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Analysis of Capture Zones of the Buckman Wellfield and a Proposed Horizontal Collector Well North of the Otowi Bridge

Author(s):

Velimir V. Vesselinov, EES-6, LANL
Elizabeth H. Keating, EES-6, LANL

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Velimir V. Vesselinov
Elizabeth H. Keating

Hydrology, Geochemistry, and Geology Group
Earth and Environmental Sciences Division
Los Alamos National Laboratory

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EXECUTIVE SUMMARY

The management of the Department of Energy (DOE) and the Los Alamos National Laboratory (LANL) is concerned about the potential effect of past and present activities at LANL on groundwater quality in the Española basin. The basin is an important source for municipal and agricultural water supply in Northern New Mexico. The Buckman wellfield provides more than one third of Santa Fe municipal water supply and its withdrawal rates are among the highest in the region. To increase the Santa Fe water supply, a new horizontal collector well is planned for construction on the east bank of Rio Grande. Analysis of capture (well-head protection) zones of these water supply wells is one way to address the water-quality concerns. The work presented in this report is based on results obtained by the ongoing regional hydrogeological study and modeling of the Española basin (LANL, 1998; Keating et al., 2000, 2001).

The major questions that we have addressed in this study are as follows. What is the source of groundwaters pumped at the Buckman wellfield? What would be the source of groundwaters pumped at the new horizontal collector well? What are residence times for waters extracted by these systems? If groundwater from the aquifer beneath LANL is pumped at either or both of these water-supply systems, what would be the groundwater travel times and how much mixing of groundwaters originating from various different sources would occur at the wellheads?

Our initial analysis considers the Buckman wellfield alone (without pumping at the collector well). The three-dimensional capture zone of the wellfield includes areas both west and east of the Rio Grande and a portion of the Rio Grande itself. At steady state, the predicted relative proportions of water extracted at Buckman are 27% from the Rio Grande and the Pojoaque river, 34%—western basin, including the Pajarito Plateau, and 39%—eastern basin. Of the water originating in the west, most is recharged at high elevations, outside the LANL boundaries, but flows through the regional aquifer beneath the laboratory.

Our second analysis considers both Buckman and the proposed horizontal collector well simultaneously. According to our model, there will be interference between the Buckman wellfield and the horizontal collector well; however, this interference is not substantial and does not significantly change our estimate of the Buckman capture zone. In our first analysis (without the collector well), it was predicted that a small portion of water pumped at Buckman comes from the Pojoaque sub-basin to the north. A portion of this water will be now captured by the new collector. At steady-state, the predicted ratios of water extracted at the collector well from rivers, western and eastern recharge are respectively 45%, 43% and 12%. The predicted collector-well capture zones include portions of western parts of the basin, entirely outside (north of) the LANL boundaries.

We also simulated the advective-dispersive groundwater transport of hypothetical non-reactive, non-decaying, aqueous species from the water table at five locations in vicinity of LANL. The hypothetical sources at the water table are assumed to be permanent in time with a constant concentration. A portion of species originating from these locations will be captured at Buckman. The dilution factors at Buckman averaging over all pumping wells range from 3.4×10^{-7} to 5.8×10^{-5} from the source concentration. The mean advective-dispersive travel times to Buckman (defined by the arrival of a half of the respective highest concentrations) are on the

order of thousands years. There is no advective-dispersive groundwater transport from beneath LANL in the direction of the horizontal collector well. However, groundwater from these five water table locations in vicinity of LANL will be also captured by the Los Alamos water-supply wells on the Pajarito Plateau; more importantly, the dilution is less, and the travel times are shorter compared to those for Buckman.

The model we have applied to this problem is limited by the amount of the available hydrogeological data and is based on many assumptions and simplifications of the actual hydrogeological conditions. Adding complexity and detail to the model and collecting new data would not significantly change our estimates of the spatial extent of the Buckman capture zone beneath the Pajarito Plateau. The predicted travel-time and dilution results are meant to be illustrative and are best used by comparing one to another, rather than as absolute concentration predictions. The computed travel times represent the mean arrival of the hypothetical plumes at the wells. However, due to dispersion of the aqueous species in the aquifer, part of the plume would arrive faster, part of it would arrive slower. The calculated dilution factors depend on the size and duration of the source. If the hypothetical releases at water table were simulated with a smaller size or for shorter time the dilution factors would be smaller.

As more data is collected as part of our ongoing hydrogeological characterization study of the region (LANL, 1998), the results presented in this report will be updated.

INTRODUCTION

The management of the Department of Energy (DOE) and the Los Alamos National Laboratory (LANL) as well as the public are concerned about the potential effect of past and present activities at LANL on groundwater quality in the Española basin (Figure 1). The basin is an important source for municipal (Los Alamos, Santa Fe, Española, and other smaller communities) and agricultural water supply in Northern New Mexico. The Rio Grande and its tributaries are a regional drainage system of the basin. The Rio Grande is subdividing the basin into western and eastern parts (Figure 1). Groundwaters from both parts of the basin predominantly discharge at the river. The Buckman wellfield is located to the east of the LANL boundaries on the east bank of Rio Grande (Figure 2). It provides more than one third of Santa Fe's water supply (Duke Engineering and Services, 2000) and its withdrawal rates are among the highest in the region (Figure 6). To increase the Santa Fe water supply, a new horizontal collector well is in construction on the east bank of Rio Grande (Figure 2).

Analysis of capture zones (also called well-head protection areas) of the water supply wells is one way to address the water-quality concerns. The zones define the three-dimensional regions from which the wells are capturing their water. Key questions that we have addressed in this study are: What is the source of groundwaters pumped at the Buckman wellfield? What would be the source of groundwaters pumped at the potential new horizontal collector well? What are residence times for waters extracted by these systems? If a contaminant were present in the regional aquifer beneath LANL, would it eventually reach either or both of these collection systems, and, if so, how much dilution would occur?

The work presented in this report is based on the ongoing regional hydrogeological study and modeling of the Española basin (Keating et al., 2000, 2001). It is also closely related to one of the objectives of the LANL Hydrogeological Characterization Program (LANL, 1998), which is to define zones of capture for water supply wells on the Pajarito Plateau. The basin hydrogeological model allows consistent capture-zone delineation, analysis and updates for any existing or new groundwater-supply system in the region. The model also allows basin-scale evaluation of groundwater resources, recharge, subsurface- and surface-water interaction, flow and transport.

Since the estimated capture zone of Buckman wellfield includes portions of the aquifer beneath LANL, advective-dispersion simulations of groundwater transport are conducted to estimate travel times and dilution factors of hypothetical aqueous species originating at the water table beneath LANL. We also assessed the sensitivity of our predictions in respect to some of the model parameters.

HYDROLOGIC SETTING

In support of the LANL Hydrogeologic Characterization Program (LANL, 1998), Keating et al. (2000, 2001) have analyzed the available hydrogeological information about the Española basin and developed a three-dimensional model of the regional groundwater flow and transport. The analysis presented in this report is based on their results. Here we will present only the part of the hydrogeological information that is directly related with the studied area, and will briefly discuss the model; for more details, the reader is referred to the prior publications (Keating et al., 2000, 2001).

The Buckman wellfield is located to the north of the Santa Fe, east of LANL, very close to the Rio Grande (Figures 2 and 3). It includes 8 pumping wells (B-1 to B-8) as well as several monitoring (piezometer) nests (SF-2 to SF-5) and boreholes (Duke Engineering and Services, 2000). The aquifer at Buckman is entirely composed of the Santa Fe Group sediments. The logs of Buckman wells demonstrate significant heterogeneity of the pumped aquifer (Shomaker, 1974).

The City of Santa Fe uses both surface and ground waters for municipal water supply (Duke Engineering and Services, 2000). The groundwater withdrawals are from the Buckman wellfield and wells within the limits of Santa Fe. The Buckman wellfield currently provides about 42% of the water supply. Some of the available data about the wellfield are summarized in Table 1 and Figures 4 and 5. The pumping started in 1972. Figure 4 shows how the pumping rates of the wellfield and individual wells fluctuated in time (some of the data is missing for the period before 1982). Figure 5 presents the observed decline of the groundwater levels in piezometer nests as a result of the pumping. Most of the drawdown is observed about 100 m below the ground surface, which might indicate that a substantial portion of the pumped water comes from this part of the aquifer. The differences in the observed drawdown among the intervals for each monitoring nest demonstrate the significant heterogeneity of the aquifer in vertical direction. Figure 4 shows the total averaged annual pumping rates at Buckman (in kg/s). There was significant increase (approximately factor of two) in the pumping rate in the late 1980's. The averaged annual pumping rate for the last 5 years is 191.1 kg/s (3029 gpm); the corresponding averaged rates for each borehole are listed in Table 1.

To increase the groundwater supply of the City of Santa Fe, a new horizontal collector well is planned for construction on the east bank of Rio Grande (Lewis, 2001; Bailey, 2002), approximately 1,000 ft upstream from the Otowi Bridge (Figure 2). It would be designed to pump at rate of 44 kg/s (700 gpm). A demonstration collector has been constructed and currently tested to obtain preliminary information about the hydrodynamic and hydrochemical conditions. The vertical caisson will have inside diameter of 10 ft and will be installed 30 ft below the ground surface. The horizontal intakes will be 150 ft long with diameter of 8 in and will be placed 4 ft above the caisson bottom.

Close to Buckman and the collector well, there are other water-supply wells. Our model simulates the pumping for groundwater supply of Los Alamos county and LANL (Figure 6). All of these wells are located west of the Rio Grande (Figure 2). However, it is unknown whether there is additional groundwater discharge in the basin, including from wells in close vicinity to the Buckman wellfield and the collector well (e.g. wells in San Idelfonso, Pojoaque and Nambe Pueblos). Due to lack of information about the well locations and their rates this additional discharge is not incorporated in our model. This, however, could have an important impact of our predictions about the size of capture zones and distribution of groundwater resources.

For the Rio Grande reaches in the vicinity of Buckman there is no information about groundwater recharge/discharge after 1969 when the Cochiti streamflow gage station on Rio Grande was eliminated due to the construction of the Cochiti reservoir. Based on the known pumping rates of the wellfields in the region (Los Alamos, Buckman, Santa Fe), we can conclude that at present the averaged annual total rate (about 450 kg/s) exceeds the measure annual groundwater discharge to the Rio Grande before 1969 (about 380 kg/s) (Figure 6). The unaccounted groundwater pumping discussed in the paragraph above would further increase this gap. Since June 2001, there is a new gage station on Rio Grande at the confluence of the White Rock and Frijoles Canyons, downstream from Buckman (USGS station # 08313268). For January 2002, the difference in the measured flow at this gage and the one close to the Otowi bridge, upstream from Buckman (USGS station # 08313000), defines discharge of river water to the aquifer at rate of about 1,000 kg/s (the location of both gages is shown in Figure 2). This could indicate a substantial depletion of surface water resources.

The available surface water for groundwater recharge is controlled by the water consumption along the rivers and the existing reservoirs (Heron, El Vado, Abiquiu, Cochiti) which are part of the San Juan-Chama Diversion Project. Since 1960s, water of the Colorado River Basin in southern Colorado has been diverted through 26 miles of tunnels under the Continental Divide into the Rio Grande Basin.

The available regional data for the pre-development (circa 1950) and present hydraulic heads are used to generate maps of water table elevation presented in Figures 7 and 8, respectively. The structure of groundwater flow is impacted by the topography. The low hydraulic heads in middle parts of the basin is due to the interaction between surface and subsurface waters. The high hydraulic heads east and west of the Rio Grande are due to higher precipitation along the mountain ranges. The horizontal gradients are towards the Rio Grande and the river is a regional groundwater discharge zone. This observation is supported also by the upward vertical gradients measured in the Buckman wellfield and by the numerous artesian wells along the river to the north of the wellfield (Keating et al., 2000). Vertical cross-sections of three-dimensional hydraulic-head field close to Buckman based on present data are shown in Figure 9. The figures demonstrate the complex three-dimensional structure of groundwater flow including the upward vertical gradients close to Rio Grande.

Precipitation is an important source of groundwater recharge. A map of the average annual precipitation in the region is given in Figure 10. In the vicinity of Buckman, precipitation rates increase much more quickly to the west than to the east.

