# Geologic and Hydrogeologic Framework of the Española Basin -- Proceedings of the 6th Annual Española Basin Workshop, Santa Fe, New Mexico, March 6, 2007

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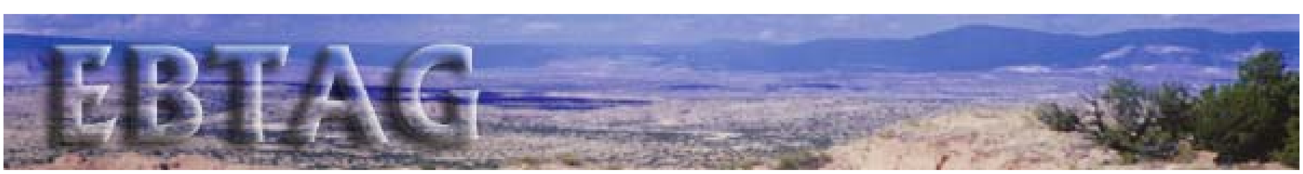


A product of the Española Basin Technical Advisory Group (EBTAG)

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## INTRODUCTION

By Claudia I. Borchert

This report presents abstracts of technical studies that pertain to the hydrogeology of the Española basin, a major subbasin of the Cenozoic Rio Grande rift. Sediments and interbedded volcanic rocks that fill the Española basin comprise an aquifer system that is currently one of the primary sources of water for residents of the basin, including people in the cities of Santa Fe, Española, and Los Alamos as well as Native Americans in eleven Pueblos.

The abstracts describe results of technical studies that were presented either as poster exhibits or oral presentations at the sixth annual Española basin workshop, held March 6th of 2007 in Santa Fe, New Mexico. The principal goals of this workshop were to share information from ongoing water- resource related studies and to seek input on important topics for further study.

The Española basin workshop was hosted by the Española basin technical advisory group (EBTAG) and sponsored by the U.S. Geological Survey, the New Mexico Bureau of Geology and Mineral Resources, Los Alamos National Laboratory, and the City and County of Santa Fe. The abstracts have been grouped into themes: geology and stratigraphy, three dimensional hydrogeological architecture, hydrogeology, ground-water flow, ground-water contamination, and hydrologic models. Additional technical information and previous workshop abstracts are available at http://esp.cr.usgs.gov/ebtag/ and a listing of studies in the basin grouped into themes is available at http://esp.cr.usgs.gov/ebtag/themes.html.

Abstracts in this report submitted by U.S. Geological Survey and Los Alamos National Laboratory authors have had their technical content peer reviewed before they were included in the report. There was no technical review requirement for abstracts submitted by non-USGS authors (although many did receive peer or agency review). Taken together, the abstracts in this report provide a snapshot of the current status of hydrogeologic research within the Española basin.

**CENOZOIC STRATIGRAPHY IN THE SANTA FE EMBAYMENT AND NORTHWARDS TO THE BUCKMAN WELL FIELD, ESPAÑOLA BASIN, NM**

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We use several cross-sections, primarily constructed using well data, to demonstrate stratigraphic relations in the southern Española basin. The Santa Fe embayment refers to the southernmost part of the Española basin that extends south of the city of Santa Fe. There, a Pliocene-age, west-sloping, alluvial-slope deposit called the Ancha Fm overlies pre-Pliocene strata deformed into a north-plunging syncline. The Ancha Fm pinches out north of Santa Fe against the Santa Fe uplands, and attains a 90 m thickness near the center of the syncline. The folded and faulted Cenozoic units beneath the Ancha Fm include, from bottom to top, the Galisteo, Espinaso, and Tesuque Fms. The Eocene-age Galisteo Fm underlies the Santa Fe embayment south of the Santa Fe River. It consists of SE-flowing axial river deposits to the WSW (bearing much quartzite and chert gravel) and tributary fluvial deposits to the NNE (bearing granite and subordinate limestone gravel). The Espinaso Fm generally extends across the entire southern Española basin, and represents a volcaniclastic alluvial fan shed ENE from latitic-intermediate eruptive centers in the Cerrillos uplift and Cerrillos Hills.

The Tesuque Fm consists of several units, informally referred to as lithosomes, which laterally interfinger with one another. On the southeast side of the embayment lies lithosome E, consisting of latitic and basaltic volcaniclastic sediment eroded from the Cerrillos uplift to the SSW. Lithosome E interfingers to the ENE with two fluvial units derived from the southern Sangre de Cristo Mountain (SdC Mtns). One of these two fluvial systems is called lithosome S. Lithosome S was deposited by a west-flowing, ancestral Santa Fe River sourced in the present-day Pecos River drainage. This lithosome is relatively coarse (mostly a pebbly sand), contains minor quartzite and Paleozoic sedimentary detritus, and is generally not strongly cemented. Lithosome S grades north and south into alluvial-slope deposits derived from the western flanks of the SdC Mtns. Called lithosome A, these alluvial-slope deposits consist of silty arkosic sand and minor pebbly sand channel-fills, where the clasts are predominately granitic.

The lower strata of the Tesuque Fm are more complicated than previously realized. It has recently been demonstrated that SdC Mtns-derived sandy gravels and sands interfinger with the distal parts of the Espinaso Fm volcaniclastic apron (equivalent to the Bishop's Lodge Member of the Tesuque Fm) and have large ranges in thickness. Overlying the Bishop's Lodge Member is a 100-125 m-thick interval characterized by widespread lithosome A strata intercalated with basalt flows probably correlative to the Cieneguilla basanite (25-26 Ma); lithosome S is much restricted in extent. The prevalent lithosome A sediment was restricted to the east side of the syncline axis, whereas lithosome E was restricted to the west side of the syncline axis – suggesting that synclinal folding exerted a control on sedimentation patterns at this time. Following 25 Ma, lithosome S deposits greatly expanded at the expense of lithosome A.

Exposed strata at the old Buckman well field are late Miocene in age. Here, wells largely pump from sandy axial river deposits belonging to the Vallito Member of the Chamita Formation. The Vallito Member interfingers eastward with distal alluvial-slope deposits of lithosome A. It overlies noticeably finer-grained, basin-floor deposits of the Pojoaque Member of the Tesuque Fm that consists of muddy floodplain deposits with subordinate sandy channel-fills.

