embayment, where they commonly serve as the only water-bearing strata available for domestic development. Neither the Espinaso nor the Galisteo Formations produce high well yields, but they do provide the only accessible aquifer in parts of the Santa Fe embayment south of Gallina Arroyo. The Galisteo Formation, which stratigraphically underlies the Espinaso, is relatively more productive in its upper section (Finch, 2007). Paleozoic and Mesozoic rocks provide limited aquifer potential for areas on the eastern and southeastern margins of the embayment. In the El Dorado area, where a horst of locally fractured Paleozoic limestone and shale is penetrated by wells belonging to El Dorado Utilities, the highest yield well produced a transmissivity of 14,000 to 17,000 gallons per day per foot when tested (Tim Decker, written communication, February 25, 2000). Other Mesozoic sedimentary units have little to no aquifer potential.

The Proterozoic granites and associated rocks of the Sangre de Cristo mountain block, which for the purposes of this study are undifferentiated and termed "Proterozoic crystalline rocks", host disconnected fractured aquifers with considerable variability in permeability and porosity. Mountain-front structures such as the Santa Fe River fault and the Aztec Springs syncline (Figure 3) have been identified as target aquifers (Paul Bauer, written communication, July 10, 1977) and are believed to facilitate mountain block recharge through the Santa Fe River canyon. Extensive breccia zones within the Proterozoic granites south and west of interstate 25 are commonly associated with locally productive wells along the mountain front. The Tijeras-Cañoncito fault is a major regional structure associated with a significant fracture zone. Other mountain-front faults, such as the Hondo, Seton Village and minor unnamed faults, are hydrologically significant in that they may enhance local permeability through fracturing, reduce permeability through grain size reduction and cementation, or interrupt hydraulic continuity between offset hydrostratigraphic units, depending on local conditions.

Horizontal hydraulic gradients. Horizontal ground water flow in the Tesuque aquifer system is primarily east to west (Figure 9), with local aberrations caused by the Buckman and Santa Fe well fields. Horizontal hydraulic gradients vary from roughly 100 to 200 feet per mile, to as much as 400 to 600 feet per mile and as little as 15 feet per mile. Factors controlling the shape of the water table and magnitude of the gradient are topography, permeability distribution, and the structure, geometry and thickness of the basin fill and underlying pre-Santa Fe Group bedrock. Steep hydraulic gradients across the San Isidro Crossing fault, the crystalline bedrock in the Sangre de Cristo Mountains and a north-trending zone west of the Archery well (Figure 4, NMOSE piezometer C) indicate zones of low permeability. In the case of faults, such as the San Isidro Crossing fault, barriers and partial barriers to horizontal ground water flow exist. Relatively large gradients in the Tesuque Formation along the mountain front, particularly east of Tesuque, reflect low horizontal hydraulic conductivity associated with steeply dipping beds (up to 30 degrees) of older, consolidated Santa Fe Group strata. The steep hydraulic gradient east of the Santa Fe well field occurs where well drawdown is amplified due to thinning Tesuque Formation and adjacent low permeability rocks of the mountain block.

Diminished hydraulic gradients and a flat, shallow water table dominate the basin west of Agua Fria and the San Isidro Crossing fault. Here, the local relief and regional topography have little influence on the water table. We interpret these observations to reflect the relatively high transmissivity of a thick sequence of coarse-grained lithosome S (Tesuque Formation) (Figure 7, Table 1) along the central axis of the Miocene-age Santa Fe River alluvial fan. Recharge through the channel of the Santa Fe River is indicated by a large water table mound between Agua Fria and Cieneguilla. Geochemical data further indicate upwelling of a deep circulation system west of Agua Fria, which may also contribute to flattening of the water table (discussed in later sections).

Vertical hydraulic gradients. Seven new multilevel piezometers installed by NMOSE and USGS from 2003 to 2006 provide depth-specific water level measurements and, when combined with limited, provisional data from paired domestic wells at different depths (Table 2), provide information on vertical hydraulic gradients in the upper 2400 feet of the Tesuque Formation and between the Tesuque Formation and overlying and underlying geologic units (Figures 4 and 9). The data set provides a foundation for defining gradient domains in the southern Española Basin and illustrates both the dimensionality of ground water flow and some insight into possible geologic controls.

Vertically downward gradients consistently prevail along the mountain front south of Arroyo Hondo and in the Tesuque river valley, a condition consistent with mountain-front recharge. However, a strong upward gradient measured in SF-1 (Figure 4, piezometer A) and the Hickox wells (Figure 4, EB-123) occurs near the mountain front between the Santa Fe River and Arroyo Hondo. The upward gradient is anomalous at the mountain front and is perhaps caused by two flow barriers to the west – the San Isidro Crossing fault and a bedrock high west of Santa Fe, north of the Santa Fe River. A slight upward gradient probably also occurred under pre-development conditions at the Archery well (Figure 4, NMOSE piezometer C), now observed only when pumping ceases at the nearby Northwest well (Figure 4, EB-122). Downward gradients occur in piezometers at the County fairgrounds (Figure 4, NMOSE piezometer F), the Santa Fe River (Figure 4, NMOSE piezometer E), and the College District exploration well (Figure 4, EB-355 and EB-356; Balleau Groundwater, Inc., 2002). These local downward-flow systems are associated with flat or low horizontal gradients and reflect zones of high transmissivity related to thickening of coarse Tesuque Formation lithosome S in the center of the basin. Neutral or slight downward gradients are documented by sparse data at the basin fringe near San Marcos and La Cienega, respectively. This flow condition is consistent with leakage and subsurface outflow from the southwest boundary of the basin.

A strong upward gradient is displayed in all other wells in the western half of the basin – Las Campanas (piezometer H), Buckman (piezometer D), the County jail (piezometer G) and domestic well pairs (Table 2). This upward-gradient domain generally coincides with the trough of the basin syncline and suggests that the center of the syncline corresponds to the flow hinge of the regional aquifer system in the Santa Fe embayment. Bedrock highs under the La Bajada constriction (Minor 2006) and the nose of the Cerrillos uplift, probably contribute to upwelling in the area between Agua Fria and Buckman. This conceptualization is consistent with continuity of an upward-flow domain westward to the Rio Grande, which acts as the primary discharge area for the southern Española Basin. Upwelling of deep ground water into the shallow aquifer in this domain is consistent with distribution patterns in the geochemical data.

Sedimentary and fault-related anisotropy. Water table maps (Mourant 1980; Johnson and Frost 2004) have shown that the San Isidro Crossing fault in the vicinity of the Santa Fe River strongly perturbs the regional hydraulic gradient, and the regional ground water flow model of McAda and Wasiolek (1988) required a low permeability zone at the fault to accurately simulate head conditions. This gradient anomaly is not observed to be continuous for long distances north or south, and in general most intrabasin faults seem to have little effect on the regional hydraulic gradient. However, impediments to flow can emerge when the aquifer is subjected to the stresses of pumping. For example, the elliptical geometry of the cone of depression surrounding the Santa Fe well field reflects anisotropy within the Tesuque Formation caused by a combination of sedimentary and structure-related factors.

The dipping strata of the Tesuque Formation create aquifer anisotropy, such that the greatest hydraulic conductivity occurs in a north-south direction, parallel to bedding and perpendicular to the westward dip of strata. Sedimentary anisotropy promotes a preference for ground water flow parallel to bedding (north-south). This anisotropy manifests more dramatically in the highest dip domains of older strata along the mountain front, which can reach 30 degrees in places. Mountain-front faults bounding the east side of the Santa Fe well field create a boundary condition that magnifies drawdown against the mountain front, possibly contributing to the north-south extension of drawdown. Thinning of the Tesuque aquifer over the Oligocene bedrock high underlying the west side of the well field may also contribute to this water-table anomaly, as drawdown is focused in the trough between the bedrock high and the mountain front.

Effects of pumping. Ground water pumping has perturbed both horizontal and vertical gradients at both the Buckman and Santa Fe well fields, such that ground water from shallow zones is diverted into deeper pumping horizons. Pumping from the Northwest well (Figure 4, EB-122), located approximately 4800 feet southwest of the Archery piezometer (piezometer C, Figures 4 and 9), draws down water levels in the middle zone of completion, sometimes creating a gradient reversal between the shallow and middle aquifers. Prior to development of the old Buckman well field, a strong vertically upward gradient created flowing artesian conditions in the early exploration wells. Long-term pumping from the upper 1400 feet in Buckman wells 1, 2, 7 and 8 has reversed the upward gradient across part of this horizon. Based on water levels in Buckman piezometers (SF-2 and SF-3) in August 2006, ground water between 120 and 1600 feet is drawn into the depth horizon monitored by SF-3A and SF-2C, at 280 to 340 feet. The deepest piezometer, SF-2A at 1860 feet, still retains the highest water pressure in the Buckman piezometer set, at 5490 feet of elevation head, and preserves a vestige of the overall upward gradient. The gradient reversal in the Buckman field is coupled with geochemical anomalies consistent with the downward movement of shallow, meteoric water from the Rio Grande into the intermediate depth horizon.

Recharge and discharge. Most recharge to the Tesuque aquifer system is believed to originate at or near the eastern margin of the basin and enter the aquifer through mechanisms that include: (1) influent seepage in stream and arroyo channels, (2) subsurface flow from the Sangre de Cristo mountain block, and (3) infiltration of areal precipitation, or combinations of the above.

Discharge from the Tesuque aquifer system occurs along the Rio Grande in White Rock Canyon and at the southwestern and southern perimeter of the basin via springs, seeps, streams and perennial wetlands along lower reaches of Cienega Creek, Arroyo Hondo near its confluence with Cienega Creek, Bonanza Creek, the Santa Fe River at and downstream of Cieneguilla, and San Marcos Spring and San Marcos Arroyo. Subsurface outflow into Quaternary valley fills, leakage at the southern and western margins of the embayment and evapotranspiration from perennial surface water and shallow ground water also contribute to ground water discharge. The relative proportion of subsurface leakage and surface discharge is unknown.