There are several indications in groundwater chemistry data that very old groundwaters are present near the Rio Grande. First, as shown in Figure 11, the ^{14}C age of groundwater increases across the Pajarito Plateau from west to east (Rogers et al, 1995). Near the Rio Grande, waters older than 30,000 years have been sampled. Young waters are also present near the river, as both short and long flowpaths are expected to be converging in a groundwater discharge zone (Figure

9; see also Figure 13 described below). In addition, stable isotopes (^{18}O and deuterium) have been measured in waters on both sides of the basin (Anderholm, 1994; Blake, 1995). Very light $\delta^{18}O$ values (<–13 permil) have been measured in several wells near the Rio Grande (Figure 12). Such light values were not observed in any wells far from the river. These values were interpreted by Anderholm (1994) to indicate very old waters that were recharged tens of thousands of years ago in a significantly colder climate.

This description of hydrologic conditions in the Española basin suggests complex groundwater flow in the aquifer. A textbook example of the groundwater flow from mountain ranges towards rivers is presented in Figure 13. The conceptualization assumes uniform recharge and unconfined, uniform and isotropic aquifer without pumping. It is important to note that there are groundwater divides below the river and the mountaintops. A groundwater divide restricts any mixing of water from opposite sides of the aquifer except at the point of discharge. However, due to recharge non-uniformity, aquifer heterogeneity and anisotropicity, and groundwater pumping we can expect a more complex flow system which will not have groundwater divides below the river. Schematic representations of different recharge/pumping scenarios are shown in Figure 14. The first graph (a) shows the pre-development situation when the recharge from west (Pajarito Plateau) and east (Sangres de Cristo) are discharged to the river (Rio Grande). If the well pumping (at Buckman) is much less than the amount of water recharged to the east (b), there could be no pumped water coming from the river or the western portion of the aquifer. If the well pumping is higher (c), it can produce discharge of the river water to the aquifer. Further increase in the pumping (d) can cause groundwater from the western portion of the aquifer to flow beneath the river towards the wells.

GROUNDWATER FLOW AND TRANSPORT MODEL

General model development

The regional groundwater inverse model of the Española Basin has been developed (Keating et al., 2000, 2001) using finite-element heat and mass transfer code FEHM (Zyvoloski et al., 1997), grid generator LaGriT (Trease et al., 1996), and automated parameter estimator PEST (Doherty et al., 1994).

The horizontal extent of the model domain is presented in Figure 1 (the red line). The northern and southern boundaries of the basin model were located according to structural transitions between the Española Basin and neighboring basins where basin-fill sedimentary rocks are relatively thin. The eastern boundary corresponds to a topographic divide; the western boundary is a combination of topographic divides and the western margin of the Valles Caldera. The caldera is within the Jemez river basin but we have included it in our model due to its close proximity to LANL and the uncertain location of groundwater divide between the Española and Jemez basins.

The top model boundary represents the pre-development water table. The model bottom is a flat surface defined to be substantially below the water table so that the model can simulate deep water circulation through the aquifer and there will be no boundary effect on the shallow groundwater flow. The elevation of the model bottom is -400 m above the sea level. The vertical thickness of the model varies from about 2,000 to 3,000 m depending on elevation of the water table.

Three-dimensional hydrostratigraphic zonation is established according to a geologic framework model (Carey et al., 1999). The geologic model is most detailed on the Pajarito Plateau; fewer details about the geologic structure and the aquifer heterogeneity are currently known for the rest of the domain. This is especially true of the region along and to the east of Rio Grande. This limitation could impact the predicted groundwater flow and transport from the river and the eastern portion of the basin towards the Buckman and the collector well. We should note that even in the region of the Pajarito Plateau, there are uncertainties associated with boundaries of hydrostratigraphic units as defined by the current geologic model; however, to date, we have not estimated the impact of these uncertainties on the model predictions presented in this report.

The three-dimensional grid of regional model utilizes 277,951 nodes and 1,528,407 elements (Figure 15). The grid is uniform and structured except for a transitional region between areas of coarser (1,000×1,056 m^2) and finer (250×264 m^2) horizontal gridding; the latter is in the center of domain, enclosing the LANL boundaries. The size of grid cells in vertical direction is 50 m in the upper part of the domain and 500 m at the bottom of the domain. This grid structure is due to the fact that the model is designed to perform flow and transport analyses predominantly for the Pajarito Plateau. The grid was not designed for capture zone analysis of the Buckman wellfield and the horizontal collector well; hence, the grid presents some limitations for this analysis, described later in this chapter. We also have developed a smaller local-scale model for the region in close vicinity to LANL (Figure 1) which, however, is not used in this study.

There are two previous models for portions of the Española basin developed by USGS (Hearne, 1985; McAda and Wasiolek, 1988; Frenzel, 1995). The model of Hearne (1985) was originally designed to simulate the response of the aquifer to an irrigation development plan. The heterogeneity in the Santa Fe Group is represented in the model using dipping but uniform layers. The model of McAda and Wasiolek (1988) was originally applied to simulate the aquifer response to existing and future pumping scenarios. Frenzel (1995) later improved this model adding more detail to aquifer heterogeneity close to Los Alamos.

There are important differences between our basin-scale and previous USGS models. The domains of USGS models are much smaller than our model (Figure 1), encompassing only a small portion of the Española basin. Our model is also much thicker including deeper portions of the basin aquifer which proved to be important to represent adequately the three-dimensional hydrostratigraphy and to simulate the observed complex three-dimensional structure of groundwater flow in the basin. The USGS models are quasi three-dimensional, while our model is fully three-dimensional. The grid resolution of our model (even outside the refined gridding in the domain center) is much higher that the grid resolution of previous USGS models. The USGS models were calibrated manually and most of the model parameters and characteristics are defined subjectively based on the authors' expert knowledge. Our model is based on key assumptions of the hydrogeological conditions in the basin (which are consistent with USGS models and previous studies of the region); however, the estimation of model parameters and more importantly of their estimation uncertainty is fully objective using automated calibration.

Further, the applied methodology allows for objective analysis of not only uncertainty in the model predictions but also importance of the data, existing and planned for collection, for decreasing the prediction uncertainty (Keating et al. 2000; Vesselinov et al., 2001).

Keating et al. (2002) coupled the basin-scale model with a smaller local-scale model. The coupling allows the design of sub-models that are consistent with the basin model, but simulate hydrogeological processes at a much smaller scale than is possible with the basin-scale model. In this way, we can use our models to investigate local groundwater quality and quantity issues.

Model boundaries

Although the available data suggests a complex regional aquifer with confined and unconfined zones, in our model, the entire aquifer is simulated as confined. This assumption is justified due to the significant thickness of the saturated zone and is expected to have little effect on the results presented in this report. The top model boundary represents the pre-development water table. Along this boundary, a spatially distributed flux is specified to simulate aquifer recharge from infiltration of precipitation through the unsaturated zone. We use a simple three-parameter model of infiltration recharge (Keating et al., 2000) which assumes that (1) recharge increases with elevation, due to increased precipitation (as illustrated in Figure 10), (2) there is an elevation (Z_{min}) below which essentially no recharge occurs and (3) above Z_{min}, recharge is a constant fraction of precipitation. This simple model of recharge is very effective for identifying the range of elevation (> Z_{min}) where the vast majority of recharge occurs. Our previous reports have documented that Z_{min} is fairly well defined in this basin, ranging from 2,000 to 2,200 m. The contour of Z_{min} defines the zone of the so-called diffuse or mountain-front recharge. It is known, however, that relatively small amounts of the recharge occur at lower elevations, focused along the streams. Maps of the precipitation and groundwater recharge used in our model are presented in Figures 16 and 17, respectively.

The bottom and predominant portion of side boundaries of the model are defined as no-flow. Laterally, there is flow out of the model domain to the South (Cochiti area) and West (Jemez canyon). There is also flow into the model along Chama river and the Rio Grande (near Embudo). These flows represent the hydraulic connections between the Española basin and its neighboring basins. There is no data with which to compare the model predictions of these inter-basin fluxes. We do, however, expect them to be small compared to the total mass flux through the basin as suggested by estimates reported by McAda and Wasiolek (1988) and Kernodle and Thorn (1995) as well as data presented by Coon and Kelly (1984).

Rivers

The Rio Grande and its major tributaries are simulated as fixed head boundaries, assuming perfect hydrodynamic connection between the surface and subsurface waters. Flow can occur either towards the aquifer (groundwater recharge from losing reach) or towards the river (groundwater discharge into gaining reach). Rivers are assumed to be “constant” over time; in other words, there is no limit to the amount of water they can supply to the aquifer. The measured pre-development water fluxes between the rivers and the aquifer are applied as calibration targets.

If new data were available to suggest that the connection between surface and subsurface waters is not perfect, incorporating these data into the model would impact the amount and spatial distribution of the river-water recharge to the aquifer and of the groundwater discharge to the river. This would impact our predictions of the extent of the capture zones close to the rivers and the amount of the river water captured by the water-supply wells. The uncertainty in surface/subsurface water interaction is particularly limiting for our capture-zone analysis of the horizontal collector well (see below).

Water-supply wells

In the model, the water-supply wells are defined as three-dimensional line sinks, representing the actual spatial configuration of the well screens. For our transient simulations (used for model calibration), the pumping rates are specified according to data summarized in Figure 6. For future steady-state simulations (used for the capture-zone, travel-time and dilution-factor analyses presented below), current rates (averaging the available records from 1997 to 2001) are assumed to remain constant and extend indefinitely into the future. All the pumping wells used in the model and their respective rates are shown on Figure 18.

Horizontal collector well

Horizontal collector wells are specially designed water-supply wells capable of withdrawing significant quantities of groundwater without generating substantial drawdowns in the pumped aquifer. Typically, they are shallow in depth, but with extensive horizontal dimensions. They are located close to surface-water sources where groundwater recharge can be significantly increased by pumping. Usually, some of the horizontal intakes of the collector are located directly beneath the surface water bodies to improve further the collector efficiency. As a result, groundwater travel times from the source to the well can be extremely short. Although capable of pumping at high rates, the horizontal collector wells are much more vulnerable to contamination than boreholes due to their shallow depth and virtually direct pumping of surface waters. The assessment of their capture zones requires information about the well design, aquifer heterogeneity and hydraulic connection between surface and subsurface waters. If the pumped water comes from the surface-water body only, the capture zones can be small. The most important factor in the capture-zone analysis is the hydraulic connection between surface and subsurface waters. Unfortunately, this information is not available for the location of proposed new horizontal collector well (as well as for the basin in general). Medium properties can be estimated by interpretation of specially designed cross-hole pumping tests. Such tests are currently being conducted on the collector site by City of Santa Fe.

An additional problem prevents adequately simulation of the collector well is the model grid resolution. The size of the grid cells is comparable with the well dimensions. To perform a better analysis, a finer grid is required in the vicinity of the collector. This would allow us to represent adequately the aquifer heterogeneity and to better simulate the groundwater velocity field. In our model, the collector is simulated within in a single grid cell. When included in the future steady-state simulations, the new horizontal collector well is pumping at its projected rate (44 kg/s).

Model parameters and calibration results

The hydrostratigraphic units defined by the three-dimensional geologic model are assumed uniform and either isotropic or anisotropic. The regional groundwater model is automatically calibrated against available flux and time-dependent head data (Keating et al., 2001). During the optimization, permeability and recharge parameters are adjusted so as to minimize the weighted squared-difference between observed and simulated data. The simulated groundwater flux and head data obtained by the calibrated model is compared against the respective measurements in Figure 19. The figure demonstrates that our model matches the measurements reasonably well and without bias. The estimated uniform specific storage coefficient, rate and Z_{min} of the recharge model, and uniform permeability of the various hydrostratigraphic units are listed in Table 2. The table not only gives our current best estimates but also the respective estimation uncertainty, where ± defines 95% confidence intervals.

The discrepancies between measured and simulated heads shown in Figure 19 are largely due to heterogeneities within the aquifer that are unaccounted for in this model. As further evidence of this, in Figure 20, we compare the currently observed and simulated drawdowns (from 1970 to 1995) in one of the piezometer nests close to Buckman (SF-2). In our model, the pumped aquifer is assumed to be uniform and this is the reason for the similar drawdowns predicted for the middle (B) and top (C) intervals. The observed drawdowns are much higher in the middle interval than the top interval due to aquifer heterogeneity. The integration of the heterogeneity in our model would help us to resolve this discrepancy.