**STRATIGRAPHIC AND GEOCHEMICAL RELATIONS OF PLIOCENE TEPHRA IN THE PAJARITO PLATEAU**

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The Pajarito Plateau, a deeply dissected east-tilted tableland capped by Quaternary Bandelier Tuff, occupies the western part of the Espanola Basin. At least six separate episodes of volcanism ranging in age from upper Oligocene to Pleistocene are recorded in and around the plateau (WoldeGabriel et al., 2006). Lava flows of variable compositions dominated the earliest volcanic eruptions; however, small-volume pyroclastic deposits were erupted in the southern and northeastern parts of the Jemez volcanic field during the upper Miocene and Pliocene. In contrast, Pleistocene volcanic activities culminated in large-volume caldera-forming pyroclastic eruptions.

We report here stratigraphic relations and geochemical characteristics of more than a dozen proximal tephra units from some of the Pliocene explosive eruptions that are recorded within volcaniclastic deposits of the Puye Formation in Ancho, Bayo, Rendija, Guaje, Sawyer, and Santa Clara Canyons. In Ancho Canyon at the southern part of the plateau, two primary tephra units are interbedded within pumice-bearing volcaniclastic sandstone below a thick conglomerate of Totavi Lentil at the base of the Puye Formation. A basaltic lava directly above the conglomerate yielded a $^{40}Ar/^{39}Ar$ age of 3.04±0.5 Ma. In Bayo Canyon, primary pumice and vitric ash units occur at the base of the Puye Formation about 2 m above upper Miocene basalt (8.86±0.05 Ma). The vitric ash yielded an age of 5.3±0.02 Ma. None of the tephra units in Rendija, Guaje, and Santa Clara Canyons were dated but they mostly occur in the upper half of the Puye Formation. The tephra units in Rendija and Guaje Canyons occur about 3 to 4 m above the conglomerate of Totavi Lentil. In Santa Clara Canyon, the thick tephra sequence is interbedded within fanglomerate units in the upper half of the north wall upstream of the Pajarito fault zone.

The major element chemistry of the tephra was investigated by analysis of discrete glass shards using an electron microprobe. The tephra samples range in composition from rhyodacite to high-silica rhyolite. The upper and lower tephra in Ancho canyon are rhyodacite and high-silica rhyolite, respectively. This is also true for the pumice and vitric ash layers in Bayo Canyon. Four of the tephra samples from Rendija and Guaje Canyons are chemically correlative and represent low-silica rhyolite, whereas three other samples have distinctive compositions of low-and high-silica rhyolite. Despite its occurrence below the Totavi Lentil, the lower tephra in Ancho Canyon is chemically correlative to a bedded tuff in Guaje Canyon that crops out about 3 to 5 m above quartzite pebble-bearing conglomerate. One of tephra from Rendija Canyon correlates with a major tephra unit exposed on the north wall of Santa Clara Canyon.

The tephra units intercalated within the Pliocene basin-fill sediments are useful time-stratigraphic markers and they provide temporal and spatial constraints on sedimentation and erosion processes and provenance in the Pajarito Plateau. The Ancho and Bayo tephra units occur within different lithologic units compared with correlative tephra in Rendija, Guaje, and Santa Clara Canyons, suggesting different source areas and sedimentation processes for the clastic deposits.

**PRELIMINARY CHARACTERIZATION OF FAULT ZONES AND POTENTIAL IMPACTS ON GROUND-WATER RESOURCES: ESPAÑOLA BASIN, NEW MEXICO**

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Fault zones within and flanking the Española basin of the Rio Grande rift show great diversity in structural style, orientation, scale, displacement magnitude and direction, fault rocks, cements, and geochemistry. Characterization of such structures is important for understanding how and at what scales they may influence ground-water supply and quality. Fault zones in the Española basin and east flanking Santa Fe Range of the Sangre de Cristo Mountains fall into several groups based on host and fault rock lithology, orientation and kinematics, age, permeability structure, and composition. These groups include: 1) steep ENE- and NE-striking, combined conduit-barrier faults that cut Proterozoic crystalline basement rocks, localized hydrothermal alteration, and show likely early strike-slip and possible normal-slip reactivation; 2) steep N- and NE-striking combined conduit-barrier normal faults involving Proterozoic crystalline and Phanerozoic sedimentary rocks that have hosted hydrothermal alteration; 3) generally NNE-striking, steep, partial-barrier normal and normal-oblique faults in poorly lithified Neogene basin-fill sediments that commonly have thin clay-rich cores and host variable degrees of localized cementation by calcite and silica; 4) NNW- to NNE-striking, normal and strike-slip, distributed deformation zones in Tertiary basaltic flows and shallow intrusions that may act as conduits; and 5) generally N-striking, steep, partial-barrier normal faults in Tertiary volcanic rocks.

Each group of faults has distinctive mineralogical and elemental geochemical signatures mainly associated with fault cores where most of the fault motion has been accommodated. Fault geochemistry generally is a product of protracted uplift and erosion of the crystalline basement rocks and coeval deposition of texturally and compositionally immature basin-fill sediments. This geochemical pattern is modified by variations in the types and duration of fault-related fluid flow processes as the rift flank-basin system evolved. For example, illite is the dominant clay in faults mainly in crystalline basement rocks that have localized hydrothermal alteration that is possibly related to the early evolution of the rift. In contrast, kaolinite is dominant in faults cutting both Proterozoic and Phanerozoic rocks, and smectite is dominant in faults in the basin-fill sediments. Aluminum and iron are prevalent in faults in the Proterozoic crystalline basement, whereas calcium and barium are prevalent in faults in basin sediments.

Observations and measurements that help characterize fault zone architecture and permeability structure indicate two fundamental differences between the rift flank and basin. Faults in rift-flank crystalline rocks appear to have some architectural attributes that could make them partial conduits for ground-water flow. In contrast, faults in the poorly lithified basin sediments show pervasive clay-rich cores, fault-localized cements, and no well-developed open fractures in damage zones, as are found in the crystalline rocks, suggesting that intrabasin faults are partial barriers to ground-water flow. At the mountain front-basin interface there does not appear to be a major fault zone that impedes recharge to the basin, but in the vicinity of wells and well fields within the basin, faults likely compartmentalize the aquifer. Future work will investigate if there are correlations between fault-rock and present-day ground-water geochemistry, as well as what role, if any, basement faults and other discrete geological features play in transporting natural constituents into the sediments of the Española basin.