Ground water basins. Four ground water flow units can be delineated between the Rio Tesuque and Galisteo Creek watersheds, with each region generally maintaining a discrete pattern of recharge, flow and discharge. Ground water divides between flow units are delineated by drawing streamlines from discharge areas eastward to the mountain front and perpendicular to water-level contours (Figure 9). Divides are drawn where there is a downstream divergence of flow lines. The four flow units include, from north to south, Tesuque-Pojoaque, Rio Grande, Cienega, and Galisteo, each named for their respective discharge area. Spiegel and Baldwin (1963) defined three such flow units in a similar way, but combined the Rio Grande and Rio Tesuque into one basin. Because they are based on streamlines rather than hydrogeologic features, boundaries of the ground water basins are approximate and mutable. While these divides may behave as no-flow boundaries under natural (pre-development) conditions, under pumping conditions the divides are dynamic and ground water can flow across a divide, as can be seen in the Santa Fe well field and the Santa Fe River divide (Figure 9). These divides are not physical barriers to flow and pumping in one unit can affect ground water levels in an adjacent flow unit.

Ground water in the Tesuque-Pojoaque basin moves from the upper Tesuque-Pojoaque Creek drainage system in the Sangre de Cristo Mountains, through the subsurface beneath the topographic valley and discharges to the lower Rio Tesuque, the Rio Pojoaque and the Rio Grande. The Tesuque ground water divide generally parallels the surface water divide between the Tesuque basin and the Santa Fe and Jacona uplands to the south.

A ground water divide generally parallels the south side of the Santa Fe River valley and separates the greater Santa Fe area into two flow regimes. North of the Santa Fe River, ground water flows west and southwest from recharge areas in the upper Santa Fe canyon to the Rio Grande. South of the Santa Fe River, ground water flows from the mountain front west-southwest to La Cienega. The Santa Fe River divide is disrupted by the Santa Fe well field, which overlaps the divide. The zone of influence of the Santa Fe well field extends for a significant distance, north and south of the divide, across the up-gradient end of these two ground water basins.

At the southern end of the Santa Fe embayment, the Galisteo ground water basin captures recharge from the southern tip of the Sangre de Cristo Mountains. The Galisteo Creek divide extends from El Dorado west across lower Gallina Arroyo and into the Turquoise and Cerrillos Hills. Ground water flows southwest through the Ancha and underlying bedrock aquifers before discharging to San Marcos Arroyo and Galisteo Creek and as subsurface outflow in Quaternary valley-fill. Limited water level data in the area of highway 14 create some uncertainty in the position of the ground water divide at the southwest basin boundary.

CHEMICAL AND ISOTOPIC COMPOSITION OF GROUND WATER AND SURFACE WATER IN THE SOUTHERN ESPAÑOLA BASIN

Chemical and isotopic data for ground water of the southern Española Basin (SEB) were examined for spatial patterns and relations that can be useful in determining recharge sources, directions of ground water flow, geochemical domains, areas of mixing, and the degree to which ground water is stratified chemically and with respect to age. Hydrogeochemical diagrams and the spatial distribution of water types and select chemical and isotopic data are presented in this section. Contours of chemical and isotopic data were interpolated with a kriging function in ARCINFO 9.2, followed by manual manipulation and smoothing at study area boundaries and concentration anomalies. The hydrologic implications of the observed patterns are discussed. Correlative relationships between chemical and physical constituents were evaluated using Pearson and Spearman correlation analyses, which measure the strength of association between pairs of variables without regard to which variable is dependent or independent. Correlation results for select chemical parameters from the SEB are presented in Table 3.

Field Parameters

Ground water in the Tesuque and Ancha Formations in the SEB is relatively dilute in dissolved minerals. The concentration of total dissolved solids (TDS) in basin-fill deposits ranges from 90 to 860 milligrams per liter (mg/L) (Figure 10). Specific conductance varies almost directly with dissolved ion content and serves as a rough indicator of overall water quality. Values of specific conductance vary within the Tesuque aquifer system from about 110 to about 1400 microsiemens per centimeter at 25ºC (µS/cm). Specific conductance is a conservative parameter and typically does not change significantly as water moves down a flow-path unless mixing occurs. Thus it is useful in defining areas of generally similar ground water chemistry. Contours of specific conductance in ground water in the SEB (Figure 11) indicate that the lowest values for dissolved solids and specific conductance occur in the upper 1000 feet of aquifer in the center of the basin west of Santa Fe and along the Santa Fe River downstream of the San Isidro Crossing fault. The highest values (greater than 900 µS/cm) occur in intermediate to deep zones (≥ 800 ft) of the old Buckman wellfield. Specific conductance increases with depth in samples from Buckman piezometers with the highest values at 800 and 1850 feet in SF-2 (EB-268, 269) and at 2400 feet in Buckman piezometer D (EB-298). When combined with evidence of an upward hydraulic gradient (Figure 9), this indicates that ground water at 800 feet and below in the Buckman field (and possibly shallower) originates as upward flow from deep, regional ground water circulation. Specific conductance in the shallow zone at Buckman (above 350 ft) varies around the values measured in the Rio Grande at Otowi, suggesting that well-field pumping has caused infiltration of surface water and mixing of waters between deep and shallow zones.

Intermediate to high specific conductance also occurs in bedrock units (defined here as pre-Santa Fe Group rocks and strata). Tertiary intrusive rocks along the southwest margin of the basin have the highest specific conductance, with values exceeding 2400 µS/cm. Proterozoic granites and related rocks in the southern end of the Sangre de Cristo mountain block have intermediate specific conductance, between 600 and 900 µS/cm, as do a few wells in basin fill along the mountain front. With the exception of these few mountain-front wells, high specific conductance associated with the mountain block does not persist into the basin-fill sediments. A discussion of chloride ion concentrations later in this report suggests that high specific conductance in the vicinity of Santa Fe may be associated with anthropogenic sources such as road salt.

Regression relationships between dissolved solids concentration and specific conductance for ground water in the SEB indicate that for all water samples (Figure 12A) specific conductance varies with dissolved solids by a factor of 0.67. However, because specific conductance for solutions of different minerals is not the same, a unique relationship between dissolved solids and conductivity exists for ground water from different geologic formations. For ground water from the Tesuque aquifer system, specific conductance relates to dissolved solids by a factor of 0.57 (Figure 12B). For ground water from the Espinaso Formation the parameters relate by a factor of 0.48 and from Proterozoic crystalline rocks by a factor of 0.44 (Figures 12C, 12D).

Limited temperature data from bulk ground water samples are sufficient to define general temperature domains within the study area. Temperature data have been shown to closely reflect hydrological conditions and are useful in distinguishing waters originating from different depths (Mazor, 1991). Many workers have relied on temperature perturbations in ground water to identify recharge and discharge zones as being cooler or warmer than expected under local climate and geothermal conditions (e.g., Reiter, 1999; 2001). Ground water with temperature close to the local average surface temperature belongs to the shallow, active water cycle, with circulation limited to the upper 300 to 500 of subsurface, and temperatures colder than the local annual surface temperature indicate recharge from higher altitudes and/or snowmelt recharge (Mazor, 1991). Temperature of ground water in the SEB varies between 10 and 29 ºC (Figure 13), is warmer than the mean annual temperature for Santa Fe (9.6 ºC) and is also generally warmer than the mean non-winter temperature (13 ºC), a condition consistent with minor heating under a strong local geothermal gradient and/or warm season recharge. The coldest ground water temperatures (below 13 ºC) are observed in the mountain block, along the Santa Fe River corridor, and at depths down to 900 feet in the Archery middle piezometer and Valle Vista #10 well. The warmest ground water temperatures are observed in shallow and deep wells northwest of Arroyo Calabasas, including the Buckman wells, in a northwest-trending band across the Santa Fe embayment from El Dorado to Arroyo Hondo, and in the deepest zones of the Archery and Santa Fe River piezometers. Most wells penetrating deeper than 800 feet in the Tesuque aquifer system west of the San Isidro Crossing fault produce water with temperatures of greater than 19 ºC, suggesting source waters with significant depth and regional circulation. Ground water with a temperature colder than 13 ºC likely reflects recent recharge originating at higher elevation or from direct infiltration of mountain runoff along the Santa Fe River.

Most ground water in the Española Basin is slightly to moderately alkaline, with pH values ranging from 6.4 to 9.3. Contours of pH (Figure 14) show that the highest pH values, greater than 8.0 standard units, occur in the Ancha and adjoining formations between Arroyo Hondo and Gallina Arroyo, in the Espinaso and Gallisteo Formations near San Marcos Arroyo, and in parts of the Tesuque Formation north and south of the Santa Fe River. Values of 7.5 or less occur along the mountain front south of Santa Fe and along the Santa Fe River downstream of the wastewater treatment plant.

Water Type

The major ion content of ground water in the southern Española Basin varies both horizontally and vertically within the Tesuque aquifer system, and differs between geologic formations. Differences in chemical composition across the study area are evident in Piper diagrams, which illustrate the relative concentrations of major ions for a large number of samples. A piper diagram of all ground water and surface water samples from the southern Española Basin (Figure 15) shows a variety of water types ranging from calcium bicarbonate to sodium bicarbonate, with 45 percent of the samples being sodium rich. Other ion compositions include calcium-magnesium and bicarbonate-sulfate. Because the samples are not distributed evenly across the study area, the dominant water type illustrated in the piper plot is not necessarily the most common type in the study area.

Generally speaking, different water types tend to group in distinct areas of the basin and within different geologic formations. The Tesuque Formation exhibits the greatest variability in water type and chemical composition, reflecting variable lithology, great geographic extent, and mixing of multiple ground water systems. Calcium-bicarbonate water dominates in the eastern half of the basin and grades westward into more sodium-rich waters (Figure 16), consistent with down-gradient chemical evolution by cation exchange along regional ground water flow paths. Additional discussion on this topic is included in a later section on sodium.