Two additional model parameters, porosity and dispersivity, are important for groundwater transport simulations and are not estimated using the model calibration process. There are measurements of porosity obtained from geophysical borehole logs and laboratory analyses of core samples. However, these estimates not only do not represent the effective porosity of the medium for groundwater transport, but also are measured at a scale much smaller than the scale of our simulations. Keating et al. (2000) estimated the effective porosities of the various hydrostratigraphic units using data obtained from published studies for similar rock types (Table 3). We should note that these estimates are very important since groundwater dilution and travel times are directly proportional to the medium porosity. Estimates of the effective porosity can be obtained with our model, if we incorporate the available ^{14}C data in the calibration process; this activity is planned to be performed in the near future.

For the simulations presented in this report we assume a horizontal dispersivity of 125 m, vertical dispersivity of 25 m, and molecular diffusion coefficient of 10^{-9} m^2/s. The horizontal dispersivity is close to what is reported in the literature (cf. Neuman, 1990) for the scale of our simulations (~10 km). There is a little information in the literature about the vertical dispersivity. Typically, the heterogeneity is anisotropic due to layering and can be expected that the vertical dispersivity is smaller than the horizontal one (Lichtner et al., 2002). Therefore, our results should not be significantly overestimating the dispersion. The process of dispersion and diffusion impact the groundwater dilution and first arrival times.

Simulated groundwater flow

Based on our inverse estimates of model parameters, the simulated pre-development (steady-state) heads are illustrated in Figure 21. Figure 22 shows a map of the present drawdowns computed from pre-development steady-state and present transient heads. The map suggests substantial but localized decline of the groundwater levels in the aquifer.

Our model predicts that if current pumping rates continue, water levels will continue to decline over the next ~100 years, then water levels will start to stabilize. During this transient period, some portion of the pumped water will be drawn from storage; afterwards all the pumped water will originate from recharge. Since 100 years is a relatively short time compared to typical residence times in this aquifer (see Figure 11), we base the calculations presented in this report on the predicted "future" steady-state flow field, assuming current pumping rates continue.

This predicted flow field, including the effect of pumping at the collector well, is shown in Figure 23. The respective drawdowns without and with potential pumping at the proposed collector well are shown in Figure 24. The collector well pumping produces a spatially limited cone of depression due to the impact of the river recharge. Still, there is interference between the Buckman wellfield and the horizontal collector well; the addition of the horizontal collector well increases the steady-state Buckman drawdowns by as much as 50 m. Therefore, the estimation of the capture zones of both water-supply systems has to be performed simultaneously.

Figure 25 shows a vertical cross-section through the steady-state post-development flow field (with the collector well pumping). The cross-section is passing through Buckman at y = –133,000 m. The groundwater flowpaths reveal a complex flow structure that is quite different from the textbook example in Figure 13. The flowpaths demonstrate a groundwater flow from west beneath the river towards Buckman as well as from the east.

It is important to note that the model predicts that there is substantial infiltration recharge in the Valles Caldera (Figures 17 and 25). Our current model predicts that very little (if any) of this recharge flows to the east (Figure 25), but the groundwater flux across this topographic boundary is very uncertain (Keating et al., 2002). This flow rate is controlled by the Pajarito Fault permeability that our model estimates to be relatively low (Table 2).

Using these modeling results in our analysis, we assumed that current hydrogeological conditions in the basin would remain unchanged in the future. However, it is quite reasonable to expect changes in pumping rates (increased water demand), river flows/levels (reservoir controls), and infiltration (climate change) as well as construction of new and/or closing of existing water-supply systems.

ORIGIN OF PUMPED WATER

To estimate the origin of the groundwater pumped at Buckman, we have simulated the advection-dispersion transport of hypothetical non-reactive aqueous species with constant input concentration of 1.0 from the existing groundwater sources to the sinks within the model. These simulations allow us to “tag” water recharging from the west, from the east, and from the river, and to calculate their respective ratios in the water extracted at the Buckman wellfield and the collector well.

The simulation showing the ratio of water from river recharge is presented in Figure 26. The blue regions (ratio equal to 0.0) define parts of the domain where the groundwater is not impacted by the river recharge. The Buckman wellfield is capturing water coming from the Rio Grande and the Pojoaque river. River water from both sources (total) is estimated to be 27% of the water pumped at Buckman. Similar simulations for the infiltration recharge from western and eastern parts of the basin define that 34 and 39 % are respectively coming from west and east (Table 4)..

For the collector well, the predicted ratios of pumped water from rivers, western and eastern recharge are respectively 45%, 43% and 12% (Table 4). The respective ratios for Buckman slightly change due to the interference between both systems; the new values are 29% (+2%), 35% (+1%) 36% (-3%) (Table 4).

There are two important assumptions that are relevant to these results. First, as mentioned in the previous section, we are neglecting any contribution from storage that would be extracted during the transient period (including present conditions). Including this contribution would decrease the predicted percentages of water captured from recharge and rivers. Secondly, in the model rivers can provide an indefinite supply of water and are in perfect connection with the aquifer. If, in reality, because of pumping the rivers were to become dry or even detached from the water table (and thus the rate of exchange between the aquifer and river would become much more slow), our model would be overestimating the contribution of river water to the water supply wells.

CAPTURE ZONES AND TRAVEL TIMES

Capture zones define the regions from which pumping wells are obtaining their water supply. The size and shape of the capture zones are impacted by spatial structure of the flow between groundwater sources and sinks. In this report, we simulate the capture zones for the Buckman wellfield and the potential new horizontal collector well.

Capture-zone analyses are typically performed using two-dimensional models. It is assumed that the flow in the vertical direction is negligible and the zones encompass the whole aquifer thickness. A limitation of the two-dimensional analysis is the strong impact on capture-zone boundaries of rivers simulated as constant-head boundaries. The capture zones will be extended up to the rivers only and there will be no water coming from the aquifer on the other side of the river. In our case, if the model were two-dimensional, all of the water pumped at the Buckman would have originated only from the river and recharge in the eastern half of the basin. Three-dimensional analysis allows for extension of the capture-zone on the both sides of the river. To delineate capture zones predicted by our model, we use the particle-tracking capability of

FEHM. The algorithm allows computationally efficient and accurate simulation of advective flow paths.

We use forward particle tracking to identify locations at the water table from which water is captured at the water-supply wells. The initial locations of the particles are shown in Figure 27. On the figure, the initial locations of the particles are colored depending on where they exit the aquifer. The Buckman capture zone includes portions of the aquifer to the west of Rio Grande. The capture zone has a complex structure due to pumping of the wells on Pajarito Plateau. Figure 28 shows what are the advective travel times from water table to Buckman. Alternative analysis including the collector well is presented in Figure 29. The Buckman zone is similar to the previous estimate (Figure 27). The collector-well capture zone is outside LANL boundaries.

To better visualize the three-dimensionality of the capture zones, we also present a cross-section through the model where initial particle locations are again colored based on where the particles are exiting the aquifer (Figure 30). Figure 31 shows the advective travel times to Buckman only. Clearly, some of water captured at Buckman is relatively old (more than 30,000 years), which is consistent with the available hydrogeochemical data (Rogers et al., 1995; Keating and Warren, 1999). However, there is young (less than 100 years old) water pumped at Buckman as well.

If the flow from the ground surface to the water table were strictly vertical, the water table capture zones would represent also a ground-surface projection of the capture zone. Lateral flow (to the east) in alluvial aquifers along some canyons on the Pajarito Plateau may represent an important transport mechanism, both diverting flow and causing dispersion. In this report, we make no attempt to estimate travel times, flowpaths, or dispersion within alluvial aquifers or the vadose zone. Since these processes are not included in our analysis, the results presented in this report should not be used to estimate the ultimate fate of a source at the ground surface; rather, simply to estimate the ultimate fate of a source at the water table.

Changes in the hydraulic properties of the connection between the surface and subsurface waters connectivity would impact the amount and spatial distribution of the river-water recharge to the aquifer and of the groundwater discharge to the river. Imposing an imperfect hydraulic connection between the surface and subsurface waters would increase the size of Buckman capture zone in the vicinity of Rio Grande, but would not significantly change the overall size and shape of our predicted capture zones.

Alternative analyses (not shown) with lower and higher pumping rates at Buckman demonstrate that the pumping rates are important for the size of capture zones and the travel times. Decreasing the pumping rates reduces the amount of water captured from the west and decreases the groundwater gradients; increasing the pumping rates produces larger capture zones and faster travel times. This effect is further analyzed below using sensitivity analysis. We did not investigate another potential scenario, assuming that the pumping at Buckman is discontinued.

GROUNDWATER TRANSPORT AND DILUTION FACTORS

To estimate potential dilution factors, we perform finite-element advective-dispersion simulations of hypothetical aqueous species introduced at specific locations at the water table (not on the ground surface) in vicinity of LANL. The hypothetical aqueous species are simulated as non-reactive and non-decaying. The resulting dilution is due to mixing, advection, dispersion and diffusion. The pumping well mixes waters coming from different parts of the basin and from different sources. Advection causes aqueous species to travel along various flow pathways characterized with dissimilar spatial orientation and groundwater gradients. Dispersion produces further dilution due to similar processes at a scale smaller than the heterogeneity defined in our model. Diffusion will produce dilution on much smaller scale due to Brownian motion.

We simulate the advective-dispersion transport of the aqueous species from five water table locations in vicinity of LANL: (1) the confluence of the Los Alamos and Pueblo Canyons; (2) R-22 (Area G); (3) the County Sewage-Treatment plant in Pueblo Canyon, (4) R-25 (TA-16) and (5) Mortandad Canyon. All the sites except Mortandad are defined as "point" sources with the size of our model cell (250×250×50 m^3); along Mortandad Canyon, we delineate a "line" source (approximately 2,500×250×50 m^3). Assuming that the concentration of aqueous species at the source is constant in time, we have modeled the spatial distribution of the relative (to the source concentration) steady-state concentrations in the aquifer. The concentrations at the water table are presented in Figure 32. Dilution factors at Buckman (mixing all the pumped water) range from 3.4×10^{-7} (County Sewage-Treatment plant) to 5.8×10^{-5} (Mortandad Canyon) from the source concentration (Table 5). There is no transport of aqueous species in the direction of the horizontal collector well, which confirms the capture-zone results described in the previous section. The spatial distributions of concentrations are impacted by the pumping at the water-supply wells on the Pajarito Plateau (Figure 32). Their dilution factors (if all the pumped water were mixed) range from 0.0 (no aqueous species are captured) to 2.7×10^{-3} (Table 5). Except for the case of R-22, the estimated dilutions are smaller for the water-supply wells on the Pajarito Plateau than for Buckman.

The advective-dispersive arrival times of a half of the respective highest concentration at Buckman are also presented in Table 5. The fastest travel time is from the water table beneath County Sewage-Treatment plant—8,000 years; the slowest is from the water table beneath Area G—25,000 years. The computed travel times represent the mean arrival of the hypothetical plumes at the wells. However, due to dispersion of the aqueous species in the aquifer part of the plume will arrive faster, part of it will arrive slower. The higher the dispersion, the faster the first arrival times. However, the first arrivals will be also associated with concentration much lower than the peak concentrations.

In addition, we simulated the five hypothetical sources assuming instantaneous release of unit mass. The ratios of the mass captured by Buckman, Pajarito wells and Rio Grande are also listed in Table 5.

The results presented in this chapter are meant to be illustrative and are best used by comparing one to another, rather than as absolute concentration predictions. The calculated relative concentrations and dilution factors depend on the size and duration of the source. If the hypothetical releases at water table were simulated with a smaller size or for shorter time the concentrations and dilution factors would be smaller.

SENSITIVITY ANALYSES

Through sensitivity analysis, we can determine the model parameters to which predictions are particularly sensitive. We investigated only some of the model parameters, excluding the impact of dispersion parameters and porosity. The increase of groundwater dispersion will increase the dilution but will also decrease the first arrival times. The decrease in porosity estimates will proportionally increase the travel times and the decrease the dilution. In general, porosity and dispersion parameters in hydrogeological settings similar to those at the Española basin can be expected to be within an order of magnitude of our estimates. Still a half order of magnitude change in porosity would produce a half order of magnitude change in the travel times.