**REVISITING THE USE OF MAGNETIC DEPTH ESTIMATES TO MAP THE THICKNESS OF THE SANTA FE GROUP IN THE SOUTHERN ESPAÑOLA BASIN**

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The Santa Fe Group sediments represent the primary aquifers within the southern Española basin near Santa Fe, New Mexico. These weakly magnetic sediments are generally underlain by moderately to strongly magnetic volcaniclastic, igneous, and basement rocks south of Santa Fe and along the eastern mountain front. Where this relationship exists in other parts of the basin, quantitative analysis of high-resolution aeromagnetic data can be used to estimate the sediment thickness, and thus the maximum thickness of the aquifers. Our previous analysis (Phillips and Grauch, 2004), which used the Euler method, revealed that sediments are generally <300 ft (91 m) thick over an irregular volcanic platform in the Santa Fe embayment and thicken dramatically to the north at a curvilinear hinge line to reach 2,000 ft (610 m) under Interstate 25 at Cerrillos Road.

Several developments have prompted us to update and expand the previous analysis: (1) a new aeromagnetic survey has extended the data area to the north and east; (2) lithologic picks in well data (used for calibration) have undergone significant updates (Koning and Johnson, 2006); and (3) magnetic analysis techniques have improved. The new magnetic depth estimates were made using the local wavenumber method. In this method, first and second derivatives of the aeromagnetic data, or of filtered versions of the aeromagnetic data, are used to construct a local wavenumber grid that forms peaks or ridges over the magnetic sources. The local curvature at the peaks or ridge crests of the local wavenumber can be used to estimate the source depth. The best overall thickness estimates for the Santa Fe Group were produced using the local wavenumber method on the first vertical integral of the aeromagnetic data. In addition, local wavenumber analysis on upward-continued aeromagnetic data provided limited information on depths to magnetic contacts within the deeper basement.

In some parts of the southern Española basin, the magnetic depth estimates show good correlation with the thickness of the Santa Fe Group sediments as measured in wells. This is especially true in the southernmost part of the basin, where the Santa Fe Group is relatively non-magnetic and is underlain by magnetic volcaniclastic rocks of the Espinaso Formation. In the southeastern part of the basin, where the Espinaso Formation is absent, the magnetic depth estimates tend to find deeper basement sources. Near Santa Fe, cultural magnetic sources mask the underlying geologic sources. In the central and northern part of the basin, where the Espinaso Formation is deep or absent, the exposed Santa Fe Group sediments tend to be more magnetic and produce anomalies that mask the effects of the deeper magnetic rocks. For example, in the Aqua Fria quadrangle the short-wavelength magnetic anomalies can be explained by a magnetic unit within the Santa Fe Group that follows the ridge tops and is displaced along north-trending normal faults. Magnetic depth estimates in the central and northern basin tend to find these shallow sedimentary sources or a combination of shallow and deeper sources. Along the eastern margin of the basin, the basement rocks exposed in the Sangre de Cristo Mountains extend beneath the basin. Where these rocks are magnetic, they can be used to estimate the thickness of the basin fill.

**PRELIMINARY INTERPRETATIONS OF AEROMAGNETIC DATA COVERING THE EASTERN MOUNTAIN FRONT OF THE ESPAÑOLA BASIN, NEW MEXICO**

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High-resolution aeromagnetic data were collected over the eastern mountain front of the Española basin to expand the existing coverage to the east and help characterize the interface between mountain-block and rift-basin aquifers. The new data, acquired by helicopter in late 2005, covers a 5-mile-wide (8-km-wide) strip from the northeastern part of Eldorado on the south to Chimayo on the north, including downtown Santa Fe. An earlier survey was flown in 1998 using a fixed-wing aircraft and covered most of the basin area east of the Rio Grande. Data from the two surveys were carefully processed into two compatible data sets then digitally merged together. Preliminary results have been obtained from depth analysis of the merged data (Phillips and Grauch, this volume) and qualitative interpretation in the area of new data.

Heterogeneity of magnetic properties within the Precambrian basement rocks has presented a major challenge to the analysis and interpretation of the aeromagnetic data. This heterogeneity was recognized in earlier interpretations and is confirmed by reconnaissance magnetic-susceptibility measurements at outcrops, which show that basement rocks range from weakly magnetic to strongly magnetic (on the order of $10^{-4}$ to $10^{-2}$ SI). The weakly magnetic rocks have little expression in the aeromagnetic data, whereas the strongly magnetic rocks produce high-amplitude anomalies that mask the effects of other rock units. Large volumes of weakly magnetic basement rocks are suspected in the subsurface from comparisons to gravity and seismic data. In these areas, aeromagnetic analysis is ambiguous, and it is important to integrate other geophysical and subsurface information. This latter step has not yet been done.

In areas where magnetic basement rocks are strongly magnetic, the expansion of the aeromagnetic data coverage to the east has helped delineate the extent of Oligocene volcaniclastic Espinaso Formation and provides new information on faulting, basement trends, and bedrock depths all along the eastern mountain front. Aeromagnetic patterns indicate that the Espinaso Formation is absent under the Ancha Formation in a triangle-shaped area in the northeastern part of Eldorado. The new data help define the northern apex of the triangle near Seton Village. The southwest corner of the triangle is near Galisteo Springs, and the eastern side of the triangle follows the mountain front in Eldorado. Linear aeromagnetic patterns occur over large areas of the mountain front. The patterns trend northwest near Eldorado but have more northerly trends further north. The northwesterly trends follow Precambrian lithologic units but appear to truncate against a major north-northeast-striking basement fault zone just west of the mountain front. North-trending magnetic patterns cross the Santa Fe River canyon with only minor disruption, suggesting that any lateral displacement along the Santa Fe River fault is minor. All along the mountain front, magnetic basement rocks can be traced 1-2 km basinward into the subsurface at depths of 500-1000 feet (150-300 m). West of this zone, it is unclear whether weak aeromagnetic signatures reflect an abrupt deepening of the basement or the presence of weakly magnetic basement rocks. In these areas, lack of strong basement signature allows the subtle aeromagnetic expression of a few north-northeasterly faults within the Santa Fe Group rift-fill sediments to be revealed.