Composition of ground water from Proterozoic crystalline rocks in the southern end of the Sangre de Cristo Mountains shows enrichment of magnesium in a calcium-bicarbonate water type (Figure 17). Over half these mountain block samples also contain significant amounts of chloride, sulfate, or both, and a higher concentration of dissolved solids than water from nearby, down-gradient wells completed in the Tesuque Formation.

The dominant water type in the Ancha Formation is calcium-sodium-bicarbonate with minor occurrence of calcium-bicarbonate in wells near the Santa Fe River (Figure 18). Mixed ion compositions also occur in the Ancha Formation with further enrichment of sodium, or addition of magnesium or sulfate. This suggests that ground water from adjacent formations, including Espinaso and Galisteo, discharges into the Ancha at certain locations and mixes with this shallow aquifer. For example, calcium-depleted, sodium-rich water occurs in sample EB-201, where a thin Ancha Formation overlies Espinaso Formation (compare with nearby EB-449 from the Espinaso Formation, Figure 19), and in samples EB-339 and EB-460, where there may be upwelling of sodium- and sulfate-rich water from deep zones in the underlying Tesuque Formation. In one sample from south of Santa Fe Canyon (EB-640), ground water from the Ancha and Galisteo Formations has mixed to produce a sodium-calcium-magnesium and bicarbonate-sulfate water type reflecting compositions of both formations.

Ground water from the Espinaso and other Tertiary volcanic rocks is generally bicarbonate-type water that is more sodium-rich than Ancha Formation water with occasional enrichment of sulfate (Figure 19). Near the mountain front, ground water from the Espinaso may take on the magnesium-rich signature of mountain-block ground water (for example, EB-217 and EB-469), but quickly evolves toward higher sodium concentrations. Other Tertiary volcanic rocks show significant variability in water type, probably due to differences in rock chemistry, but generally tend to be sodium-rich with occasional enrichment of sulfate.

Major-Element Chemistry

Cations. The following sections present data on concentrations of major cations, including calcium (Ca), sodium (Na), magnesium (Mg) and potassium (K) in the southern Española Basin.

Calcium. Calcium is the predominant cation in ground water in much of the southern Española Basin. The Ca ion is not conservative in ground water as a result of calcite or gypsum precipitation and dissolution or cation exchange. Concentrations of Ca vary across the study area from 350 to less than 1 mg/L (Figure 20), suggesting that one or more of these processes is occurring, most likely calcite precipitation and/or cation exchange. The highest concentrations (greater than 100 mg/L) occur at discrete locations within the Sangre de Cristo Mountains and in volcanic intrusive formations bounding the Santa Fe embayment. In general, ground water from Proterozoic crystalline rocks has higher Ca concentrations than from the Tesuque aquifer system. Calcium concentrations in the Tesuque Formation along the mountain front, as well as east of Agua Fria and the San Isidro Crossing fault, are similar to those observed in the mountain block. The remainder of the Tesuque Formation has lower concentrations (less than 50 mg/L) of Ca, with a general trend of decreasing concentration east to west across the basin. An exception is the area of anomalously high calcium concentrations in Ancha Formation and shallow Tesuque Formation wells along lower Cienega Creek.

Sodium. Like Ca, the Na ion is not conservative in ground water, commonly due to cation exchange or weathering of feldspar. Relatively high Na concentrations (20 to 50 mg/L) occur within the Sangre de Cristo Mountains and in wells adjacent to the mountain front. The lowest Na concentrations (less than than 10 mg/L) occur in the Tesuque aquifer system aquifers adjacent to the Santa Fe River and as far south as Arroyo Hondo (Figure 21). Sodium concentrations increase to the west (down gradient) toward the Rio Grande and the Buckman well field, with the highest concentrations (up to 300 mg/L) observed in deeper zones of the Buckman wells. Sodium concentrations generally increase with depth in the aquifer in the western part of the basin, although the trend is not consistent across all depth intervals (see for example Buckman 10 through 13 (John Shomaker & Assoc. 2004)). Sodium concentrations decrease with depth at locations between the mountain front and east of the San Ysidro Crossing faults (see the Archery piezometer C, the Fairgrounds piezometer F, SF-1 piezometer A, and the college district well).

The map of ratios of calcium to sodium (Figure 22) provides additional insight regarding distribution of these two cations and the controlling processes. The ratios of Ca to Na ions (in units of milliequivalents per liter, meq/L) are greater than 1 throughout most of the basin, reflecting the general dominance of calcium over sodium. Ratios greater than 5 occur within the Tesuque aquifer system in the area of the city from the Santa Fe River south to Arroyo Hondo. The lowest average sodium concentration (22 mg/L) and highest Ca to Na ratio (4.8) occurs in water from lithosome S of the Tesuque Formation. The second highest values, 25 mg/L average Na and 3.1 Ca to Na ratio, occur in the Ancha Formation aquifer. Ca to Na ratios less than 1, indicating enrichment of Na with respect to Ca, dominate the Tesuque aquifer in the western part of the basin beneath the Cerros del Rio volcanic field, along Cañada Ancha through the Buckman well field, and in the Las Dos/Jacona fault system. Sodium enrichment also occurs in ground water from Tesuque and Ancha wells along lower Arroyo Hondo and Cienega Creek, and near La Cienega. Lithosome B and the fine-grained portion of lithosome S of the Tesuque Formation produce waters with the highest average Na concentrations (117 and 73 mg/L, respectively) and the lowest Ca to Na ratios (0.4 and 0.5, respectively). A generalized rock sourcing model (AquaChem v. 5.0 2005) indicates that the likely source of Na enrichment in the western portion of the basin is cation exchange. In addition, Pearson correlation analysis (Table 3) indicates a significant positive correlation between Na and HCO3 ($r = 0.66$, both variables increase together), which suggests sodium enrichment through cation exchange along a flow path rather than via feldspar weathering. This finding is consistent with predominance of mudstone, siltstone and claystone in lithosome B (Table 1, unit Ttbfml) and clay, silt and very fine sand in the fine-grained facies of lithosome S (Table 1, unit Ttsf). In samples from the Santa Fe embayment near San Marcos Arroyo, enriched Na is likely due to silicate and plagioclase weathering, which affects ground water in the Espinaso Formation, Proterozoic crystalline rocks, and Mesozoic strata. The coincidence of Na-rich and warm ground water at shallow depths west of Santa Fe, along the basin syncline, is consistent with long residence times and upwelling of ground water from a deep circulation system.

Magnesium. Magnesium concentrations are generally less than 10 mg/L in the Tesuque aquifer system in the southern Española Basin (Figure 23). Concentrations greater than 10 mg/L occur in the Sangre de Cristo Mountains and adjacent mountain-front wells, in Tertiary volcanic rocks and Galisteo Formation near Turquoise Hill, and in the eastern portion of the old Buckman well field. Ratios of calcium and magnesium in mountain-front wells ($Mg/(Ca+Mg) < 0.5$) indicate that enrichment of magnesium along the mountain front may originate from weathering of dolomitic limestone. Pearson correlation analysis (Table 3) also indicates a significant positive correlation between Ca and Mg ($r = 0.76$), which is consistent with limestone and dolomite sources.

Anions. The following sections present data on concentrations of major anions, including bicarbonate (HCO3), chloride (Cl), sulfate (SO4), nitrate (NO3), and fluoride (F), in the southern Española Basin.

Bicarbonate Alkalinity. Bicarbonate (HCO3) is the dominant anion in ground water with concentrations ranging from 35 to about 900 mg/L across the study area. Bicarbonate alkalinity values are somewhat variable and the concentration contours (Figure 24) depict generalized trends. Alkalinity in the Ancha and Tesuque Formations in the center of the basin is commonly less than 150 mg/L. Higher alkalinity values (150 to 300 mg/L) occur along the mountain front, around the perimeter of the Santa Fe embayment, and along lower Arroyo Hondo and Cienega Creek. Particularly high alkalinity values (greater than 300 mg/L) are present in the Buckman well field and in a band along the western base of the Sangre de Cristo range. Calculations in PHREEQC indicate that most ground water samples are saturated with respect to calcite.

Chloride. Chloride, a conservative constituent in ground water, is generally present in low concentrations throughout the study area. Contours of Cl concentration (Figure 25) indicate that concentrations less than 10 mg/L occur throughout most of the Tesuque and Ancha Formations. Wells near the mountain front, in the mountain block and around the perimeter of the Santa Fe embayment generally have concentrations between 10 and 60 mg/L. Chloride concentrations greater than 60 mg/L occur in isolated zones beneath urban Santa Fe, producing a spotty distribution pattern for this anion. Elevated Cl in the Saint Michael's piezometer nest (EB-244) indicates the presence of higher concentrations at depth (1920 feet below land surface) in this area, and is consistent with a Cl source associated with the upward movement of deep mineralized water along mountain-front faults or structural highs. Hydraulic heads in this piezometer nest indicate a vertically upward hydraulic gradient to drive upward movement of Cl.

Further evidence of the origin of elevated Cl beneath Santa Fe is gained by evaluating distribution of the bromide ion (Br) and ratios of Cl/Br concentrations. Bromide, like chloride, behaves conservatively in ground water, but bromine is generally 40 to 8000 times less abundant in the environment than chlorine (Davis et al. 1998). Consequently, relatively small changes in total mass of bromine give rise to large variations in ratios of Cl/Br. Bromide has not been commonly tested for in the study area nor is it detected using normal analytical procedures; hence the data set for Br is limited. Concentrations of Br (Figure 26) range from less than 0.01 to 0.8 mg/L, with the highest concentrations occurring in samples from the mountain block, older Tertiary, Mesozoic and Paleozoic rocks around the southern perimeter of the embayment, and an isolated zone beneath urban Santa Fe. This is a similar distribution pattern as observed for Cl.