The sensitivity coefficients represent partial derivatives of the predictions with respect to the parameters. Positive/negative sensitivity coefficients define respectively positive/negative correlations. In the sensitivity analyses, pumping rates in the Buckman wellfield is included as an additional parameter. Figure 33 shows the sensitivity coefficients for the portion of water originating in the western part of the domain and pumped at Buckman. Our prediction is most sensitive to the parameters of recharge and the Buckman pumping rate. Figures 34 and 35 show similar results for the minimum (first) and arithmetic average (mean) travel times, respectively, of the particles from the western recharge area to the wellfield. The minimum travel time is most sensitive to the pumping rate, the recharge parameters as well as the permeabilities of Pajarito Fault Zone, Cerros del Rio basalts, and the Santa Fe Group. The average travel time is most sensitive to the pumping rate, the recharge parameters, and permeability of the Santa Fe Group. All of these parameters important for our predictions are associated with some uncertainty (Table 2). The decrease in their estimation uncertainty will potentially decrease the uncertainty in the predictions.

There is not enough information about the medium heterogeneity within the Santa Fe Group (the hydrostratigraphic unit containing the Buckman wellfield), Cerros del Rio basalts and Puye Formation (through which a significant amount of groundwater captured at Buckman passes beneath LANL). In our model, these units are assumed uniform. Their heterogeneity (as well as the uncertainty in their spatial extent) could have an impact on the groundwater transport travel times and the spatial distribution of the hypothetical plumes. The introduction of unit heterogeneity in our model could potentially decrease the first arrival times and dilution factors at Buckman, but would have limited impact on the general flow directions in the aquifer and the mean arrival times at Buckman.

However, the sensitivity analysis is not enough to accurately estimate which of the parameters is most important for the predictive uncertainties. Using predictive analysis, we can better investigate the sensitivity and uncertainty of our model predictions. We would be able to identify model parameters that not only produce a satisfactorily calibrated regional model, but also define extremes in the capture zones boundaries, travel times and/or dilution factors of the potential contamination from LANL to the water-supply wells (e.g. Vesselinov et al., 2002).

FINDINGS AND CONCLUSIONS

This report is based on results obtained by the ongoing regional hydrogeological study and modeling of the Española basin (Keating et al., 2000, 2001). The permeabilities and recharge parameters come from the regional model, which matches the existing measurement data for the basin. The dispersivity and porosity values are based on literature data, and are uncertain. The basin hydrogeological model allows consistent capture-zone delineation, analysis and updates for any existing or new groundwater-supply system in the region. The model also allows basin-scale evaluation of groundwater resources, recharge, subsurface- and surface-water interaction, flow and transport. The model we have applied to this problem is based on many assumptions and simplifications of the actual hydrogeological conditions and is limited by the amount of the available hydrogeological data. Adding complexity and detail to the model and collecting new data would not change our fundamental conclusions. Our results can be summarized as follows:

- According to our basin model, at steady-state, the water pumped at the Buckman wellfield originates from infiltration in both western (34%) and eastern (39%) portions of the basin and river recharge (27%).

- The model predicts that some of water captured at Buckman is very old (more than 30,000 years), which is consistent with the available hydrogeochemical data (Anderholm, 1994; Blake, 1995; Rogers et al., 1995). According to our model, there is also young water (less than 100 years). The introduction of geochemical data in our inverse model could further decrease uncertainty of our estimates and predictions (especially travel times).

- The predicted capture zone of Buckman extends beneath Pajarito Plateau on the western bank of Rio Grande. Groundwater passing beneath LANL in the regional aquifer will be captured at Buckman. However, the advective travel times are estimated to be in orders on thousands years.

- The available hydrogeological information for the site of the potential new horizontal collector well is insufficient to estimate precisely its capture zone. It is likely that the most significant amount of the pumped water will be recharged from the adjacent surface-water sources (Rio Grande, Pojoaque river). This amount depends on the hydrodynamic properties of underground medium defining the hydraulic connection between surface and subsurface. Medium properties can be estimated by interpretation of specially designed cross-hole pumping tests. Such tests are being conducted presently on the collector site by City of Santa Fe. However, we doubt that the new information will impact the most important result of our study, that no groundwater passing beneath LANL will be captured by the potential new well.

- Our model predicts interference between the Buckman wellfield and the potential new horizontal collector well. According to our model without pumping at the collector well, some of the water pumped at Buckman is coming from north along the Rio Grande and it is originating from the Pojoaque sub-basin. The potential new horizontal collector well would be capturing a portion of this water.

- Dilution factors are estimated using advective-dispersion groundwater transport simulations from five water table locations in vicinity of LANL assuming that the source concentration of the hypothetical aqueous species is constant in time. In all the cases, the dilution factors at Buckman is smaller than 10^{-5} from the source concentration. The dilution factors depend on the size and duration of the source. If the hypothetical releases at water table were simulated with a smaller size or for shorter time, the dilution factors would be smaller. The mean advective-dispersive travel times to Buckman (defined by the arrival of a half of the respective highest concentrations) are on the order of thousands years. The first arrival times will be shorter, due to dispersion, but with much lower concentrations.

- From the five water table locations selected for study, there is no groundwater transport flow in the direction of the horizontal collector well, which confirms our capture-zone estimates.

- Groundwater transport from these five water table locations, however, would have less dilution at and faster travel times to the water-supply wells on the Pajarito Plateau, compared to the dilution and travel times to Buckman.

- Sensitivity analyses demonstrate that the capture-zone and groundwater transport predictions obtained by our model are most sensitive to the recharge parameters and properties of Pajarito Fault Zone, Cerros del Rio basalts, Santa Fe Group and Puye Formation.

Potential future developments of our work include:

- Updating the presented results as more data are collected and the inverse model of the basin improves.

- Improvements in the model grid resolution to the east of Rio Grande in the region of existing and potential new water-supply wells. This is important not only to be able to characterize with more detail the aquifer heterogeneity, but also to calculate with greater accuracy the flow velocities in the vicinity of the pumping wells and the rivers.

- Assessment of the spatial boundaries and the hydraulic and transport properties of Cerros del Rio basalts, Puye Formation and Santa Fe Group and their impact on the capture zones. This will result in the identification of the probabilistic capture zones which will characterize with more fidelity uncertainty in our estimates.

- For the predictions presented in this report, there are more thorough analyses that can be conducted to better understand the prediction uncertainties. Using predictive analysis, we can identify model parameters that not only produce a satisfactorily calibrated regional model but also define extremes in the capture zones boundaries, travel times and/or dilution factors of the groundwater transport to the water-supply wells (e.g. Vesselinov et al., 2002).

- Collection and analysis of additional hydrogeologic information about the region of Buckman and Rio Grande (e.g. logs for wells in San Idelfonso Pueblo, pumping rates of water-supply wells, pump tests at the collector site) will improve our understanding of (1) the subsurface heterogeneity, (2) the interaction between the surface and ground waters, and (3) the available groundwater resources.

- Analysis of the aquifer vulnerability to contamination from all potentially existing sources, both natural (e.g. arsenic and uranium) and anthropogenic.

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TABLES

Table 1. Summary of the Buckman wellfield data (after Duke Engineering and Services, 2000; Lewis, 2000).

Well	Elevation [m]	Depth [m]	Depth to the screen top [m]	Depth to the screen bottom [m]	Average 1997-2001 pumping rate [kg/s]	1999 water level elevation [m]
Production wells						
B-1	1682.2	337.7	75.9	329.8	21.5	1595.3
B-2	1688.3	449.0	91.4	426.7	28.1	1606.6
B-3	1712.5	437.7	115.8	396.2	7.1	1585.8
B-4	1721.1	—	61.0	442.0	25.2	1561.0
B-5	1764.7	351.7	75.0	325.5	7.4	1659.0
B-6	1745.2	429.8	56.1	421.8	41.6	1643.5
B-7	1708.4	429.5	61.0	426.7	30.0	1506.8
B-8	1680.7	—	61.0	426.7	30.2	1525.0
Monitoring wells						
SF-2A	1688.6	567.8	563.9	566.9	—	1679.8
SF-2B	1688.6	251.2	244.4	247.5	—	1536.2
SF-2C	1688.6	105.5	98.8	101.8	—	1620.3
SF-3A	1670.3	89.6	83.5	86.6	—	1616.4
SF-3B	1670.3	51.5	45.4	48.5	—	1666.6
SF-3C	1670.3	18.3	12.2	15.2	—	1665.5
SF-4A	1667.3	85.3	79.2	82.3	—	1622.5
SF-4B	1667.3	39.6	33.5	36.6	—	1666.7
SF-4C	1667.3	18.3	12.2	15.2	—	1663.9
SF-5C	1662.7	21.0	14.9	18.0	—	1661.4

Table 2. Parameter estimates obtained for the Española basin model (after Keating et al., 2001).

Parameter		Inverse estimate
Name	**Code**	
Specific Storage [log$_{10}$]	Ss	–3.85±0.37
Recharge		
Minimum elevation [m]	Zmin	2195±177
Rate [kg/s]	inflow	3845±511
Permeability [log$_{10}$ m^2]		
Deep Aquifer (Pre-Cambrian, Santa Fe group, Tschicoma Formation)	Deep	–15.56±8.64
Paleozoic/Mesozoic	P/M	–15.01±3.18
Pajarito Fault Zone	Paj.Fault	–15.33±0.83
Shallow Precambrian (Sangres)	Frac. PC (1)	–12.62±0.24
Shallow Precambrian (Ojo Caliente/Penasco)	Frac. PC (2,3)	–13.07±0.58
Tschicoma Formation – shallow	Frac. Tt	–12.99±0.20
Cerros del Rio basalts	Tb	–12.15±0.19
Puye Formation	Tpf	–14.20±1.34
Chaquehui Formation (horizontal)	Tsfuv (xy)	–13.24±0.26
Chaquehui Formation (vertical)	Tsfuv (z)	–15.53±0.86
Santa Fe group – West (horizontal)	Tsf (west, xy)	–13.24±0.16
Santa Fe group – West (vertical)	Tsf (west,z)	–15.04±0.43
Santa Fe group – East	Tsf (east)	–14.07±0.41
Santa Fe group – Airport	Tst (SF)	–12.58±0.78
Santa Fe group – North	Tsc	–13.44±0.49
Santa Fe group – Ojo Caliente sandstone	Tso	–13.26±0.18
Santa Fe group – Penasco embayment	Tst (Pen)	–12.35±0.28
Ancha Formation	Ancha	–12.26±0.51

Table 3. Porosity data derived from the literature (after Keating et al., 2000).

Parameter		**Porosity**
Name	**Code**	**[–]**
Pre-Cambrian	PC	0.02
Paleozoic/Mesozoic	P/M	0.10
Pajarito Fault Zone	Paj.Fault	0.10
Tschicoma Formation	Tt	0.05
Cerros del Rio basalts	Tb	0.05
Puye – Fanglomerate	Tpf	0.25
Puye – Totavi Lentil	Tpt	0.30
Chaquehui Formation	Tsfuv	0.30
Santa Fe group	Ts	0.25
Ancha Formation	Ancha	0.25

Table 4. Origin of the pumped water at Buckman and the new collector well.

Groundwater supply system	**Groundwater origin [%]**		
	Rivers	West	East
Buckman (without the collector well)	27	34	39
Buckman (with the collector well)	29	35	36
Collector well	45	43	12

Table 5. Travel times (defined by the arrival of a half of the respective highest concentrations) and dilution factors for advective-dispersive groundwater transport of hypothetical non-reactive and non-decaying aqueous species from five water table locations beneath LANL to the water-supply wells.