## MAGNETOTELLURIC SOUNDINGS AND DEEP BOREHOLE GEOPHYSICAL DATA CONSTRAIN INTERPRETATIONS OF SUBSURFACE GEOLOGY OF THE SOUTHERN ESPAÑOLA BASIN, NEW MEXICO

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Magnetotelluric (MT) soundings, calibrated by sparse borehole geophysical data from deep wildcat petroleum exploration wells in the Albuquerque and Española basins, significantly improve geologic constraints for mapping subsurface stratigraphy and lithology in the Rio Grande Rift near Santa Fe and Los Alamos, New Mexico. Many of the borehole logs extend to 1.5-3 km depth, and a few to 5-7 km. Careful examination of the geophysical log response to lithology and porosity of Precambrian crystalline rocks and Pennsylvanian-Permian, Mesozoic, and Tertiary sedimentary rocks in the northern New Mexico region permits construction of physical-property-based stratigraphy. Oligocene, Miocene, and Pliocene igneous rocks, encountered in a number of holes, also have distinctive physical-property signatures.

In the upper crust, the resistivity of geologic units is largely dependent upon their fluid content, pore-volume porosity, interconnected fracture porosity, and conductive mineral content. Fluids within the pore spaces and fracture openings, especially if saline, can reduce resistivities in what would otherwise be a resistive rock matrix. Resistivity can also be lowered by the presence of electrically conductive clay minerals. Saturated, fine-grained sediments, such as clay-rich alluvium, marine shales, and other mudstones, are normally conductive from a few ohm-meters (ohm-m) to a few tens of ohm-m. In-situ measurements from local data show that coarser-grained sediments, such as gravels and clean sands, are commonly moderately conductive (tens of ohm-m). Similar in-situ resistivity measurements for sands and gravels are reported elsewhere in North America. Metamorphic rocks and unaltered, unfractured igneous rocks are normally moderately to highly resistive (a few hundreds to thousands of ohm-m). Carbonate rocks can have similarly high resistivities depending on their fluid content, porosity, and impurities. Fault zones may be moderately conductive (few to tens of ohm-m) when they are comprised of rocks fractured enough to have hosted fluid transport and consequent mineralogical alteration.

In the Española basin, MT soundings, located south of Los Alamos across the Pajarito fault and west of Santa Fe across the Cerros del Rio volcanic field, provide significant new geologic interpretations of buried Cenozoic sedimentary and igneous rocks, Santa Fe Group, Espinaso Formation, Galisteo Formation, and older Mesozoic and Paleozoic sedimentary rocks. Borehole resistivity data for Santa Fe Group and the Galisteo Formations below the water table were moderately conductive (greater than about 10 ohm-m), while Tertiary igneous rocks were resistive (greater than about 100 ohm-m). Resistivity data for the Mancos Shale indicate that it is a strong (2-10 ohm-m) electrical conductor. Where the Mancos occurs in the upper kilometer of crust it may function as local hydrogeologic basement. Permian rocks generally had both conductive and resistive signatures, while Pennsylvanian carbonates and Precambrian crystalline rocks were resistive (greater than about 100 ohm-m). Conductive Mesozoic rocks appear to be down-dropped about 600 m across the Pajarito fault accompanied by about 1 km thickening of Tertiary sediments. Conductive Mesozoic rocks appear to be down-dropped beneath the Cerros del Rio volcanic-field near the 1200’ well by about 900 m, accompanied by about 900 m thickening of Tertiary sediments.

## HYDROGEOLOGIC CHARACTERISTICS OF THE TERTIARY-AGE GALISTEO FORMATION, SANTA FE COUNTY, NEW MEXICO

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Ground-water supply development in the Santa Fe area has been primarily focused on the Santa Fe Group sediments of the Española Basin and the adjoining Santa Fe Embayment, while the underlying Espinaso and Galisteo Formations have been perceived as poor units for ground-water supply.

For the most part, the Galisteo Formation is a thick sequence of fine-grained sedimentary rocks that formed during the Eocene-time sedimentation in the Galisteo Basin. The Upper Galisteo Formation and part of the Espinaso Formation contain largely well-sorted sand and volcaniclastics. The surface expression of the Upper Galisteo Formation is south of Santa Fe, largely in rural areas of Santa Fe County north of the Galisteo Creek. With the exception of domestic and stock wells, ground-water development has not targeted the Upper Galisteo Formation.

Recent geologic mapping was coupled with exploratory well drilling to better define the character and extent of the Galisteo Formation as a ground-water supply near Eldorado. Test wells completed in the Upper Galisteo Formation produce 20 to over 50 gpm. The saturated thickness of the Upper Galisteo governs the well yield. Although, apparent hydraulic conductivity of the Upper Galisteo Formation is considered low (0.1 to 0.2 ft/d), the storage capabilities and water quality are appealing.

As a potential water supply, is the hidden Galisteo Formation the mother lode, fools gold, or somewhere in between?

**COMPLETING OUR UNDERSTANDING OF THE HYDROLOGIC CYCLE**

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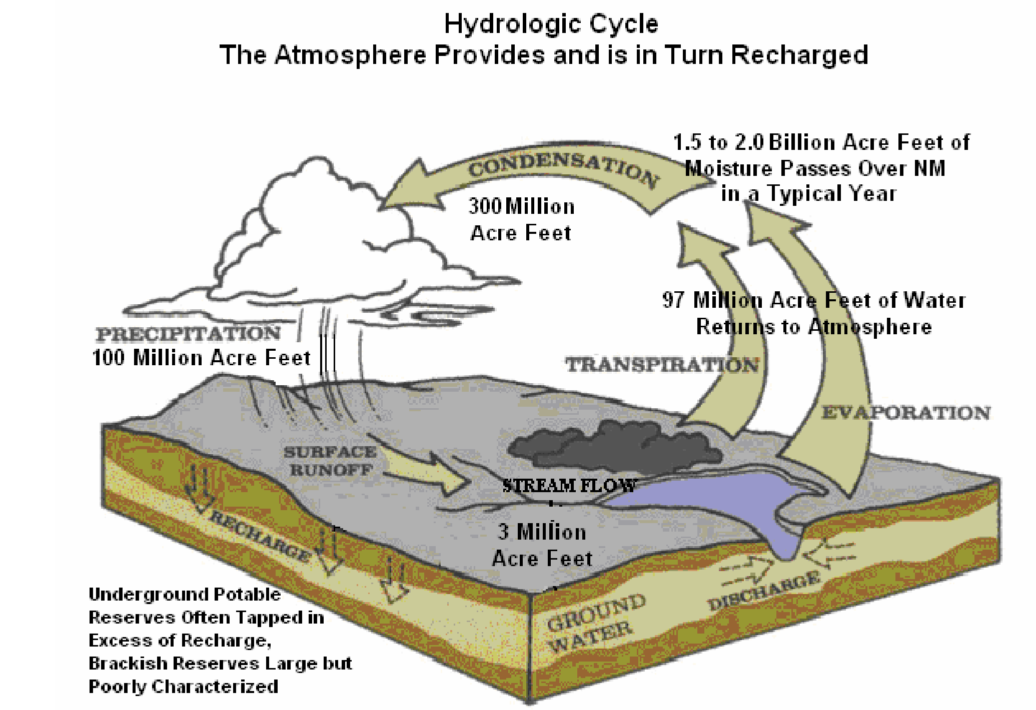
We need a better understanding of the atmosphere - Region 3 and all of New Mexico…Clouds do not respect Water Region boundaries. The atmosphere is part of the hydrologic cycle. We need to better understand:

Moisture patterns and their potential to produce precipitation

- Wind directions
- Temperature
- Altitude

Aerosols and their impact plus and minus on precipitation

- Particle size distribution
- Ability to function as CCN and IN




*Depiction of the hydrologic cycle.* ***Precipitation is not "lost"****, but is recycled through runoff, evaporation, and transpiration. New Mexico data added to a drawing created by the ND State Water Commission. Precipitation of 100 million af is an approximation derived by multiplying the area of the state times annual precipitation. If less than one-third of moisture in clouds falls as precipitation, then 300 million af of moisture passes over the state annually as clouds. If only 20% of atmospheric moisture condenses into clouds, then 1.5 to 2.0 billion af of moisture passes over New Mexico annually.*

**WHERE ARE THE TARGET AQUIFERS? -- A PRELIMINARY ASSESSMENT OF HYDROGEOLOGIC CHARACTERISTCS OF LITHOSTRATIGRAPHIC UNITS NEAR ESPAÑOLA, NORTH-CENTRAL NEW MEXICO**

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For various lithostratigraphic units near Española, potential hydrologic differences were assessed by estimating hydraulic conductivities from aquifer test transmissivity values. These transmissivity values were obtained from pumping tests of wells (120-1500 ft deep) screened across one or more of these lithostratigraphic units, which include Quaternary valley-fill and units in Santa Fe Group basin-fill (late Oligocene to late Miocene). Depths of particular Santa Fe Group lithostratigraphic units vary with location due to faulting and west-tilting of the Española half-graben. These hydraulic conductivity values ranged over two orders of magnitude, from 0.1 to 34 ft/day. The Quaternary-age valley fill has the highest hydraulic conductivity (K) values (range of 0.7 to 34 ft/day, averaging 10 ft/day). The Chamita Formation and middle to upper Ojo Caliente Sandstone of the Tesuque Formation may provide the most productive water-bearing zones in the Santa Fe Group proper (with most K values ranging from 0.7 to 7.3 ft/day), followed by a combined unit consisting of interbedded Ojo Caliente Sandstone-Cejita Members and underlying lithosome B of the Pojoaque Member of the Tesuque Formation (0.7 to 1.4 ft/day). In general, hydraulic conductivity values for the remaining lithostratigraphic units, located in a lower stratigraphic position, range from 0.1 to 2 ft/day, with lithosome B of the Pojoaque and Skull Ridge Members being on the higher end of that range. In general, hydraulic conductivity values seem to decrease with stratigraphically lower units. Other influences on hydraulic conductivity values and well yields include faults that act as barrier boundaries, stratified anisotropy from dipping beds, and secondary mineralization (cementation).

**GEOCHEMISTRY AND AGE OF ESPAÑOLA BASIN GROUND WATER**

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Ground water samples were collected from 44 locations in the Española Basin and analyzed for major and trace elements, carbon isotopes, noble gases, and tritium. The two dominant water types in the basin are $Ca/CO_3 + HCO_3$ and $Na/CO_3 + HCO_3$, followed by mixed-cation/$CO_3$ + $HCO_3$. Waters generally evolve from $Ca/CO_3 + HCO_3$ to $Na/CO_3 + HCO_3$ with increasing residence time through Ca-Na cation exchange with clay minerals. Basin ground water can be divided into four hydrochemical zones based on chemical and isotopic composition: (1) the West zone, including water on the Pajarito Plateau; (2) the Southeast zone, including water in the Santa Fe area; (3) the Northeast zone, including water in the Pojoaque, Chimayo, and Española areas; and (4) the Central Deep zone, including water underlying the lower Cañada Ancha area (Buckman well field vicinity) at depths >100-200 m below the water table. Central Deep zone waters have the highest concentrations of dissolved constituents (total dissolved solids [TDS], Mg, Na, K, and alkalinity), suggesting the greatest water-rock interaction. They have the heaviest $\delta^{13}C$ values, and probably have encountered a subsurface source of $CO_2$. West zone waters have the lowest concentrations of dissolved constituents (TDS and all major ions except Mg), suggesting the least water-rock interaction, and they have the lightest $\delta^{13}C$ values. Northeast zone waters have the highest concentrations of Cl and $SO_4$, probably due to mixing with deep-circulating brines. Southeast zone waters have locally elevated Cl concentrations, probably due to mixing with human-impacted waters. Hydrochemical zone boundaries appear roughly correlated with contacts between geologic units or lithosome transitions within the Tesuque Formation.

Geochemical mass transfer modeling was performed using NETPATH, and $^{14}C$ ages were adjusted accordingly. Isotopic input parameters were varied within reasonable limits to assess uncertainty in the adjusted $^{14}C$ ages. For each sample, a preferred adjusted age was selected from multiple possible adjusted ages based primarily on the fit between measured and modeled $\delta^{13}C$ values. The range of possible age adjustments for most samples is about 6000 years or less, indicating that the preferred adjusted age for most samples has a total range of uncertainty of <6000 years. Preferred adjusted ages range from 0 to 35,400 years. First-order trends include generally older ages occurring farther from major streams/rivers other than the Rio Grande, and farther from the mountain fronts. Ages also increase with depth in the Southeast zone, the only area where discrete-depth samples could be collected. Younger ages associated with the major surface water courses (including the Cañada Ancha arroyo) extend far out into the basin from the mountain front, suggesting that recharge in the form of stream loss may do the same. Tritium concentrations and apparent $^{3}H/^{3}He$ ages indicate that water in mountain block aquifers is dominantly <50 years old, and water in the basin fill is dominanty >50 years old, consistent with the $^{14}C$ ages. Terrigenic He (produced in the subsurface) concentrations are generally higher in the Northeast than the Southeast zone, possibly due to the greater number of mapped faults that might enhance the upward migration of deep crustal fluids that carry He produced in the basement. Concentrations of mantle-derived $^{3}He$ are generally the highest ($R/R_a$ of 1-2 in the terrigenic component) closest to the Quaternary to Miocene volcanics of the Cerros del Rio, Pajarito Plateau, and Jemez Mountains.