Chloride-bromide ratios have been shown to be distinct for various natural and anthropogenic sources (Davis et al 1998): for example, precipitation (50-150), shallow ground water (100-200), domestic sewage (300-600), volcanic rocks (500-545), and urban runoff and road salt (+/- 1170) all possess unique ratio values. Ratios of Cl to Br in the study area (Figure 27) are generally less than 100 and almost always less than 200, and hence consistent with values for precipitation and shallow ground water. One notable exception occurs in a shallow UST monitor well (EB-141) along Alameda Street, which has a ratio value of 1353 consistent with urban runoff. In general, ratios in shallow ground water replicate atmospheric precipitation. The slightly elevated Cl values along the mountain front appear to suggest localized upwelling and mixing of deep mineralized water or sources from volcanic rocks. The ground water sample from the deepest Jail piezometer G (EB-605A) completed in Espinaso Formation reflects a Cl/Br ratio sourcing from volcanic rocks.

Sulfate. Sulfate is present in the Tesuque aquifer system in concentrations ranging from 3 to 120 mg/L, with higher values up to ~1500 mg/L occurring in Tertiary volcanic intrusive rocks and Mesozoic and Paleozoic strata. The median sulfate concentration is 18 mg/L. Contours of SO4 concentrations (Figure 28) show that values less than 20 mg/L dominate in shallow Ancha and Tesuque wells in the center of the basin, and values between 20 and 60 mg/L occur around the perimeter of the basin, in Ancha and deeper bedrock wells south of Bonanza Creek and along lower Cienega Creek, and in Tesuque wells along the mountain front, in the Las Dos/Jacona fault system, and in parts of the Buckman well field. The highest SO4 values (greater than 100 mg/L) are commonly associated with Tertiary intrusive rocks, Proterozoic crystalline rocks in the southern end of the Sangre de Cristo Mountains and Mesozoic strata near Lamy. Most of the lowest concentrations of sulfate, less than 10 mg/L, are clustered in shallow wells within the urbanized area of the City of Santa Fe. These depressed sulfate concentrations may be due to microbial sulfate reduction and correlate to elevated barium, which is discussed in more detail in a subsequent section.

Ratios of SO4 to Cl have been used by other researchers in the Rio Grande Valley to evaluate sources of ground water recharge and underflow. In geochemical studies of the Middle Rio Grande Basin, Plummer et al. (2004) used a ratio of SO4 to Cl of 5.2, measured from average bulk precipitation from the Sevilleta National Wildlife Refuge (Moore 1999), as a reference point for identifying recent recharge. Most ground water in the southern Española Basin, however, has ratios of SO4 to Cl that are considerably less than 5 (Figure 29). The lowest values for SO4 to Cl ratios (less than 2) occur in shallow wells along the upper Santa Fe River, adjacent to the Sangre de Cristo Mountains. In the absence of composition data from local precipitation or snowmelt, SO4 to Cl values less than 2 are used here to represent recent recharge. A band of low ratio values is also present along the Santa Fe River, between the WWTP and La Cienega, and around the southwest boundary of the basin between Arroyo Hondo and Gallina Arroyo. This area of light ratios may reflect the influence of recharge to the Ancha and upper Tesuque Formations from the lower Santa Fe River and distal arroyo channels. Areas with ratios of SO4 to Cl higher than 4 are also those that have high sulfate values; specifically, Tertiary intrusive rocks near Picture Rock, Mesozoic strata near Lamy, Tesuque Formation along the Las Dos/Jacona fault system and the new Buckman well field extension, and Ancha and shallow Tesuque Formation along lower Cienega Creek. These high-sulfate anomalies in the Tesuque aquifer system are also sites of other compositional differences.

Nitrate. Nitrate (NO3) concentration (as N) in ground water ranges from less than 0.1 to 15 mg/L in the southern Española Basin, with a median concentration of 1.5 mg/L. There are no spatial trends associated with the distribution of nitrate in Santa Fe area aquifers (Figure 30) that can be represented with standard contouring methods. Concentrations less than the median value of 1.5 mg/L intermingle with higher concentrations, suggesting that nitrate is naturally occurring across a fairly wide range of concentrations and that some wells may be affected by minor point source contamination. Nitrate concentrations above 6 mg/L are constrained to shallow wells less than 500 feet in depth. Elevated NO3 concentrations at or above the maximum contaminant level (MCL) of 10 mg/L are documented in ground water near the Santa Fe landfill west of the city, and in one well (EB-511) in fractured Proterozoic crystalline rocks where ground water may be affected by discharge from septic tanks or other domestic sources. There is no widespread or significant nitrate contamination in areas monitored by recent water quality studies. However, Pearson correlation analysis (Table 3) does indicate a significant positive correlation between NO3 and Cl ($r = 0.62$), suggesting a coincident source and possible influence from septic tank contamination.

Fluoride. Fluoride concentration in ground water ranges from 0 to 2.7 mg/L in the southern Española Basin, and is typically less than 1.0 mg/L (Figure 31). Concentrations between 1.0 and 2.0 mg/L occur in isolated pockets around the Santa Fe embayment, in wells completed in the Tesuque, Espinaso and Galisteo Formations, and in Proterozoic crystalline rocks. High fluoride concentrations are more likely to occur in water that has a low calcium and high sodium concentration (Hem, 1985) and a comparison of fluoride concentrations with ratios of calcium to sodium (Figure 22) also indicates a general correspondence for the Santa Fe area. Volcanic ash can be rich in fluoride, and ash that is interbedded with clastic sediment in the Tesuque and Espinaso Formations may contribute to high fluoride concentrations in these areas. Pearson correlation analysis (Table 3) indicates a strong positive correlation between fluoride and potassium (r = 0.88), suggesting a common source from weathering of volcanic rocks.

Minor-Element Chemistry

Minor-element chemistry in ground water is often complex and difficult to interpret, but some minor elements can provide information about different water sources or areas where particular chemical processes are occurring. This section discusses the distribution and occurrence of arsenic (As), barium (Ba), strontium (Sr), and uranium (U), with additional comments regarding lithium (Li) and boron (B).

Arsenic. Arsenic (As) concentrations in ground water of the southern Española Basin range from 54 to less than 1 µg/L, and are low (<5 µg/L) for much of the Santa Fe area (Figure 32). A region of elevated As concentrations, greater than 10 µg/L, is found west of Santa Fe and north of the Santa Fe River. Analysis of As species in samples from the Las Campanas piezometer H (EB-608, EB-609, EB-610) indicate that the arsenic present is in the form of As(V), the highest oxidation state (Los Alamos National Laboratory, written communication). Compiled data define local areas of elevated As in the old Buckman well field adjacent to the West Buckman fault, in a Rancho Viejo well near Bonanza Creek, at the Santa Fe municipal airport, and in the middle and deep completions of the Santa Fe River piezometer E.

Depth-specific ground water samples from piezometer nests and Buckman extension wells, together with samples from domestic and monitoring wells of various depths, provide information about variation of As concentrations with depth in the upper aquifer west of Santa Fe. Generally speaking elevated As concentrations are independent of depth, although concentration trends are observable in individual wells. The highest As concentration, 54 µg/L, is measured in a shallow well completed in the upper 30 feet of aquifer. The second highest As concentration, 42 µg/L, is measured in a piezometer at 1700 feet below the water table surface. Plots of As concentration with depth below the water table, grouped by piezometer locations near Buckman and Santa Fe, are shown in Figures 33A and 33B, respectively. Two wells near Santa Fe (the Santa Fe River piezometer E and the Fairgrounds piezometer F), and one well near Buckman (Buckman extension well number 13) show a consistent increase in As concentration with depth, ranging from 6 µg/L over 1080 feet of aquifer at Buckman 13 to 40 µg/L over 1300 feet of aquifer at the Santa Fe River site. Although As increases with depth in the Fairgrounds piezometer, all concentrations are less than the MCL of 10 µg/L. The remaining six piezometers, however, consistently show steady or decreasing As concentrations between shallow and deep zones, and sometimes the highest As concentration is encountered at an intermediate horizon. Arsenic concentrations in Buckman 10 and the Archery piezometer C are less than 10 μg/L in all completions. Arsenic concentrations in Buckman 11, SF-2/SF-3, Buckman piezometer D, and Buckman 13 are less than 10 μg/L in some completions, providing opportunity for dilution of elevated As concentrations by mixing with lower concentration intervals. Only one location, Las Campanas piezometer H, produced ground water with an As concentration of more than 10 μg/L from all zones. Concentration spikes occur in the intermediate zones of Las Campanas piezometer H (30 μg/L) and Buckman piezometer D (19 μg/L) at about 1100 feet below the water table. Ground water meeting the USEPA drinking water standard for arsenic (10 μg/L) should be obtainable in all represented areas, except Las Campanas and the Santa Fe River at highway 599, by either increasing depth of the well or integrating and mixing water from a large screened interval.

Sources of Arsenic. The geographic limits of the arsenic plume west of Santa Fe, defined by 34 samples with As concentrations at or above the MCL of 10 μg/L, coincide with other chemical parameters and physical features in the area (Figure 34). The center of the plume is coincident with the east side of the Cerros del Rio volcanic field and overlies the axis of the plunging syncline in the Tesuque Formation. The plume center lies northeast of the Cerrillos uplift, and the plume extends north-northwest over the Oligocene slope toward the deepest part of the basin. The eastern edge of the plume does not extend beyond the Jacona-Los Dos fault system and the northern edge does not appear to extend significantly north of the Buckman extension wells 12 and 13, although the northern limit is not well constrained. The south and southeast edge of the plume coincides with the 4000-foot depth contour at the base of the flexure in Oligocene volcanic rocks defined by Grauch and Bankey (2003). The western limits of the plume are unconstrained; thus the actual plume shape is uncertain.