Description:	**Source locations at the water table (not at the ground surface)**				
	Los Alamos/ Pueblo Canyons	R-22 (Area G)	Sewage-Treatment plant	R-25 (TA-16)	Mortandad Canyon
Travel time to Buckman [years]	11,000	25,000	8,000	12,000	14,000
Dilution factors from the permanent-source concentration (averaged over all the system wells):					
• Buckman	4.4×10^{-7}	1.8×10^{-5}	3.4×10^{-7}	2.5×10^{-6}	5.8×10^{-5}
• Pajarito wells	3.4×10^{-4}	0.0	9.3×10^{-5}	5.8×10^{-4}	2.2×10^{-3}
Ratio of mass captured from unit slug input:					
• Buckman	2.0×10^{-5}	8.6×10^{-4}	1.6×10^{-5}	1.2×10^{-4}	2.7×10^{-3}
• Pajarito wells	1.9×10^{-2}	0.0	5.0×10^{-3}	3.2×10^{-2}	1.2×10^{-1}
• River	2.7×10^{-7}	1.8×10^{-5}	2.1×10^{-7}	1.5×10^{-6}	3.5×10^{-5}

FIGURES

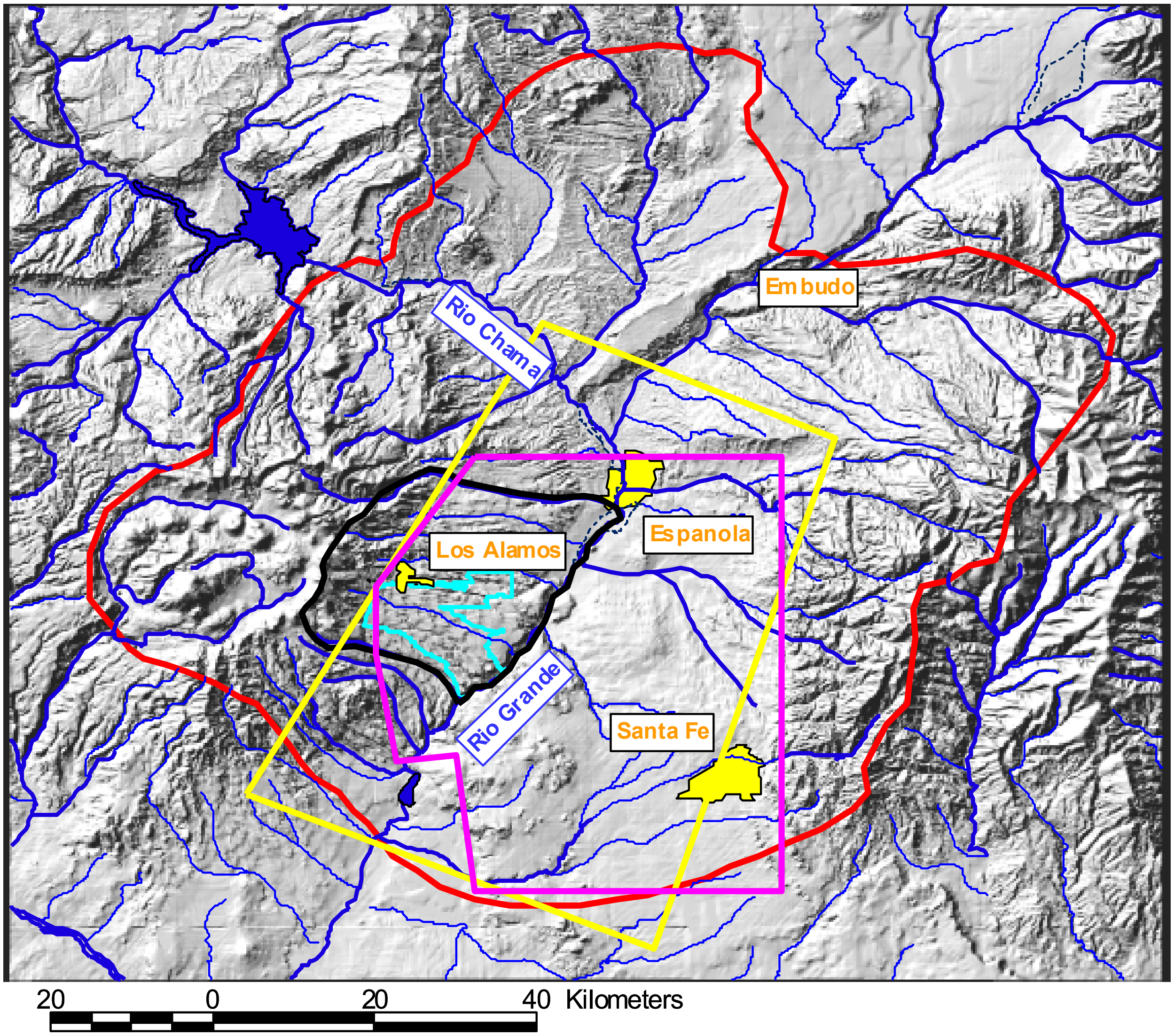


Figure 1. Domain boundaries of our basin- (red) and local-scale (black) models as well as of the previous two USGS models (Hearne, 1985—yellow; McAda and Wasiolek, 1988; Frenzel, 1995—purple); the LANL boundaries are shown in cyan.

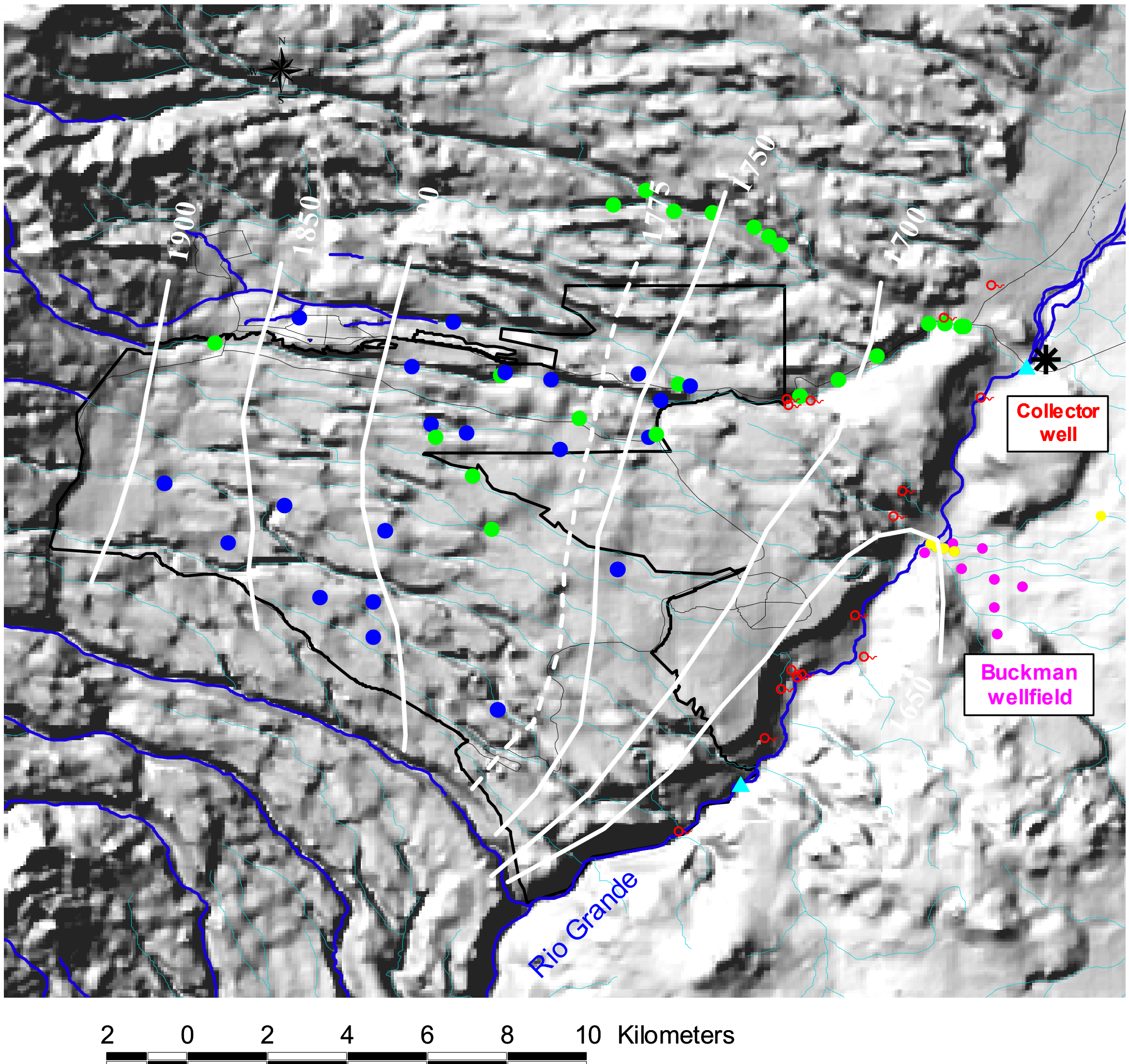


Figure 2. Locations of the Buckman wellfield (purple), the new collector well (black star), as well as springs, other water-supply (green; Los Alamos and San Idelfonso) and monitoring boreholes (blue— LANL R boreholes and test wells; yellow—Buckman). The cyan triangles define locations of existing streamflow gage stations. The contours define the present water table elevation [m] based on existing measurements.

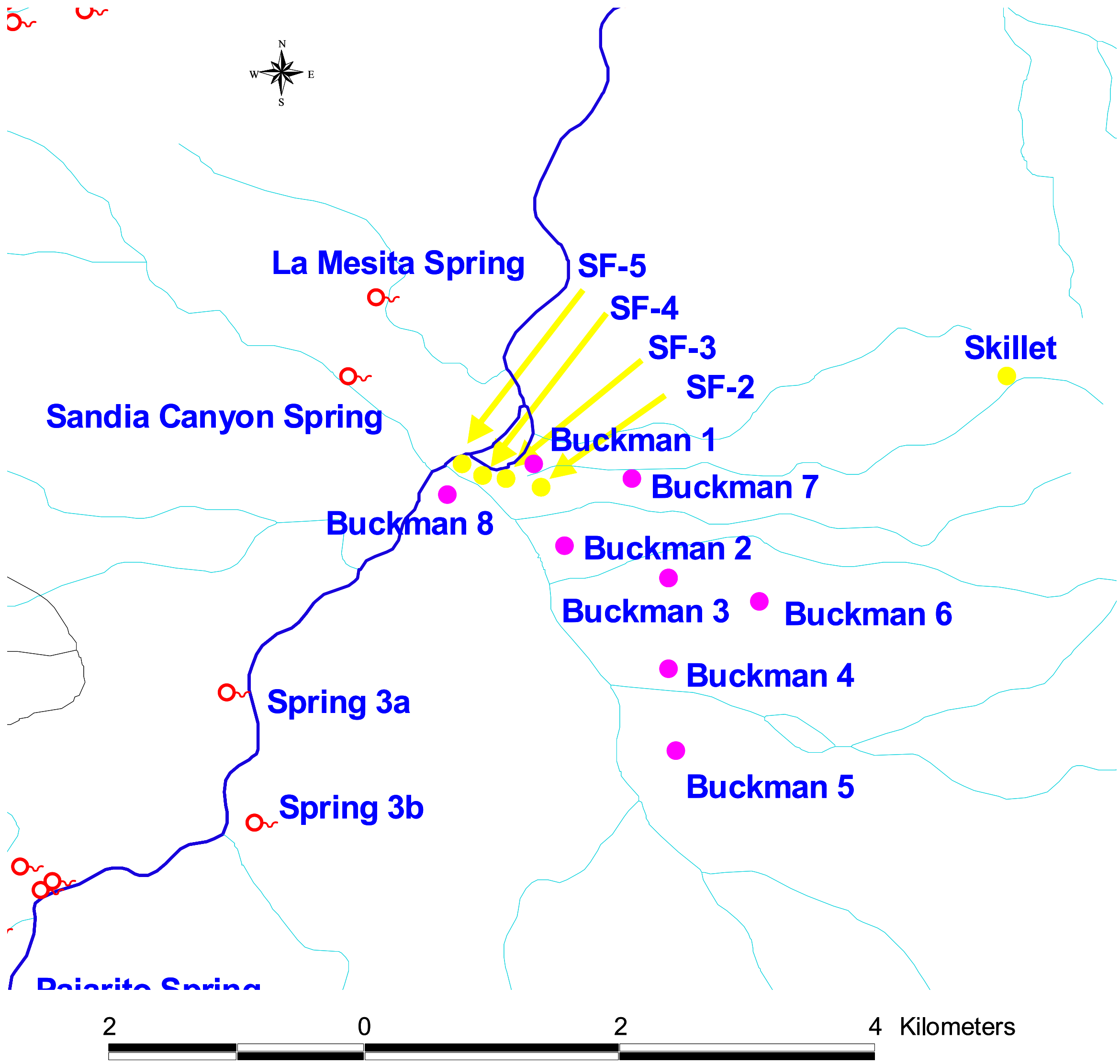


Figure 3. Detailed map of the Buckman wellfield (purple), monitoring boreholes and nests (yellow), and springs.