**RANCHO VIEJO INJECTION DEMONSTRATION PROJECT**

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In 2006, under Governor Richardson's Water Innovation Fund, Rancho Viejo de Santa Fe, Inc. drilled and tested an injection demonstration well and three observation well nests (A, B and C) in the Community College District (CCD) of Santa Fe County, in the southern Española Basin. Observation Well A penetrated the Bishops Lodge Member near the bottom of the Tesuque Formation at a depth of about 1700 feet. Geophysical and lithologic correlations with CCD Exploratory Well, drilled one mile east in 2001, indicate the Tesuque Formation dips westward about three degrees. The Injection Well and CCD Pumping Well, drilled one mile east in 2002, are screened in a common interval of Tesuque beds. Observation well nests are at distances of about 100, 500, and 2,000 feet from the Injection Well.

The Pumping and Injection wells are equipped with a pump, pipeline and mechanical control system for a six-month injection demonstration test, which was conducted from August 2006 to February 2007. The test objective is to see if the well and formation retain hydraulic efficiency through a six-month injection period. Water was pumped at 50 gallons per minute (gpm) from the Pumping Well, piped one mile, and returned to the aquifer through the Injection Well. A total of 40 acre feet was extracted from and reinjected to the Tesuque Formation. The area of pressure response reached about 1.3 miles from the injection screen due to radial displacement of injected water 40 feet into the aquifer. The CCD observation wells, Exploratory Well and four outlying wells were monitored for water-level response during the test. Recovery following shutdown is being monitored for six months until August 2007.

Response to 50 gpm injection at the site indicates the Injection Well and nearby Observation Well A (100 feet away) are completed in relatively transmissive material, partially bounded within a few hundred feet by units of lower permeability. End-of-test water-level change is 83 feet in the Injection Well and 65 feet in the Pumping Well. Water-level rise of about ten feet is measured at Observation Well C 2000 feet west. The geologic logs and hydraulic response are characteristic of a thick sequence of stacked linear channel sands at the Injection Well bounded by lateral overbank deposits. Fault displacement is mapped in the area of influence, but boundaries are not apparent in the response data.

The demonstration test results confirm that the Tesuque Formation is capable of receiving over 50 gpm artificial recharge by injection at a single well for six months. No screen clogging or aquifer permeability loss during the test is indicated.

**ALLUVIAL, INTERMEDIATE, AND REGIONAL GROUNDWATER RESPONSES TO SNOWMELT AND SUMMER RAINSTORMS ON THE PAJARITO PLATEAU, NEW MEXICO**

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Groundwater occurs in three distinct zones in the Pajarito Plateau of northern New Mexico: shallow alluvial, intermediate, and deep regional. The shallow alluvial groundwater exists in the canyon bottom sediments and is often seasonally saturated with isolated reaches of perennial flow maintained by natural spring input or anthropogenic discharges. Intermediate perched groundwater exists in subsurface bedrock above layers of low permeability or due to capillary barriers. The intermediate groundwater is highly variable in vertical and lateral extent and is an important monitoring zone for subsurface contamination. Deep regional groundwater serves as a drinking water source and is found at depths of over 1200 ft on the western side of the plateau to approximately 600 ft on the eastern edge of the plateau. There are inferred connections between the alluvial and the intermediate because contaminants i.e. high explosives, nitrate, perchlorate, and tritium are present in both alluvial and intermediate groundwater. A plateau wide monitoring network of alluvial, intermediate, and regional groundwater levels has been continuously in place for approximately two years. By thoroughly analyzing the water level data, we attempt to identify physical responses of recharge events and linkages between the three groundwater zones.

The alluvial groundwater shows immediate response to snowmelt runoff or consecutive rainstorms. Most intermediate wells do not show water level changes in response to runoff events. Isolated wells show apparent response to snowmelt runoff particularly wells completed in the Cerros del Rio basalt on the eastern edge of the plateau. The regional water level data show no apparent hydrologic response (measurable with transducers) between intermediate zones of saturation and the regional aquifer. However, the presence of anthropogenic tracers (contaminants) detected at select locations in the regional aquifer indicate linkage between the deep regional and overlying intermediate and alluvial groundwater zones.

**HELIUM/TRITIUM ISOTOPE GEOCHEMISTRY INSIGHTS, PAJARITO PLATEAU AND SURROUNDING AREAS, NEW MEXICO**

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Determining groundwater ages and flow paths within aquifer systems is essential for calibrating flow and transport models and designing and implementing effective monitoring systems. The Los Alamos National Laboratory and New Mexico Environment Department conducted an isotope and geochemical investigation from October 2004 through February 2006. The investigation evaluated groundwater flow paths and ages of samples collected from perched alluvial and intermediate zones and the upper portion of the regional aquifer beneath the eastern boundary of the Jemez Mountains (Sierra de los Valles) and the Pajarito Plateau, New Mexico. Water samples were collected at 23 single-screen wells located on the Pajarito Plateau and 27 springs discharging within the Sierra de los Valles and White Rock Canyon. Samples were analyzed for tritium, carbon-14, noble gases (helium-3, helium-4, and neon-22), stable isotopes of carbon, hydrogen, and oxygen, and inorganic solutes. Alluvial groundwater is entirely modern (recharged after 1943) based on the tritium/helium-3 dating method. Perched intermediate-depth groundwater, ranging in depths up to 600 feet, within the Sierra de los Valles and beneath the Pajarito Plateau, is either entirely modern or a mixture of modern and sub-modern (recharged prior to 1943) components. The regional aquifer is either sub-modern or mixed in age. Average groundwater ages for the regional aquifer range from 566 to 10,817 years, based on uncorrected carbon-14 measurements. The modern ages obtained for the majority of the Sierra de los Valles springs imply that most are sustained by local infiltration. The occurrence of modern recharge beneath wet canyons that dissect the Pajarito Plateau is supported by occurrence of tritium, nitrate, uranium, chromium(VI) and/or perchlorate in both intermediate perched zones and the regional aquifer. A tritium travel time of 25 years from surface water to the regional water table occurs within Mortandad Canyon. An average of 8 percent alluvial groundwater has mixed with 92 percent regional aquifer groundwater near the regional water table within portions of Mortandad Canyon, based on chloride concentrations within the two aquifers. The close similarity in stable isotope ratios between shallow regional wells on the Pajarito Plateau and some of the White Rock Canyon springs suggest the springs discharge groundwater from the uppermost portion of the regional aquifer. This is confirmed by the presence of elevated concentrations of tritium, nitrate, and/or perchlorate at some springs. Thus, it appears that perched intermediate zones beneath the Pajarito Plateau are connected to the White Rock Canyon springs.