The arsenic anomaly is also spatially coincident with sodium-rich ground water (Ca to Na ratio of less than 2) (Figures 34 and 35) that is significantly warmer (≥19 ºC) than mountain front recharge originating from the Sangre de Cristo Mountains to the east (Figure 34). Pearson and Spearman correlation statistics indicate significant positive correlations between arsenic and pH, temperature, sodium, fluoride, boron and lithium (Table 4), with stronger correlations in arsenic samples from west of Santa Fe than for arsenic-containing samples as a whole. These chemical correlations between arsenic and warm, sodium and element-rich ground water suggest that the arsenic west of Santa Fe occurs with upwelling of ground water from deep, regional circulation that is active west of the Jacona-Las Dos-San Isidro fault system. Geophysical logs from the nearby Yates La Mesa 2 exploration well verify the presence of high-gamma and thorium-rich ash beds and sills in the Cieneguilla basanite, a Tertiary intrusive rock at the base of the Tesuque Formation, that may provide a source for arsenic (Figure 36) (D. Sawyer, personal communication). The spatial association between elevated arsenic, the axis of the plunging syncline and a change in structural domain across the flexure in underlying Oligocene volcanic rocks further supports a deep structural control on upward movement of deep ground water and transport of arsenic. Occurrence of elevated arsenic in the shallow ground water system at this location strongly suggests upwelling of deep ground water and movement through fracturing of Oligocene volcanic rocks in the flexure zone.

Barium. Barium concentrations in the southern Española Basin range from less than 1 µg/L to 860 µg/L (Figure 37). An area of high Ba concentrations exists near urban Santa Fe, extending from the Santa Fe Plaza west past Agua Fria, and from Arroyo Hondo north past Tano Road. The highest concentrations (greater than 300 µg/L) are clustered along the Santa Fe River between Frenchy's Park and St. Francis Drive, an area roughly coincident with the City of Santa Fe well field. The most common geochemical control on the concentration of barium in natural water is the solubility of barite or barium sulfate ($BaSO_4$) (Hem 1985), a common mineral and a component of drilling fluid. At a SO4 molar activity of 18 mg/L (a median concentration for the study area), the corresponding equilibrium molar activity of Ba^{2+} would be 250 µg/L. Barium concentrations in and around the city well field significantly exceed this value, indicating supersaturation with respect to barite. White et al. (1963) reported high Ba concentrations in conjunction with very low SO4 concentrations that were controlled by sulfate reduction, allowing the barium to increase beyond normal barite solubility limits (Hem, 1985). The area of elevated barium along the Santa Fe River generally corresponds to low concentrations (4 to 20 mg/L) of sulfate; low sulfate concentrations in turn suggest local reducing conditions.

Barium is a highly reactive metal that occurs naturally only in a combined state. The element may be released to the environment through both natural processes and anthropogenic sources. A natural source of barium exists in granitic rocks of the Sangre de Cristo Mountains, where potassium feldspars in quartz monzonites are enriched in barium (Long 1976). There are two possible anthropogenic origins of elevated barium: contamination derived from drilling fluids containing barite and/or a disequilibrium in barite solubility driven by anaerobic conditions depressing sulfate concentration. Anaerobic conditions often occur with organic contaminants such as gasoline or solvent spills. Enrichment of heavy metals in sediments, vegetation, and formation water from drilling fluids is well documented in both marine (Boothe and Presley 1987; Bothner et al. 1986) and terrestrial (American Petroleum Institute 1982; Payne 1990) environments, resulting most commonly in elevated Ba, in addition to aluminum, chromium, iron, cadmium, copper, nickel, lead, vanadium and/or zinc. Pearson and Spearman correlation coefficients for samples from the Santa Fe area with elevated (≥150 mg/L) barium indicate significant positive correlations between Ba and aluminum, boron, calcium, chloride, chromium, iron, manganese, and nitrate (Table 5). The addition of small amounts of drilling fluid to shallow ground water can also increase microbial growth rates (Baker et al. 1998), resulting in anaerobic or reducing conditions. A similar effect may explain conjunction of elevated Ba and low SO4 in the Santa Fe well field. In summary, elevated Ba concentrations in the vicinity of the City well field likely result from either a natural source from granitic rocks, or an anthropogenic source from drilling fluid, possibly combined with input of organic contaminants and microbial facilitated sulfate reduction.

Strontium. Strontium concentrations vary from 10 to 850 µg/L in the southern Española Basin, with a median value of 270 µg/L (Figure 38). Strontium is present in concentrations less than 450 µg/L across most of the study area, with the lowest concentrations clustered in the city between the Santa Fe River and Arroyo Hondo. The highest concentrations are present in Proterozoic crystalline rocks at the southern end of the Sangre de Cristo Mountains and in the Tesuque Formation in an east-west band from the mountain front north of Tesuque to the Buckman well field. Strontium commonly replaces calcium in igneous-rock minerals, favoring granitic rocks over other types. Granitic rocks and pegmatites in the Sangre de Cristo Mountains are the likely source of strontium in the southern Española Basin, and granitic bedrock northeast of Tesuque may have higher strontium content than granitic rocks further south in the mountain range. Results of bulk rock chemistry on Precambrian rocks in the Sangre de Cristo and Picuris Mountains between Santa Fe and Taos indicates a range of strontium content, with values up to 530 ppm (Fullagar and Shiver 1973). Analyses of mineral separates further indicate that the feldspar fraction is enriched in strontium relative to other mineral fractions.

Uranium. Uranium data in the study area are fairly limited, with analytical results available only from city well fields and the most recent sampling events. Based on existing data, uranium concentrations vary significantly from 0 to 116 µg/L (Figure 39). Concentrations in the Tesuque aquifer system are typically low, less than 5 µg/L. However, concentrations greater than 10 µg/L are common in Proterozoic crystalline rocks and in deep zones in the Tesuque Formation west of Santa Fe (at 1900 feet depth in the Santa Fe River piezometer and at and below 1500 feet depth in the old Buckman well field adjacent to the Rio Grande). Granitic rocks and pegmatites in the Sangre de Cristo Mountains are the likely source of uranium in the southern Española Basin, and granitic bedrock northeast of Tesuque may have higher uranium content than granitic rocks further south in the mountain range.

Isotopes of Hydrogen-2 and Oxygen-18

The stable isotope composition of ground water typically reflects the isotopic composition of its source water. Deuterium (^{2}H) and oxygen-18 (^{18}O) are naturally occurring stable isotopes of hydrogen and oxygen and are part of the water molecule, thus they behave as ideal tracers of water movement. After recharge, no physical processes, such as geothermal isotope exchange, operate in the Española Basin that can modify the original composition of the source water. A ground water recharge study by Anderholm (1994) generated a large dataset of stable isotope composition in precipitation, surface water (30 samples) and shallow and deep ground water (79 samples) in the Santa Fe area. These data were supplemented by those from three additional studies: 22 ground water samples from the New Mexico Office of the State Engineer in 2004 (Duncan, written communication), five surface water samples documenting seasonal and annual variation in composition of the Rio Grande at Otowi (Mills 2003), and 50 ground water samples by NMBGMR as part of this study in 2005. Data from all sources were combined for analysis and interpreted relative to the local meteoric water line (LMWL) generated by Anderholm (1994). Stable isotope compositions of ground water are compared to modern surface water to evaluate recharge from streams and arroyos. Fossil ground water recharged during a cooler Pleistocene climate is significantly depleted in both deuterium and oxygen-18 relative to modern water. Ground water of mixed origin – modern and fossil – has an intermediate isotopic composition.

The $\delta\,^{2}H$ and $\delta\,^{18}O$ composition for all ground water and surface water samples in the southern Española Basin is shown in Figure 40 together with the local meteoric water line developed by Anderholm (1994). The isotopic composition of modern surface water from streams originating in the Sangre de Cristo Mountains ranges from -92 to -68 per mil $\delta\,^{2}H$ and from -13.2 to -10 per mil $\delta\,^{18}O$ (Anderholm 1994). The isotopic composition of surface water from the Rio Grande at Otowi (Mills 2003) is depleted with respect to deuterium and oxygen-18 during the cold winter season when it ranges from -100 to -95 $\delta\,^{2}H$ and -13.8 to -12.7 $\delta\,^{18}O$. Summer flow at Otowi is relatively enriched in heavy isotopes and ranges from -88 to -78 $\delta\,^{2}H$ and -12.1 to -10 $\delta\,^{18}O$.

Isotopic composition of ground water in the southern Española Basin varies from -117 to -61 per mil $\delta\,^{2}H$ and from -15.8 to -9.0 per mil $\delta\,^{18}O$ (Figure 40). Most ground water sampled lies within the range of isotopic composition of mountain streams and arroyos and generally plots parallel to the LMWL. Anderholm (1994) interpreted this relationship to indicate that winter precipitation and infiltration from mountain-front streams is the major source of recharge to the basin. About 20 percent of ground water samples (n=24) yield a deuterium composition less than -95 per mil, which is more depleted than any modern source of mountain front recharge but within the range of winter composition of Rio Grande surface water at Otowi (Mills 2003). These deuterium-depleted samples generally plot below the LMWL. More than half of these depleted samples (n=16) have a deuterium composition of less than -100 per mil, lighter than any modern surface water source including the Rio Grande. In the Albuquerque Basin, Plummer et al. (2004) recognized a group of waters more depleted than modern Rio Grande waters with $\delta\ ^2H$ values more negative than -100 and as low as -110 per mil, and referred to them as "deuterium depleted deep water", consistent with Yapp (1985). Plummer et al. (2004) also established that these "deuterium depleted deep waters" had an age on the order of 20,000 radiocarbon years. Deuterium-depleted ground water in the Albuquerque Basin definitely does not source from the modern Rio Grande, which has an isotopic composition in the range of -90 to -100 per mil $\delta\ ^2H$. Applying this $\delta\ ^2H$-versus-age correlation to isotopic data from the Española Basin, we interpret that the 16 ground water samples with a $\delta\ ^2H$ composition more negative than -100 per mil were recharged during the last glacial period in the late-Pleistocene and are likely associated with an age on the order of 20,000 radiocarbon years. The eight ground water samples with a $\delta\ ^2H$ composition between -95 and -100 are more depleted than modern mountain front recharge and either represent paleo water recharged under a cooler temperature regime, a mix of paleo ground water and younger ground water, or ground water recharged by modern winter-season Rio Grande flows. Based on the distribution of $\delta\ ^2H$ in ground water (Figure 41), particularly the vertical distribution in monitor wells near the Rio Grande at Buckman (figure 42(A)), the latter hypothesis is implausible.