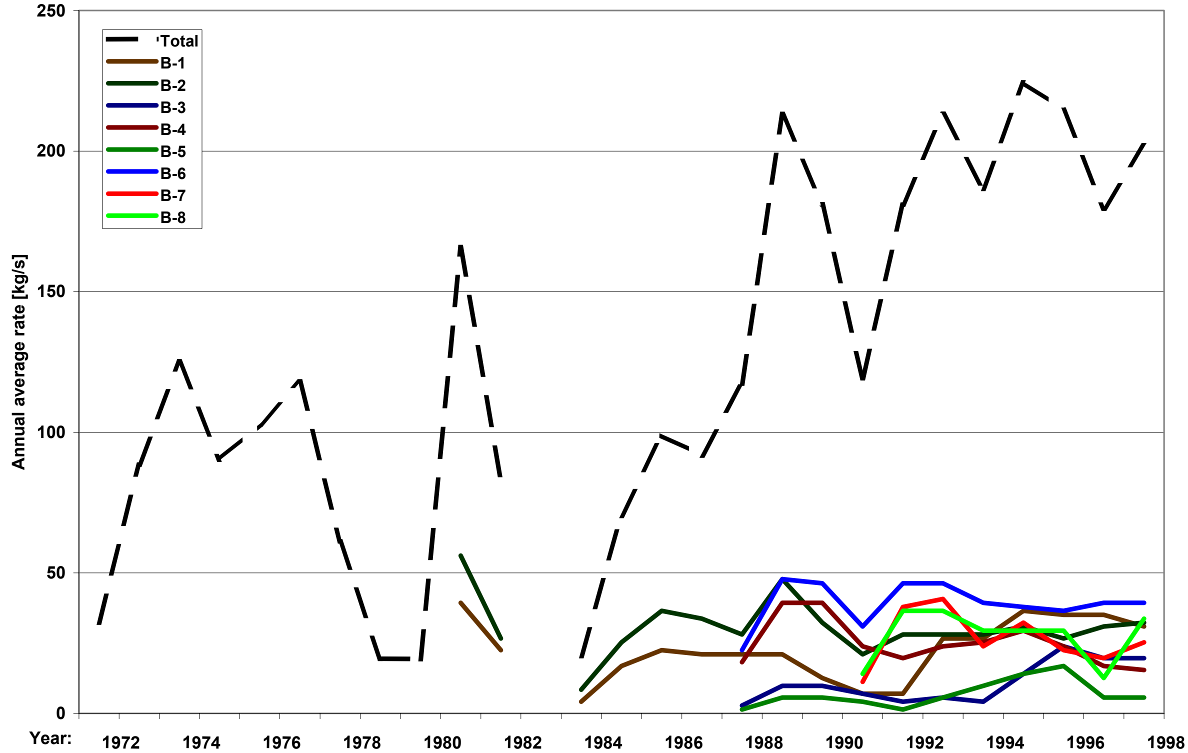


Figure 4. Averaged annual pump rates [kg/s] of the Buckman wells.

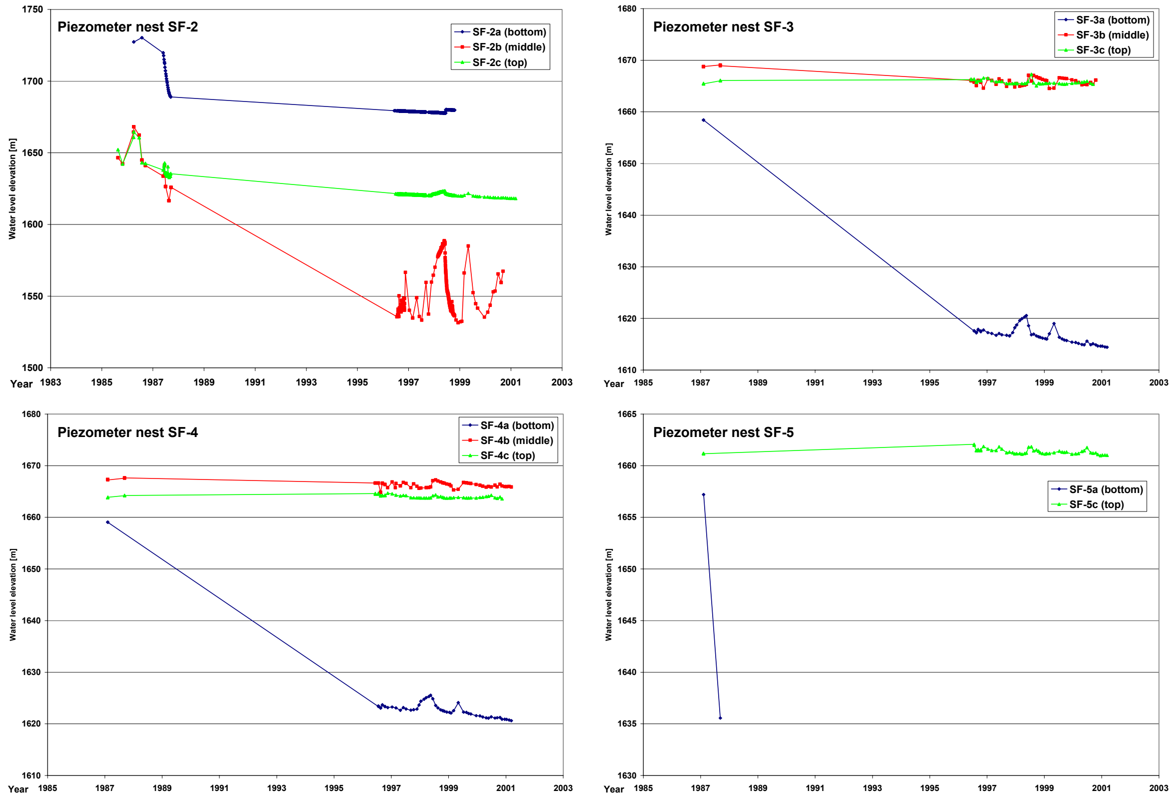


Figure 5. Groundwater water elevations measured at the Buckman piezometer nests.

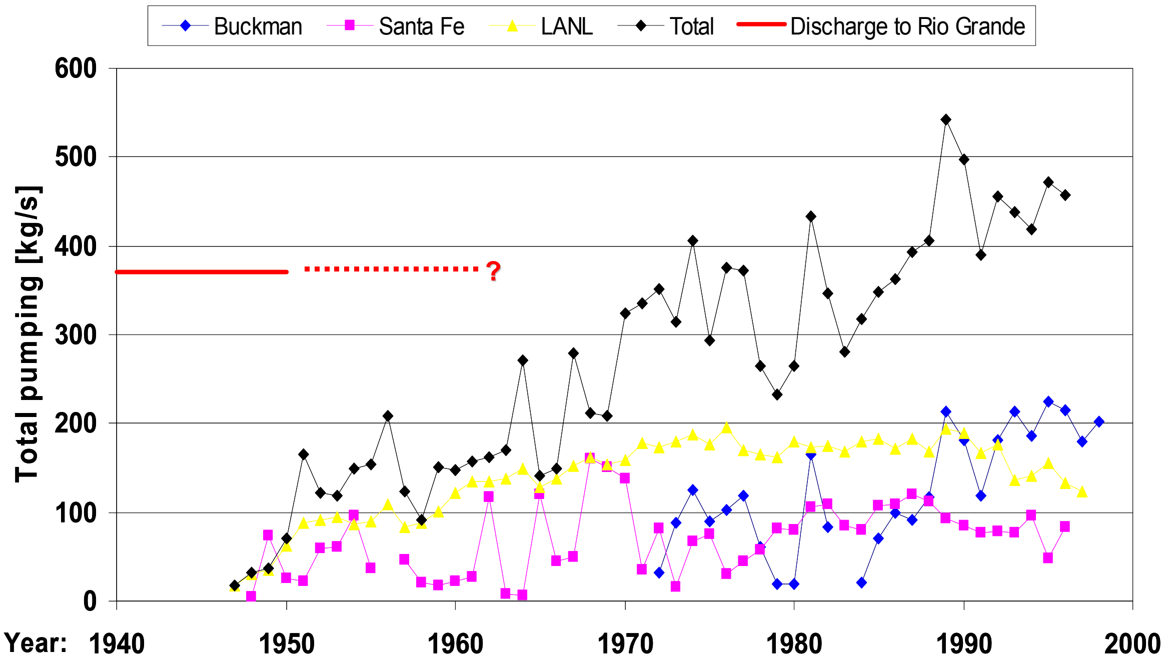


Figure 6. Time variation of the averaged annual groundwater pumping from the major wellfields in the Española Basin; the long-term average groundwater discharge to the Rio Grande is not known after 1969.

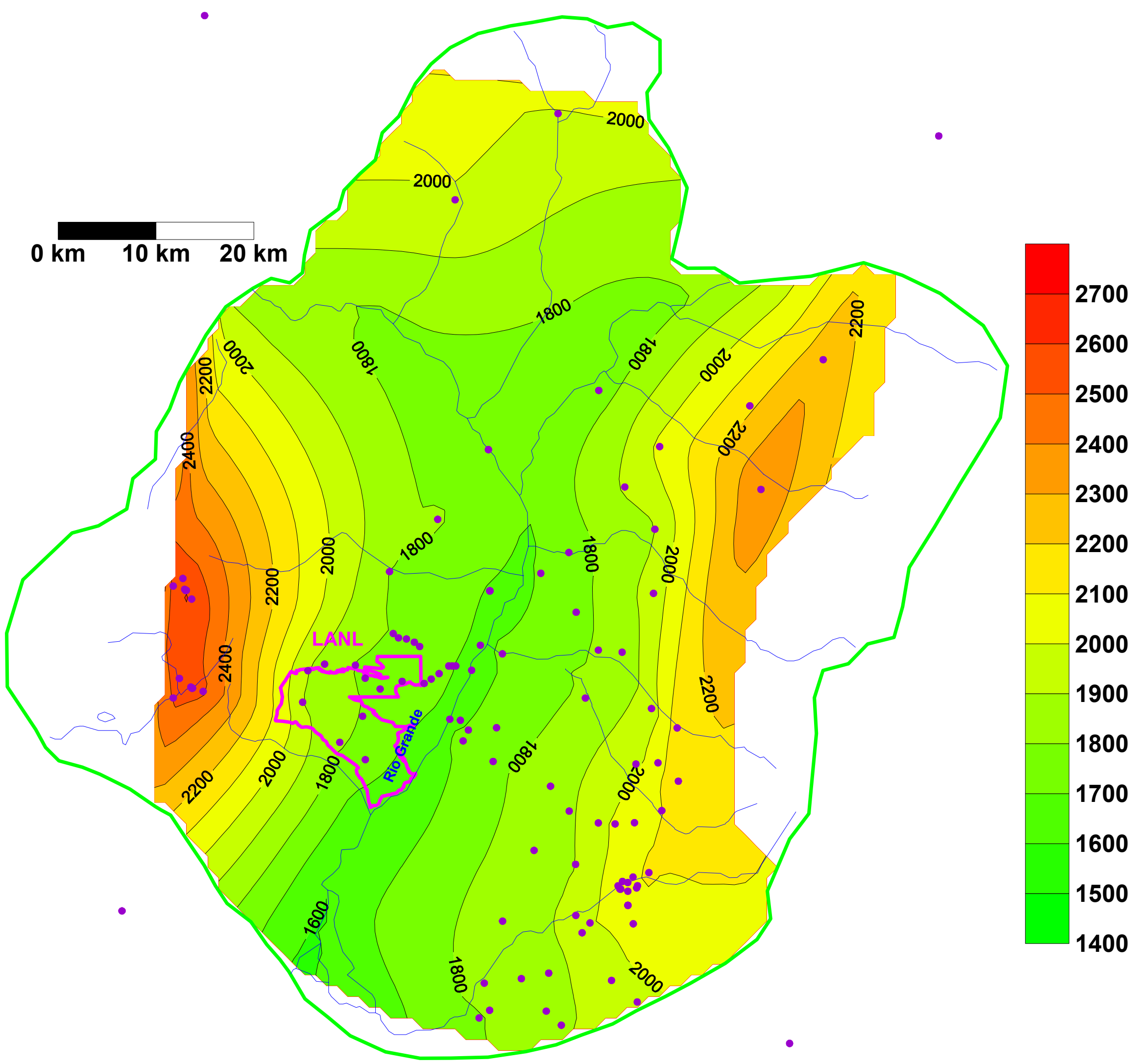


Figure 7. Contour map of predevelopment hydraulic heads [m]; dots represent measurement locations.