**ON-SITE WASTEWATER MANAGEMENT IN THE ESPAÑOLA BASIN**

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Approximately 90% of New Mexicans use ground water as a source of potable supply, and 29% of state residents use on-site sewage systems. Conventional septic tanks and drainfields are a suitable means of on-site wastewater treatment and disposal when site conditions (underlying soil and geology, lot size, soil, depth to ground water, aquifer geochemistry, setback to wells and streams) are adequate for natural attenuation. Unsuitable site conditions, especially small lot size or fractured bedrock, however, have caused ground water contamination. As early as 1959, the N.M. Board of Public Health noted the unsuitability of septic systems for use in densely developed residential areas. Septic systems constitute the single largest source of ground-water contamination in the state, and have contaminated more public and private water supply wells, than all other sources combined. Source water assessments of approximately 1250 public water systems in the state identified on-site septic systems as the single greatest potential threat to wellhead areas. In the Espanola Basin, septic tanks have contaminated ground water in Alcalde, Chamita, Chimayo, Cuyamungue, El Rancho, Espanola, Hernandez, Jacona, La Puebla, Las Placitas, Medanales, Nambe, Pojoaque, Quartales, Santa Cruz, Santa Fe, Tesuque, and Velarde.

Septic tank effluent contains elevated total dissolved solids (TDS), nitrogen, chloride, organic carbon, and microbes, and can contain organic compounds including surfactants, solvents and pharmaceuticals. Ground water impacted by septic tank effluent typically contains elevated TDS and chloride. In oxic conditions the ammonia in sewage can oxidize to nitrate and contaminate ground water. The “Blue Baby Syndrome” caused by ground-water nitrate contamination has occurred in New Mexico. In anoxic conditions, however, ammonia does not undergo nitrification, and is not detected in ground water at appreciable levels, suggesting that it is removed by cation exchange or by volatilization. Organic carbon in the effluent can be oxidized by ground-water bacteria, which will increase the demand for, and consumption of, available electron acceptors used for respiration. Ground-water bacteria will preferentially respirate, and chemically reduce, dissolved oxygen, nitrate (denitrification), geologic manganese and iron oxide minerals, sulfate and carbon (methanogenesis), in that order, based on decreasing energy yield to the organism. Reduction of manganese and iron oxides releases soluble metal ions into ground water, and sulfate reduction creates hydrogen sulfide gas. These anaerobic respiration byproducts (ARBs) can create severe aesthetic and economic problems, and high levels of manganese in drinking water may present neurological risks. Many regulatory programs for sewage discharges focus on protecting ground water from nitrate. Consideration also should be given to protecting ground water from ARBs where geochemical conditions allow their generation.

Alternatives to conventional septic systems include non-discharging systems, split flow systems, advanced treatment systems, cluster systems, and regional sewage collection and treatment systems. The Village of Cordova, where 96% of the households utilized illegal cesspools and raw sewage sometimes flowed down the streets, obtained funding to install cluster systems. Modern septic tanks are being installed at individual residences to provide primary wastewater treatment. The septic tanks will discharge to one of two tertiary (nitrogen reducing) treatment systems, which will then discharge high quality effluent to a conventional disposal system.

**NMED PETROLEUM STORAGE TANK BUREAU REMEDIAL ACTION PROGRAM**

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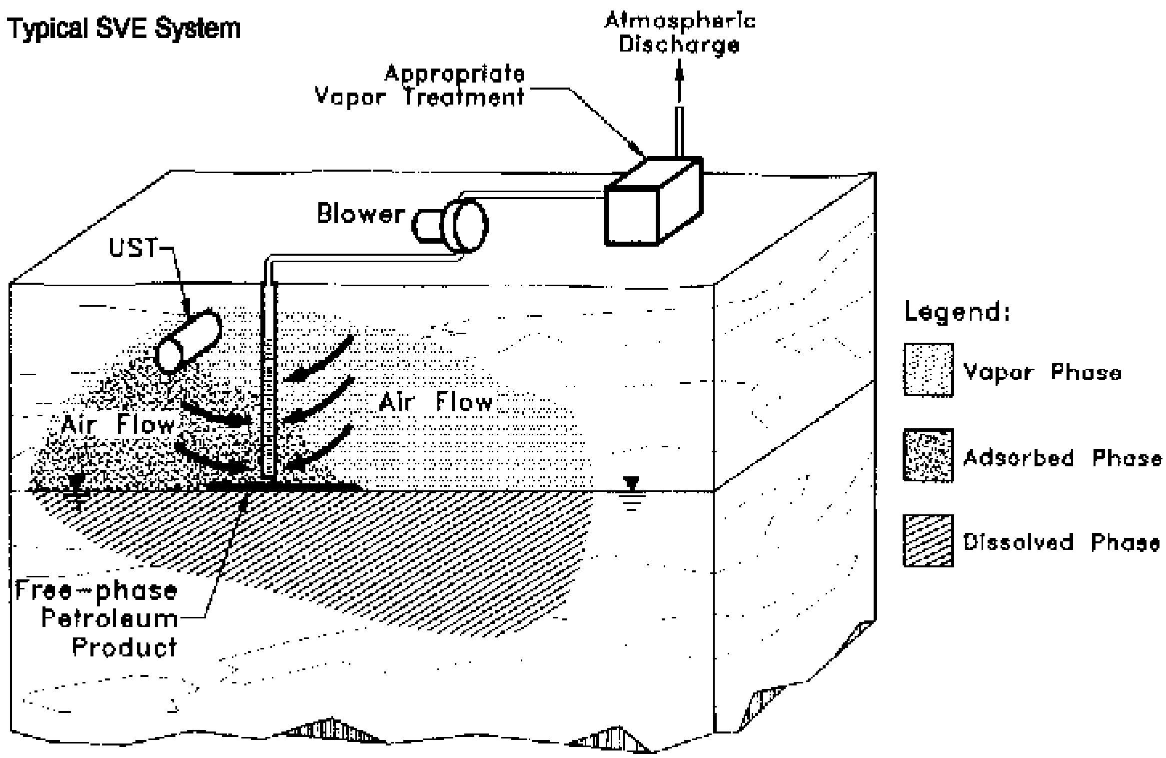
The mission of the Petroleum Storage Tank Bureau of the New Mexico Environment Department (NMED) is to reduce, mitigate and eliminate threats to the environment posed by petroleum products released from underground and above ground storage tanks. There are 303 tank facilities (past and current) in the Española Basin; the number of reported releases since the early 1990s is 137; 96 of which have been closed.