Variations in stable isotope composition of ground water in the southern Española Basin are significant in both a horizontal sense (Figure 41) and vertically with depth in the aquifer (Figure 42). Contours of $\delta\ ^2H$ composition in shallow ground water (Figure 41) illustrate that most ground water in the eastern and southern parts of the basin has a $\delta\ ^2H$ composition between -90 and -61 per mil, which is comparable to the variation in surface water composition documented by Anderholm (1994) (Figure 40). A few pockets of depleted ground water with $\delta\ ^2H$ compositions less than -90 per mil occur west of El Dorado, north of Tesuque near the mountain front, west of Santa Fe near the Yates La Mesa #2 well, and west of the Santa Fe River beneath the Caja del Rio plateau. A transition to deuterium-depleted water occurs across a narrow zone, of a mile or less in width, where the $\delta\ ^2H$ composition is generally between -95 and -100 per mil. Most ground water beneath the Jacona uplands between Tesuque and Buckman and within the

Jacona-Las Dos fault system has a much depleted δ ^{2}H composition, with values less than -100 per mil and as low as -117 per mil.

Depth-specific samples from NMOSE multi-level piezometers provide an excellent opportunity to confirm the variation in stable isotope composition of ground water with depth. Four such piezometers from the western half of the basin (Buckman piezometers B and D, Las Campanas piezometer H and the Santa Fe River piezometer E) confirm a transition between ground water with a modern signature (δ ^{2}H values greater than -95 per mil) and paleo water (δ ^{2}H values less than -100 per mil) within the depth interval of 400 to 800 feet below the water table (Figure 42). In addition, ground water in two adjacent domestic wells (EB-059 and EB-598) completed at different depths show a similar trend in δ ^{2}H composition across a depth of 300 to 450 feet below the water table (Figure 42A). Piezometers on the east and south side of the basin show no such transition, rather they indicate δ ^{2}H compositions consistent with modern mountain-front recharge to a depth of nearly 1500 feet below the water table at the Fairgrounds piezometer F and 1100 feet in the Jail piezometer G (Figure 42B).

In summary, isotopic composition of ground water is a good proxy for residence time and circulation regimes in the southern Espanola Basin and is consistent with other chemical indicators. Pearson and Spearman correlation coefficients indicate significant positive correlation between δ ^{2}H composition and calcium concentration (as calcium increases the δ ^{2}H becomes more enriched and the value becomes less negative) and a significant negative correlation between δ ^{2}H composition and sodium concentration (as sodium increases the δ ^{2}H becomes more depleted and the value becomes more negative) (Table 3). Thus sodium-rich ground water, which derives from cation exchange down a long flow path, generally co-exists with ground water depleted in ^{2}H and having an ancient recharge signature. Calcium-rich ground water, which characterizes modern mountain-front recharge, generally coexists with ground water enriched in ^{2}H and sharing an isotopic signature with modern mountain streams.

INTERPRETATIONS OF REGIONAL GROUND WATER FLOW

The chemical and isotopic information from ground water gathered in this study is used to decipher complex, basin-scale hydrologic processes and interpret important aspects of regional ground water flow. Combining the distribution of major, minor, and trace elements, stable isotopes, and physical parameters such as ground water temperature facilitates the characterization of regional ground water flow regimes. When further combined with geologic and hydrologic data, a chemical characterization provides a qualitative view of circulation pathways and residence times, differentiates between modern and paleo recharge, and provides an improved and accurate conceptual model of the movement of ground water through this complex aquifer system. This section briefly summarizes the major findings of the study.

Recharge

Ground water chemistry of Proterozoic crystalline rock in the Sangre de Cristo Mountains is distinct from the chemistry of surface water and shallow ground water in the adjacent Santa Fe Group aquifer. Evaluating geochemical data by geologic unit allows interpretation of ground water movement between bedrock and basin aquifers. Distribution patterns in ground water chemistry and temperature help trace the movement of ground water through the Tesuque aquifer system and evaluate the significance of separate sources of recharge. The distribution of dissolved mineral content (TDS), ground water temperature and pH, SO4 to Cl ratios, and other parameters (Figures 10, 13, 14, 29) supports the following interpretations regarding recharge to the Tesuque aquifer system:

1. Recharge through stream and arroyo channels dominates the shallow aquifer system in and south of Santa Fe. Significant infiltration occurs along the length of the Santa Fe River, much of Arroyo Hondo, upper Gallina Arroyo, and the distal reaches of the major arroyos crossing the Santa Fe embayment. Occurrence of cold, low TDS, calcium-rich water at shallow horizons in multi-level piezometers indicates that local recharge to the shallow aquifer may occur along the Rio Grande and the lower reach of Cañada Ancha.
2. Decreasing values of temperature, dissolved solids and major ions with depth in the St. Michaels (SF-1) and fairgrounds piezometers and the college district dual completion exploration well, and other occurrence of cold, fresh ground water at depth (for example, EB-386 Valle Vista #10) supports the limited influx of direct mountain block recharge via the Santa Fe River fault and possibly other major fracture systems to the south. The intersection of the Santa Fe River fault and the Arroyo Hondo fault may create the fracturing and dilation required for enhanced mountain block recharge and localized

upwelling of ground water at the mountain front east of Santa Fe. The coldest ground water temperatures (below 13 ºC) are observed in the mountain block, along the Santa Fe River corridor, and at depths down to 900 feet in the Archery middle piezometer and Valle Vista #10 well.

3. Effluent discharging from the Santa Fe WWTP recharges the shallow aquifer along the Santa Fe River corridor downstream of the plant to La Cienega.
4. Vertically upward gradients together with the presence of warm, sodium and element-rich water in the shallow aquifer west of Santa Fe indicate the influx of ground water from deep regional flow paths into the Tesuque aquifer system, including from underlying Oligocene bedrock aquifers.

In summary, geochemical and physical data indicate that three sources of water contribute to the Tesuque aquifer system, including: (1) modern infiltration of surface water through stream and arroyo channels, which dominates the shallow aquifer from the Santa Fe River south; (2) upwelling of ground water from subsurface fractures and faults in Proterozoic crystalline rocks near the mountain front; and (3) deep regional flow paths through Oligocene volcanic rocks along the Santa Fe flexure, with subsequent upwelling through the Tesuque aquifer system west and south of Santa Fe.

Aquifer Domains, Ground Water Flow Paths and Mixing Ground Water from Different Sources

Comparing geologic and structural features with hydrologic data plus isotopic and chemical parameters define distinct ground water circulation domains in the southern Espanola Basin (Figure 43). The ground water domains are based on hydrologic attributes such as aquifer thickness, permeability of aquifer material, and magnitude and direction of horizontal and vertical hydraulic gradient; spatial distribution of geochemical and physical parameters in ground water; and geologic features such as faults, stratigraphic contacts, bedrock basement structure, and subsurface distribution of Oligocene volcanic rocks, which appear to influence both flow and geochemical characteristics of the aquifer. The ground water domains exhibit unique flow and chemical characteristics and are briefly described below:

1. The **mountain block** encompasses the fractured aquifer contained within the Proterozoic crystalline rocks in the Sangre de Cristo Mountains, which is the major recharge zone for the Tesuque aquifer system. Water chemistry is calcium-magnesium bicarbonate with local enrichment of chloride and sulfate and a relatively high dissolved solid content.

Mountain-block ground water chemistry affects the chemistry of water occurring in the adjacent Tesuque aquifer in the mountain-front domain as it mixes with fresh water recharged via channel infiltration. Ground water moves from the mountain block into the mountain-front domain preferentially at discrete locations that are likely associated with geologic structures such as faults, joints and fractures.

2. The **mountain front domain** includes a narrow, relatively shallow Tesuque aquifer system along the mountain front, bounded on the east by the mountain block and on the west by a combination of structural impediments to ground water flow, including the San Isidro Crossing fault and the Oligocene bedrock highs that limit Tesuque Formation thickness to approximately 2000 feet (Grauch and Bankey 2003, Fig. 8). Active ground water circulation probably occurs throughout the entire thickness of Tesuque Formation at this location. The deep piezometer completion at St. Michaels (SF-1A, EB-244 in Figure 4) provides chemical and hydraulic information from the base of this aquifer domain. Near the mountain front at Santa Fe, the aquifer exhibits strong vertically upward hydraulic gradients. From Tesuque northward and from Arroyo Hondo southward, the aquifer exhibits vertically downward hydraulic gradients as are more typical of a mountain-front recharge zone. Ground water chemistry is highly variable, reflecting the diverse chemistries of ground water in the mountain block, of surface water and shallow ground water in the Tesuque Formation, and the mixtures of these two sources. Stable isotope signature is that of modern mountain-front recharge.
3. The **Barrancos structure domain** includes a narrow, north-south zone between the mountain front and the center of the basin that is characterized by anomalous flow directions and steep horizontal hydraulic gradients. Many structural features align along this zone, including (from north to south) the Jacona and Las Dos fault systems, the two structural highs topped with Oligocene volcanic rock, and the San Isidro Crossing fault. These features are believed to originate from the Barrancos fault zone, a deep Precambrian basement structure. This structure domain separates two regions with distinct hydrologic and geochemical characteristics – the relatively thin mountain front aquifer domain to the east and the deep central basin to the west. The Barrancos structure domain is a transition zone for water type and chemical concentration for many ions and elements. Concentrations of many chemical constituents – dissolved solids, calcium, sodium, chloride and deuterium – change dramatically across this domain. Calcium is the dominant cation in the mountain front domain to the east and sodium dominates to the west. Stable isotope data indicate that modern mountain-front and stream channel recharge, which dominate the thin, mountain front aquifer to the east, do not contribute significantly to ground water storage west of the Barrancos structures. In the northern

portion of the Barrancos domain, deuterium data verify the presence of paleo ground water. The Barrancos domain is clearly not a complete barrier to flow, rather it consists of partial barriers and impediments that influence hydraulic gradients and flow direction within and across the domain. For example, ground water flow beneath the Santa Fe river corridor appears to divert northward between the San Isidro Crossing fault and the southern structural high. Distribution of deuterium, barium, chloride and magnesium suggests that the San Isidro Crossing fault may shunt shallow ground water around it's southern end as well (Figures 41, 37, 25 and 23).