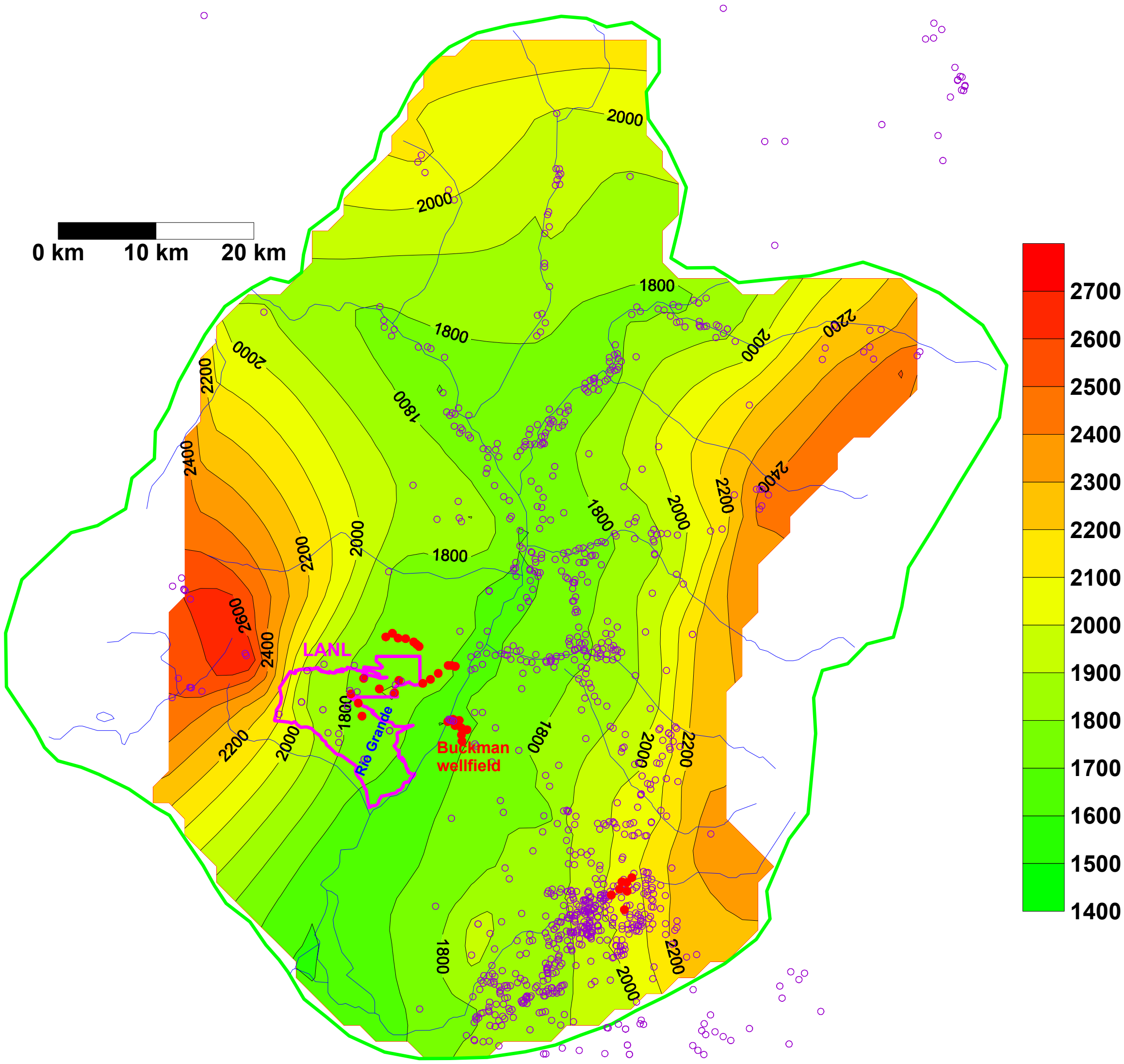
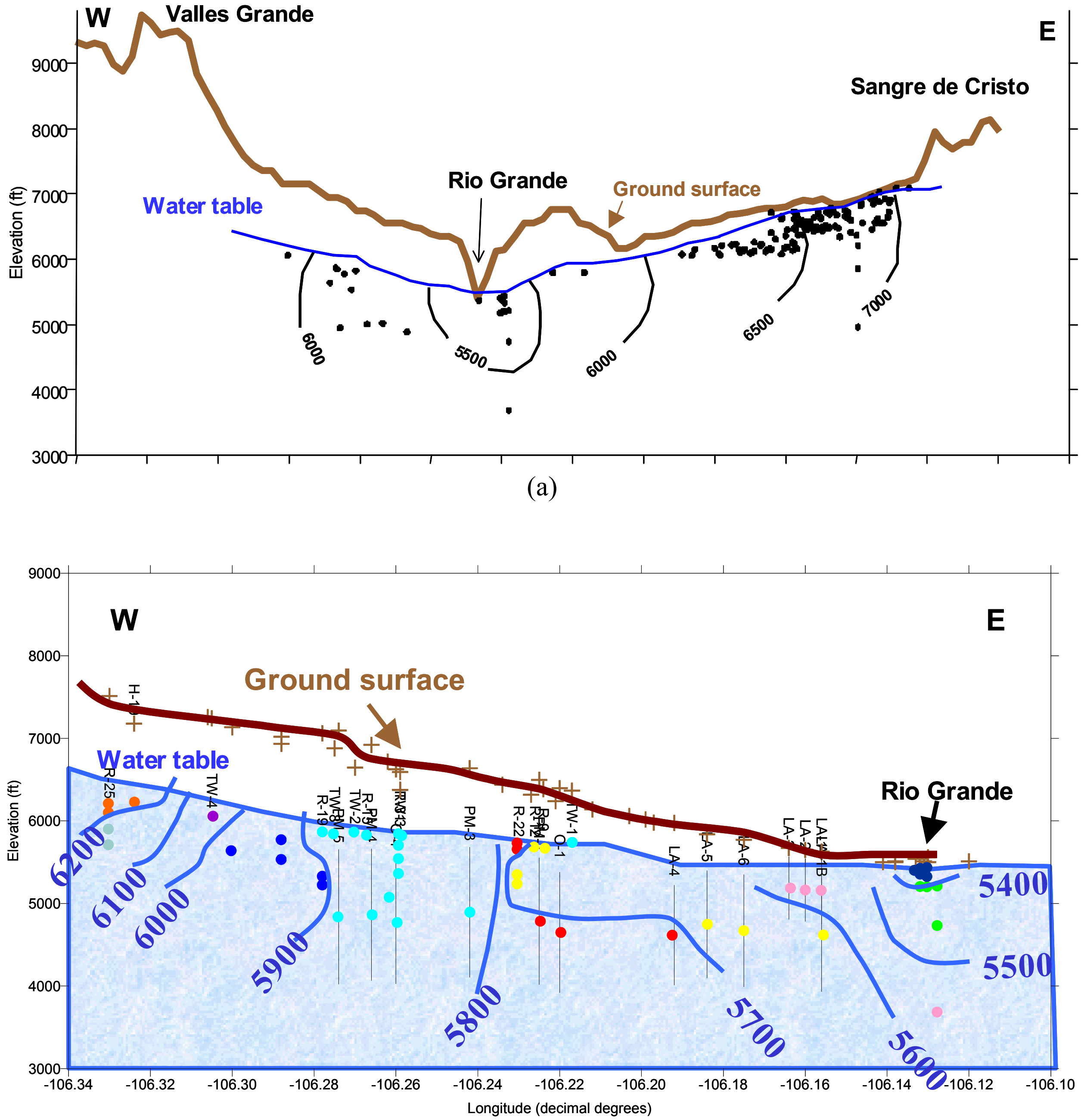


Figure 8. Contour map of present hydraulic heads [m]; dots represent measurement locations: red—municipal water-supply wells, purple—other wells.



(a)

(b)

Figure 9. Vertical cross-sections of present hydraulic heads [ft] close to Buckman: regional (a) and local (b; beneath LANL) maps.

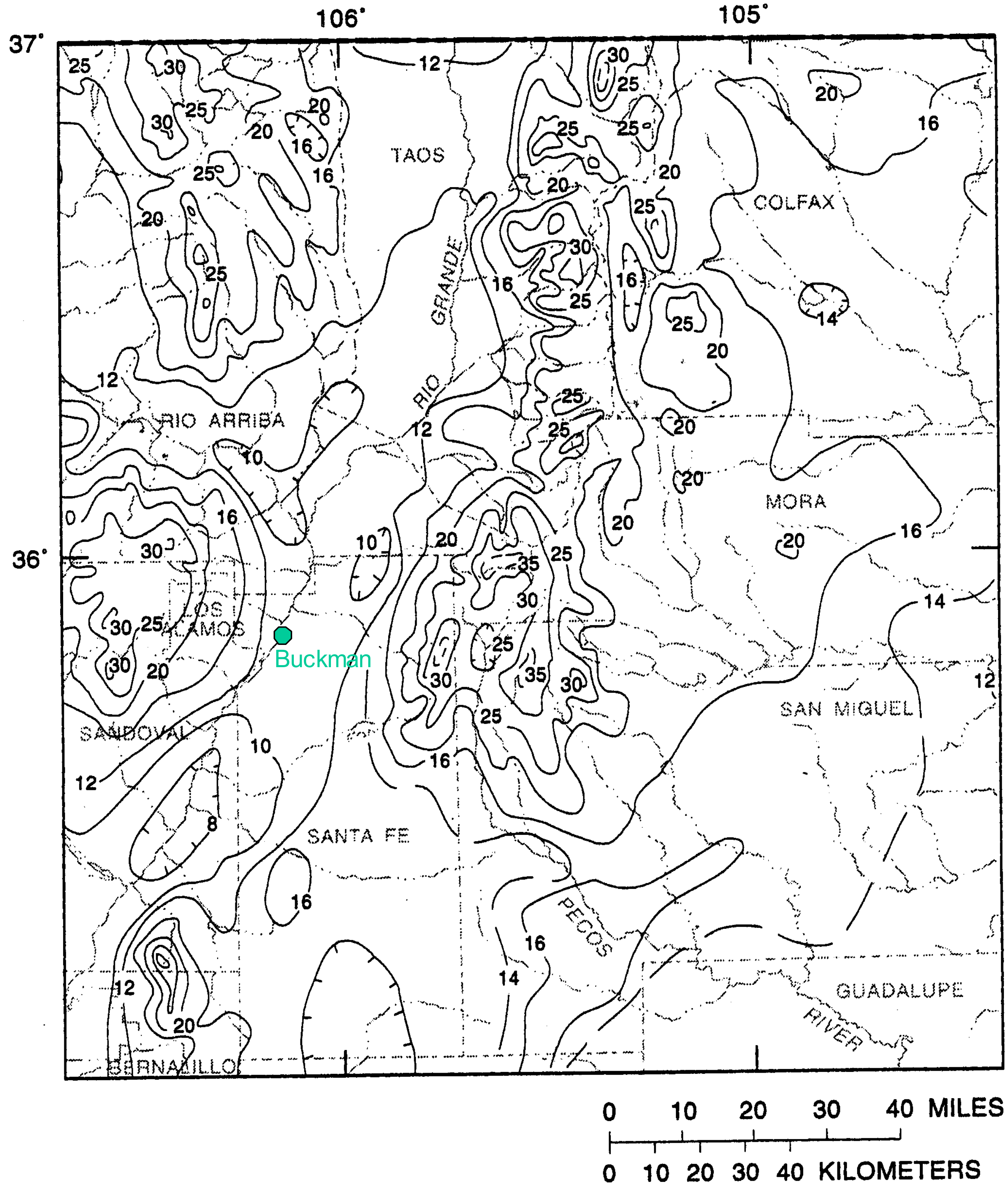


Figure 10. Average annual precipitation (in inches) for north-central New Mexico (after Wasiolek, 1995).