The Corrective Action Fund (Fund) has been used since its inception in the early 1990s to clean up storage tank leaks while protecting ground water. Funded by a petroleum products loading fee, the Fund is available to cover the costs of investigation and cleanup when a storage tank owner or operator has a release. On March 8, 2004, Governor Bill Richardson signed House Bill 19 giving the NMED the ability to shift up to 30 percent of the Fund to more broadly address the state's water quality.

It is important that cost-effective cleanup solutions be chosen, and that the technology be appropriate for the site and spill conditions. One method is soil vapor extraction (SVE). A vacuum is applied to the soil, and volatile vapors from above the water table are drawn toward extraction wells. The vapors are treated, then vented to the atmosphere.




From: *How to Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites*, EPA 510-B-95-007, USEPA, May 1995.

A trailer mounted internal combustion engine (ICE) SVE system was installed last summer at a former gasoline station facility to clean up an old petroleum hydrocarbon release. Initial results indicate that ICE is an effective technology to remediate the soil and ground water at the site.

**USE OF INTERA HYDROLOGIC MODEL FOR DETERMINATION OF GROUND WATER SUPPLY FOR SANTA FE COUNTY: NEXT STEPS**

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At the 2006 EBTAG conference, Intera and Santa Fe County presented their hydrologic modeling for the northern Santa Fe Basin, as part of an initial effort by Santa Fe County to develop a conjunctive use strategy, utilizing ground water supply to supplement the Buckman Direct Diversion surface water supply.

Based on the results of the model, certain areas were recommended for detailed analyses of specific locations. Such locations include: 1) Existing wells; 2) County-owned facilities; 3) Other potential well sites on county land. Initial locations for analysis were chosen on the basis of favorable aquifer characteristics and nearness to existing County infrastructure.

Santa Fe County has since submitted an application to the Office of the State Engineer for transfer of water rights to a listing of multiple well locations. The County has also contracted for the drilling of a well at its new Public Works facility, and is completing an RFP for the drilling of replacement wells at Valle Vista. Discussions have begun to consider acquisition of privately-owned production-level wells in favorable locations.

Intera is currently refining the model. Model results and drawdown predictions will be used in administrative hearings related to water rights transfers, and in analyzing the feasibility of well locations.

The hydrologic model is but one part of the overall water supply project. The goals of the modeling for Santa Fe County are twofold: 1) To produce a model that can be used for regional analysis as well as analysis for specific well locations; 2) To appropriately select favorable locations for ground water supply for the County utility.

**A LONG-TERM GROUNDWATER MODEL FOR THE NORTHERN ESPAÑOLA BASIN, NEW MEXICO**

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Modeling of surface water-groundwater interaction is of a great importance in groundwater management especially in arid and semi-arid regions. Traditional approach to water resources management has been treating the surface water and groundwater as separate entities. However, new trends and developments in land and water resources management have indicated that the development of either of these resources affects the quality and quantity of the other (Winter et al. 1998). Understanding the hydrologic interactions is the key element for the conservation and effective management of limited water resources in semi-arid climates such as New Mexico. In order to improve the understanding of hydrologic interactions and explain the long-term characteristics of a New Mexican hydrologic system, this research proposes the development of a 3-D groundwater model supported by a geological model for the irrigated cropland corridor and its vicinity along the Rio Grande in the Northern Española Basin. The main research objectives are (1) to create a 3-D groundwater model for the Northern Española Basin, more specifically for the portion of the Rio Grande between the Embudo gauging station and the confluence with the Rio Chama, in order to predict the aquifer head changes and directions of groundwater flow in the region and explain the hydrologic system dynamics based on the model results, (2) to develop a detailed 3-D geological model in order to produce geologic input data for the groundwater model as well as obtaining some of the aquifer parameters based on the geological properties of the model layers, (3) to investigate the effects of future management scenarios on the hydrologic response of the system in the study area, (4) to perform sensitivity/uncertainty analysis in order to determine the contribution of model parameters and assumptions to the overall validity of the model, (5) to investigate the long-term behavior and variability of the hydrologic system in response to the potential impacts of climatic change (e.g. potential evapotranspiration and precipitation), (6) to guide the development of sustainable new strategies for water resources management in the region based on the long-term behavior of the system.

**COUPLED INVERSION OF A GROUNDWATER FLOW MODEL WITH PUMP TEST DATA AND LONG-TERM MONITORING DATA**

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Long-term groundwater monitoring at the Los Alamos National Laboratory Site, New Mexico, started in the mid-1940s. Recently, pump tests at water supply wells PM-2 and PM-4 were conducted, in part, for calibrating the site numerical model. A stepwise inverse method was developed to estimate the model parameters by coupling observation data from different sources and at various spatial scales ranging from single-well test, multiple-well pumping test to regional aquifer long-term monitoring data. A stratified aquifer system with more than 20 hydrofacies was developed based on a detailed hydrogeological framework model. To determine the flow parameters for these hydrofacies, we first conducted statistical analyses of outcrop permeability measurements and single-well slug or pumping test results to define the prior distributions of the parameters. This prior information was used to define the parameter initial values and the lower and upper bounds for inverse modeling. A number of inverse modeling scenarios were conducted including using drawdown data from the PM-2 and PM-4 pump tests separately, and a joint inversion coupling PM-2 and PM-4 pump test data, and head data from regional aquifer long-term monitoring. Parameter sensitivity coefficients for different data sets were computed to analyze the parameter identifiability in different scenarios. The scale-dependence of permeability is discussed based on the influence ranges of the pumping tests and the spatial scales of the data sets. Finally, the coupled inversion results offer a reasonable fitting to all data sets. The uncertainty of estimated parameters for the hydrofacies is addressed with the eigenvalues of covariance matrix and the parameter confidence intervals.

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