4. The **Santa Fe platform** includes a thin Santa Fe Group aquifer of primarily Ancha Formation overlying Oligocene volcanic rocks of the Espinaso Formation at the southern end of the Santa Fe embayment. The Ancha aquifer is variably saturated to unsaturated in this domain. Total dissolved solids are more concentrated here than in adjacent Tesuque aquifer to the north. Water chemistry varies from a mountain-front composition of calcium-magnesium bicarbonate to a volcanic composition of sodium-calcium bicarbonate (similar to Espinaso Formation water) to mixtures of these two. A cluster of chemical and physical anomalies – warm temperature, reduced chloride, sulfate and strontium, slightly elevated arsenic, and slightly depleted deuterium – is situated west of El Dorado and aligned with structural depressions in the Santa Fe platform. Limited data on hydraulic gradients between the Ancha and underlying bedrock aquifers indicates that vertical gradients are neutral in the lower reaches of San Marcos and Gallina Arroyos to slightly downward near La Cienega. This is consistent with predominantly horizontal flow to surface discharge areas to the west and leakage across the southern and western boundaries of the embayment.

5. The **Rancho Viejo hinge zone** separates the Santa Fe platform from thicker Tesuque aquifer domains to the north and includes the portion of the Tesuque aquifer system situated over the zone of greatest slope in the plunging syncline that deforms underlying bedrock. The flexure domain exhibits great geochemical and hydrologic variability, suggesting a zone of complex ground water flow. Limited hydraulic data indicate vertically downward hydraulic gradients where the eastern limb of the flexure meets the mountain front as well as in the flexure's center. Vertically upward or neutral gradients dominate the western limb. General water type is primarily calcium-sodium and calcium bicarbonate (Figure 16), with increasing sodium concentrations with depth in the Tesuque Formation and in the Espinaso Formation (Figures 21 and 22). This zone is primarily characterized by local anomalies in ground water temperature that are consistent with zones of high heat flow and geochemical anomalies consistent with vertical upwelling of element-rich ground water, particularly arsenic and total ion content. Anomalously high

ion concentrations – calcium, bicarbonate alkalinity, chloride, sulfate and barium – are observed in wells completed along lower Cienega Creek in the Ancha and Tesuque Formations. A small band of warm, mineralized water is situated at the eastern end of the domain, from Rancho Viejo southeast toward El Dorado, and overlies a small graben associated with the southern extension of the San Isidro Crossing fault. Other local chemical anomalies of elevated arsenic (10-18 µg/L) and ions are situated between Valle Vista and Santa Fe Downs and northeast of Cieneguilla at the Santa Fe airport. Stable isotope data from shallow wells are consistent with modern recharge, but two relatively deep wells, EB-386 (Valle Vista #10) and EB-328 (the Chalmers well) indicate the presence of paleo or mixed ground water.

6. The **central basin** domain incorporates the portion of the Tesuque aquifer system centered over the northern axis of the basin syncline and extending northwest into the deepest part of the Española Basin, where the aquifer attains its greatest thickness of more than 7000 ft (Grauch and Bankey, 2003). This domain is dominated by strong, vertically upward hydraulic gradients in piezometers and domestic well pairs and a geochemical signature consistent with emergence of deep regional ground water into the shallow aquifer. Both shallow and deep wells west of Arroyo Calabasas, including the Buckman wells, have the warmest ground water temperatures in the basin (Figure 13). Water chemistry is dominated by element- and arsenic-rich, sodium bicarbonate water. Isotopic composition of ground water at depths greater than 400 feet below the water table is consistent with other chemical indicators of deep circulation and reflects the presence of paleo ground water. The chemical and hydrological characteristics of this domain suggest that ground water with deep circulation, probably including flow through the Espinaso Formation in the Santa Fe embayment, discharges across the Santa Fe flexure from the east and south to enter the Tesuque aquifer system over a range of depths. Ultimately, this ground water discharges to the Rio Grande, the Buckman well field, and other intermediate to deep water wells in the domain.

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A1. Location and well-construction information for ground water sites

A2. Summary of field parameters and major element chemistry of ground water samples

A3. Summary of minor element chemistry of ground water samples

A4. Summary of trace element chemistry of ground water samples

A5. Summary of stable hydrogen and oxygen isotopic data from ground water samples

Appendix B. Chemical and isotopic data from surface water collected in the Southern Española Basin.

B1. Location and site information for surface water sites

B2. Summary of field parameters and major element chemistry of surface water samples

B3. Summary of minor element chemistry of surface water samples

B4. Summary of trace element chemistry of surface water samples

B5. Summary of stable hydrogen and oxygen isotopic data from surface water samples

Table 1–Lithostratigraphic descriptions of Lithosomes and map units in the Tesuque Formation, southern Española Basin.

Map Unit	Unit Name	Unit Description
Tts	Lithosome S, undifferentiated fluvial deposits associated with ancestral Santa Fe River, middle to lower Tesuque formation	Pebbly sand channel deposits and fine sand, silt and mud floodplain deposits associated with a large drainage exiting the Sangre de Cristo Mountains; further subdivided on the basis of gross texture and stratigraphic position
Ttsag	Lithosomes S and A, zone of lateral gradation between lithosomes	Fine-grained lateral gradation between lithosomes S and A; predominantly fine sand, silty sand and mud; found in lower part of Archery well
Ttsc	Lithosome S, coarse-grained fluvial deposits of middle to lower Tesuque formation	Fluvial deposits characterized by a predominance of medium- to very coarse-grained sand and gravelly sand channel fills, with subordinate fine-grained floodplain deposits
Ttsf	Lithosome S, fine-grained fluvial deposits of middle to lower Tesuque formation	Fluvial deposits characterized by clay, silt and very fine- to fine-grained sand intercalated with subequal medium- to very coarse-grained, arkosic sand and gravelly sand channel fills; deposits of fine-grained lower Lithosome S are represented by intercalated fine sand and mudstone found below 2900 ft in Yates La Mesa #2 well
Tta	Lithosome A, undifferentiated	A granite-dominated gravel and arkosic sand, silt, and mud deposited on an alluvial slope, further subdivided on the basis of gross texture and stratigraphic position
Ttacu	Lithosome A, Cuarteles member of the upper Tesuque formation	Relatively coarse-grained alluvial slope deposits composed of granite-rich pebbly medium- to coarse-grained sandstone and sandy pebble-conglomerate channel deposits, with subordinate extra-channel deposits of slightly muddy, very fine-to very coarse-grained sandstone; generally reddish yellow to pink in color; interbedded sparse beds of dark gray to black basaltic ash, lithic- and biotite-rich coarse white ash, and white pumice lapilli. Unit progrades west over and laterally into distal alluvial slope sediment of upper Lithosome A (map unit Ttacuf) and south over fluvial deposits of Lithosome S
Ttacuf	Lithosome A, fine grained Cuarteles member of the upper Tesuque formation	Fine-grained extra-channel and overbank alluvial slope deposits composed of tabular beds of arkosic, very fine- to medium-grained sandstone and silty sandstone with subordinate intercalated siltstone and mudstone; 3-30% arkosic, coarse-grained, ribbon- to lenticular-shaped channel-fill deposits; pink in color; the channel-fills are relatively isolated and moderately to strongly cemented; coarse white ash and basaltic ash locally present. Unit grades laterally westward into basin floor facies of Lithosome B (map unit Ttbfu) and eastward into coarse unit of Lithosome A (map unit Ttacu)
Ttaml	Lithosome A, undifferentiated alluvial slope deposits of middle to lower Tesuque formation	Extra-channel sediment of silty sand with: 1) minor overbank sediment of silt, mud, and clay and 2) minor to subordinate channel sediment of arkosic, fine to very coarse pebbly sand and sandy pebble-conglomerate. Middle Lithosome A deposits are mostly tan and buff sand and silty sand. Lower Lithosome A deposits north of Chupadera include well consolidated, tan to buff, very poorly sorted silty very fine- to very coarse-grained sand and pebbly sand. Up to 50% of channel complexes are moderately to strongly cemented. Extra-channel sediment in distal alluvial slope is generally in very thin to thick, tabular beds of silty very fine- to medium-grained sandstone, siltstone, and claystone. Near (within 5 km) modern mountain front the proportion of channel sediment increases. Medial slope extra-channel sediment occurs in medium to thick beds of muddy to silty very fine to very coarse sand; white and gray ashes are preserved in the distal to medial slope. Unit grades laterally southward into Lithosome S.

Map Unit	Unit Name	Unit Description
Ttbfu	Lithosome B, basin floor deposits of the upper Tesuque formation	Basin-floor floodplain deposits composed of planar laminated to planar very thin to medium beds of claystone and siltstone, with minor (10-25%) thick channel complexes of fine- to very coarse-grained sand and gravelly sand; weakly to non-cemented
Ttbfm	Lithosome B, basin floor deposits of the middle Tesuque formation	Similar to map unit Ttbfu with dominance of siltstone, mudstone and claystone and very fine- to fine-grained sandstone floodplain deposits; sand is commonly grayish to pale brown with abundant greenish quartz grains and dark lithics. Unit grades laterally eastward and southward into map unit Ttaml.
Tte	Lithosome E,	Sandstone, muddy very fine- to very coarse-grained sandstone, and pebbly sandstone. It has a general gray to brownish gray color. Pebbles and sand grains are mostly composed of latite and basalt in varying proportions, but with the general trend of basalt increasing in abundance down-hole. I commonly observe that lithosome E grades upward into muddy volcaniclastic sand and then up into reddish brown sandy mud of lithosome S. Lithosome E appears to be well-consolidated in boreholes, based on caliper logs (e.g., the recent Jail well by the NM State Penitentary), and commonly is weathered and slightly muddy. Unit is not exposed so bedding character has not been observed. However, I suspect it has bedding similar to a typical alluvial fan: very thin to medium, planar to broadly lenticular beds intercalated with thin to thick, lenticular to tight and concave-up channel-fills.
Tcv	Vallito Member of Chamita Formation (ancestral Rio Grande deposits)	Channel-fills of sandstone and pebbly fine- to very coarse-grained sandstone intercalated with claystone and clayey very fine- to fine-grained sandstone floodplain deposits. Gravel consists of very weathered, intermediate(?) volcanic rock fragments and quartz; local gravel zones are rich in basalt or andesite, particularly to the south (in Buckman #2 and #3A). Sand contains abundant quartz that is subrounded to rounded and locally frosted; reddish gray to pinkish gray. Clay is light brown to very pale brown and well consolidated.
Tcvs	Sandy Vallito Member of Chamita Formation (ancestral Rio Grande deposits)	Well-sorted, subangular to rounded, light reddish brown (5YR 6/4), very fine- to coarse-grained sand intercalated with minor pink claystone and clayey fine sandstone; smoky and frosted quartz grains are present. Local pebbly fine- to very coarse-grained sand, where very coarse sand and pebbles are primarily of dacite with subordinate rhyolite and tuff.

Table 2–Direction of vertical hydraulic gradients, well data and water level elevation data from domestic well pairs, southern Española Basin.

Site ID	Site name	Screen elevation	Waterlevel elevation	Year measured	Formation	dh/dz
EB-356	CDEX	5867-5667	6313	2001	Tts	D
EB-355	CDEX	5467-5267	6270	2001	Tts	D
EB-022	Hagerman	>6759	6895	2004	Tta	D
EB-020	Hagerman	6734-6391	6868	2004	Te	D
EB-004	RanchoViejo	6357-6084	6360	2004	Tta	D
EB-005	RanchoViejo	6287-5812	6326	2004	Tta	D
EB-201	Ranney	>6240	~6276	1985-94	QTa	D/N
EB-202	Ranney	6268-6164	6265	2003	QTa/Te	D/N
EB-049	Embudo	>6868	7014	1991	pCe	D
EB-047	Embudo	6889-6709	6999	1990	pCe	D
EB-491	ElDorado	6656-6453	6962	2005	pCe	D
EB-462	ElDorado	6603-6220	6959	2001	pCe	D
EB-054	PecosTrail	7227-7120	7229	1981	pCe	D
EB-055	PecosTrail	>6927	7214	1981	pCe	D
EB-396	TurqTrail	6081-6073	6110	1977	QTa	N
EB-400	TurqHill	6103-6050	6113	1977	QTa/Te	N
EB-574	TurqHill	>6078	6114	2005	QTa/Te	D/N
EB-374	TurqTrail	6079-5978	6112	2004	QTa/Te	D/N
EB-330	LaCienega	>5964	6063	2004	QTa	D
EB-002	LaCienega	5981-5700	6043	2004	QTa/Ttc	D
EB-314	LosGolindrinas	6043	6053	2004	QTa	D
EB-313	LosGolindrinas	6001-5971	6050	2004	QTa	D
EB-113	LaCanada	6136-6116	6149	1985	Tts	D/N
EB-112	LaCanada	5989-5929	6144	1985	Tts	D/N
EB-369	Cerrillos I-25	6033-5973	6148	2004	Tts	U
EB-184	Cerrillos I-25	5922-5602	6160	2004	Tts	U
EB-130	North 14	>6096	6139	2004	QTa	U
EB-391	North 14	6103-6003	6145	2004	Tts	U
EB-148	Agua Fria LF	6129	6167	2000	Tts	U
EB-372	Agua Fria LF	5910-5730	6170	1999	Tts	U
EB-177	Leyba	5882-5822	6157	2000	Tts	U
EB-059	Leyba	5897-5697	6254	1999	Tts	U
EB-164	Peters	6297-6137	6210	2004	Tts	U
EB-611	Peters	5385-4585	6225	2004	Ttsf	U
EB-229	I-25	>6576	6576	2003	QTa	U
EB-014	MWBLujan	6555-6515	6592	2004	Tts	U
EB-229	I-25	>6576	6585	1995	QTa	D/N
EB-014	MWBLujan	6555-6515	6584	1995	Tts	D/N
EB-229	I-25	>6576	6581	1994	QTa	U
EB-014	MWBLujan	6555-6515	6604	1994	Tts	U
EB-229	I-25	>6576	6586	1993	QTa	U
EB-014	MWBLujan	6555-6515	6601	1993	Tts	U
EB-229	I-25	>6576	6584	1992	QTa	U
EB-014	MWBLujan	6555-6515	6602	1992	Tts	U
EB-170	Hickox #1	6880-6746	6827	1999	Tts	U
EB-123	Hickox #2	6563-6123	6849	1999	Tts	U
EB-095	EastTano	6844-6839	6912	2002	Tt	D
EB-087	EastTano	6761-6661	6875	2002	Tt	D
EB-178	SFO	6657-6535	6641	2003	Tts	D
EB-208	SFO	>6127	6616	2003	Tts	D

Table 3–Pearson correlation coefficients for select analytes in all water samples, southern Espanola Basin.

	Na	Mg	K	HCO3	SO4	Cl	F	SiO2	NO3	Fe	Mn	B	Ba	Li	Cr	Sr	U	2H	SpCond	TempC
Ca	-0.15	0.76	0.17	0.28	0.51	0.68	ns	ns	0.49	ns	0.26	ns	0.61	ns	0.45	0.24	ns	0.55	0.66	-0.30
Na		0.12	0.15	0.66	0.34	ns	ns	ns	-0.18	ns	ns	0.74	-0.33	0.93	ns	0.40	0.52	-0.57	0.58	0.24
Mg			0.19	0.38	0.74	0.40	ns	ns	ns	ns	0.50	ns	ns	ns	na	0.29	ns	0.40	0.75	-0.25
K				0.39	ns	ns	0.88	ns	ns	ns	ns	ns	ns	0.78	na	0.54	ns	-0.30	0.36	ns
HCO3					0.15	0.14	0.15	0.26	ns	ns	0.37	0.42	ns	0.87	na	0.53	ns	-0.39	0.68	ns
SO4						0.23	ns	ns	ns	ns	ns	0.67	-0.23	0.27	ns	0.44	ns	ns	0.66	ns
Cl							ns	ns	0.62	ns	ns	ns	0.55	ns	0.61	ns	ns	0.23	0.54	-0.23
F								ns	-0.27	ns	ns	0.48	ns	0.26	na	ns	ns	ns	0.26	0.23
SiO2									ns	ns	ns	ns	ns	0.35	na	0.25	ns	ns	0.26	ns
NO3										ns	ns	ns	0.73	ns	0.51	ns	ns	0.36	0.24	-0.23
Fe											ns	ns	0.49	ns	ns	ns	ns	ns	ns	ns
Mn												ns	0.71	0.47	ns	ns	ns	ns	0.33	-0.30
B													-0.30	0.59	na	0.46	0.62	-0.48	0.57	ns
Ba														ns	0.43	ns	ns	ns	0.21	-0.33
Li															na	0.57	0.47	-0.57	0.75	0.28
Cr																na	ns	na	na	na
Sr																	0.47	ns	0.59	ns
U																		-0.33	ns	ns
2H																			-0.27	ns
SpCond																				ns
TempC																				

Table 4—Pearson and Spearman correlation coefficients for arsenic-bearing ground water in the, southern Española Basin.

	All Arsenic Samples			West Santa Fe Arsenic Samples		
	Pearson r	Spearman rs	Number of Samples	Pearson r	Spearman rs	Number of Samples
SC	ns	ns	155	ns	ns	93
pH	0.37	0.24	150	0.28	0.21	87
Temp	0.23	0.32	104	0.25	0.40	72
Ca	-0.37	-0.53	168	-0.34	-0.49	98
Mg	-0.29	-0.35	167	-0.31	-0.40	97
Na	0.22	0.40	168	ns	0.33	98
K	ns	ns	163	ns	ns	98
SO4	ns	ns	174	ns	0.29	99
Cl	-0.18	-0.31	167	ns	ns	98
F	ns	0.26	165	0.30	0.32	94
SiO2	ns	ns	88	ns	ns	62
NO3	ns	ns	86	ns	ns	31
B	0.26	0.40	80	0.59	0.51	56
Fe	ns	ns	138	ns	ns	86
Mn	ns	ns	136	ns	ns	84
Li	0.26	0.31	74	0.28	0.45	50
Sr	ns	0.20	88	ns	0.29	63

Table 5–Pearson and Spearman correlation coefficients for barium-bearing ground water in the southern Española Basin.

	All Barium Samples			Elevated (>150 mg/L) Barium Samples		
	Pearson, r	Spearman, rs	Number of Samples	Pearson, r	Spearman, rs	Number of Samples
Al	ns	ns	72	0.65	ns	30
As	ns	ns	138	ns	ns	62
B	-0.30	-0.43	86	0.80	ns	36
Ca	0.61	0.46	157	0.64	0.52	75
SCond	ns	ns	82	ns	ns	45
Cl	0.55	0.19	161	0.60	0.54	77
Cr	0.37	ns	90	0.52	0.33	35
Cu	0.32	0.27	106	ns	0.39	51
F	ns	-0.57	153	-0.37	-0.52	76
Fe	0.49	0.30	107	0.79	0.40	58
HCO3	ns	-0.29	161	-0.21	ns	82
K	ns	-0.25	134	-0.25	-0.41	66
Li	ns	-0.43	84	0.43	ns	36
Mg	ns	0.17	154	ns	0.34	78
Mn	0.71	0.48	61	0.65	0.56	22
Na	-0.33	-0.68	160	ns	-0.48	75
NO3	0.73	0.52	153	0.71	0.70	82
pH	0.30	ns	72	0.46	0.44	34
Se	ns	ns	17	ns	ns	10
SiO2	ns	ns	25	ns	ns	14
SO4	ns	ns	135	ns	ns	72
U	ns	ns	24	ns	ns	12
V	ns	ns	15	ns	ns	7
Zn	ns	ns	74	ns	ns	39