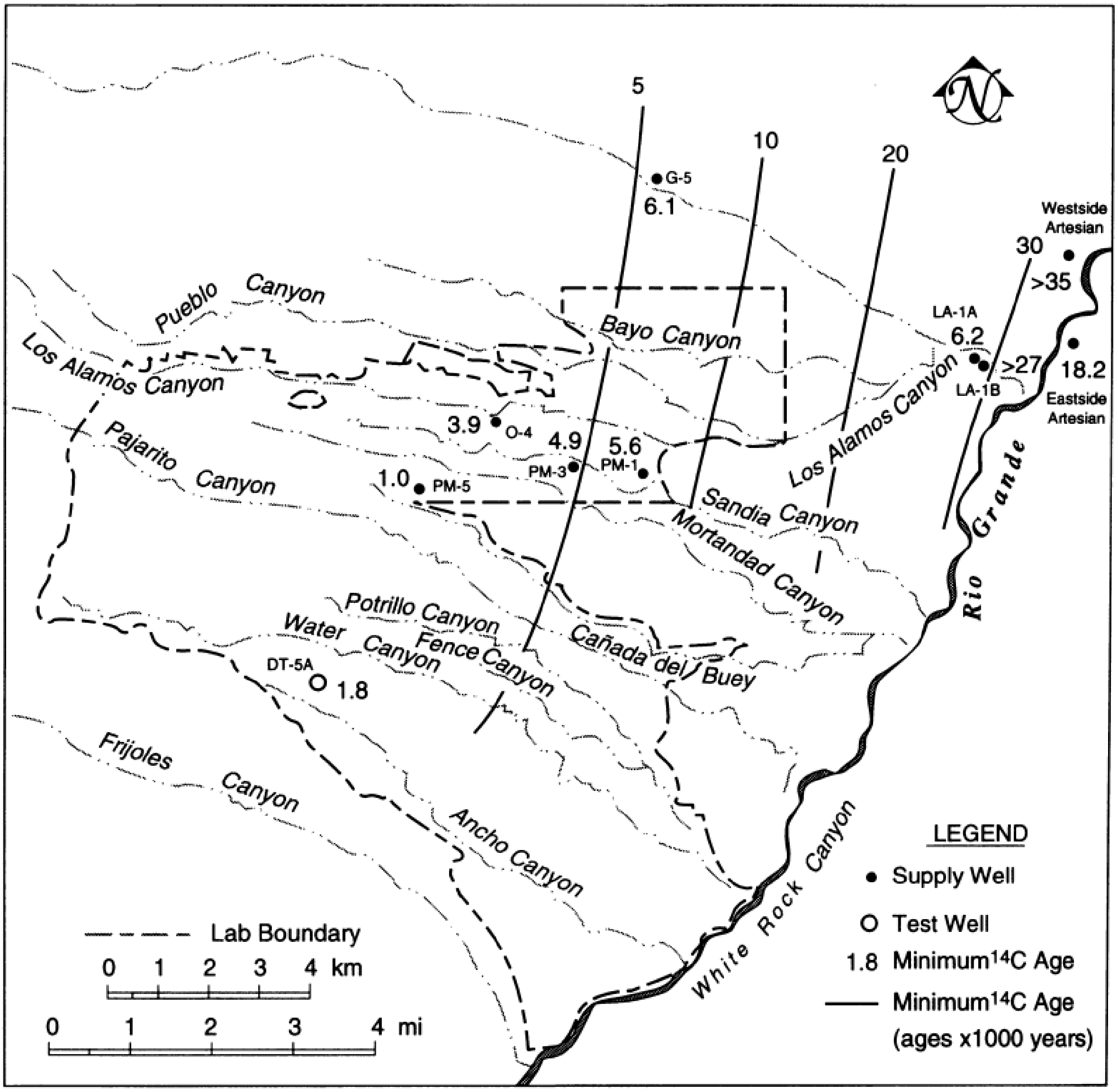


Figure 11. Groundwater ages based on carbon-14 data (after Rogers et al., 1996).

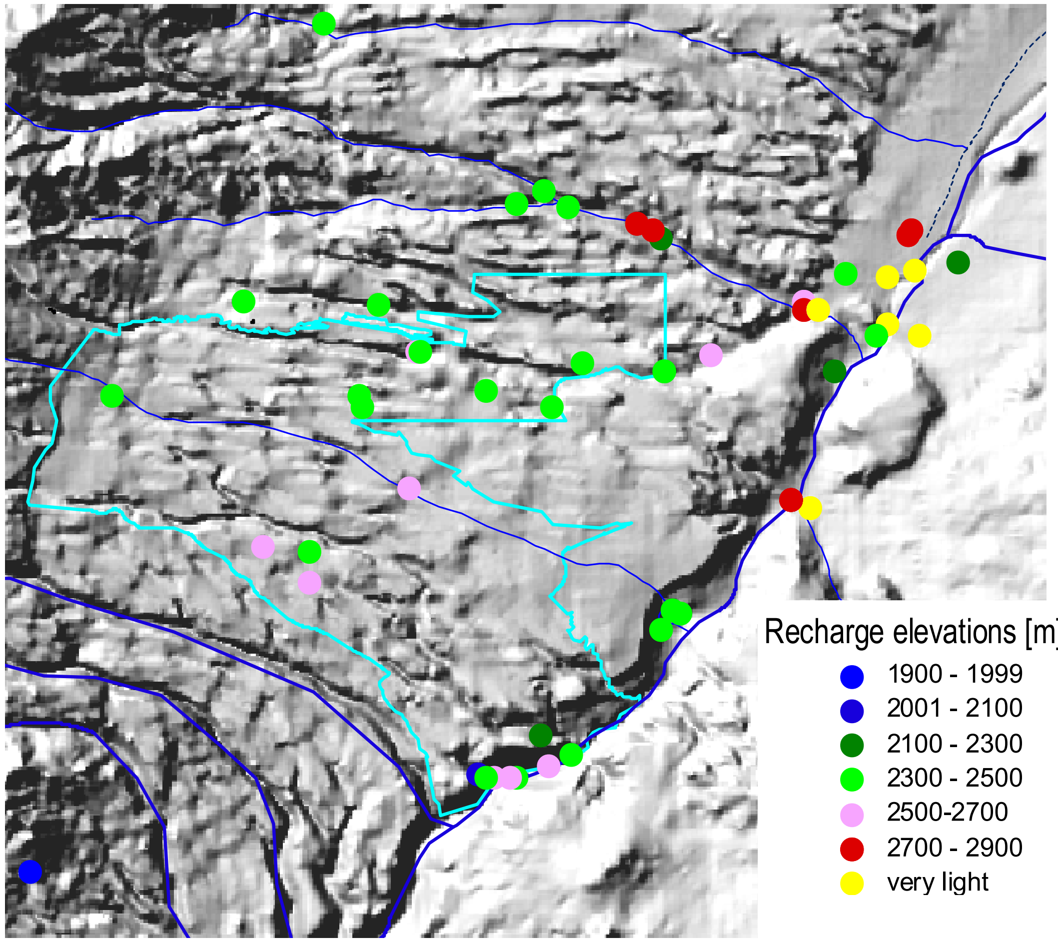


Figure 12. Estimated recharge elevations based on oxygen isotope data (after Blake et al., 1995; Anderholm, 1994).

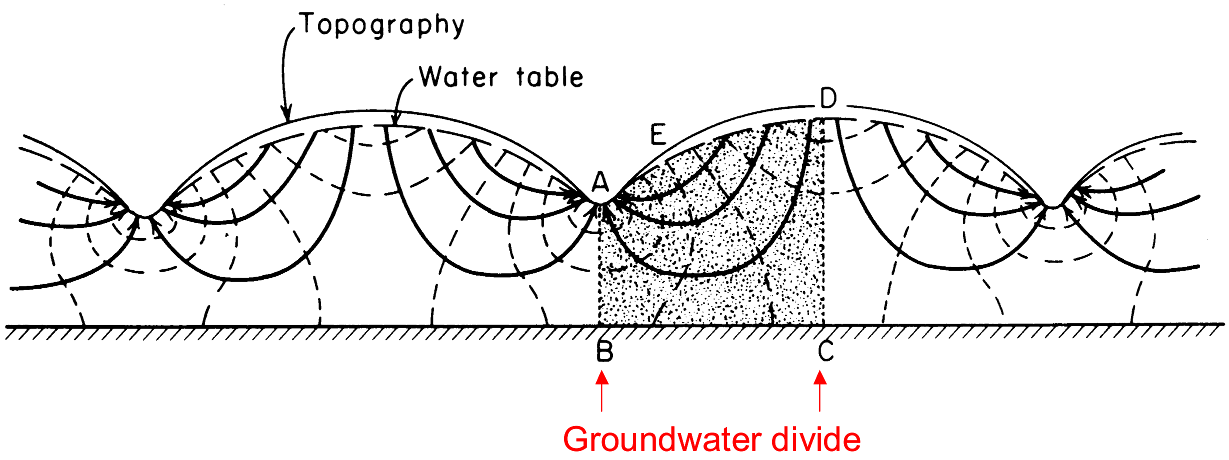


Figure 13. Vertical-cross section through a hypothetical unsaturated, uniform and isotropic aquifer; the groundwater flow-net is represented by flowpaths (solid lines) and equipotential contours (dashed lines) (after Freeze and Cherry, 1979)

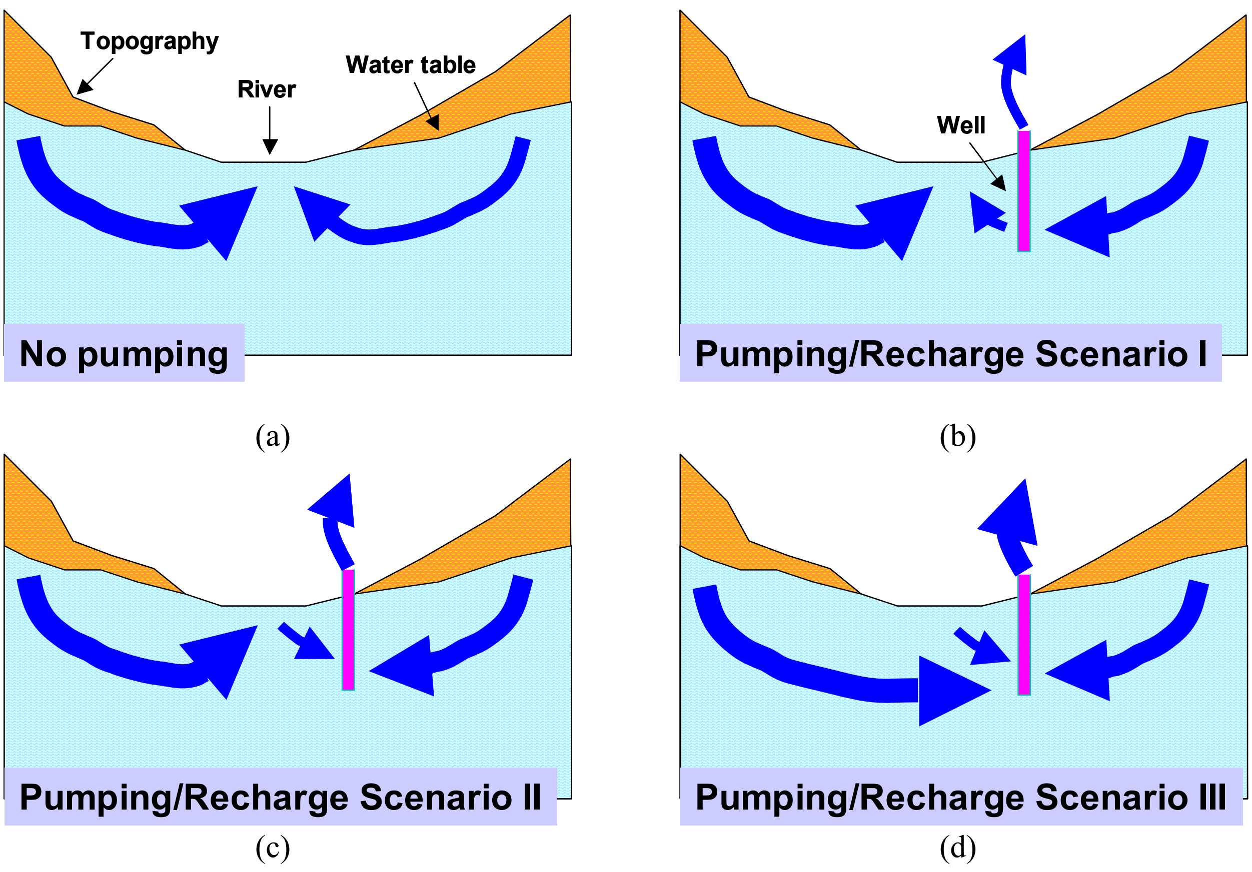


Figure 14. Various conceptual models depending on the ratio between the groundwater pumping and available recharge. Scenarios I through III reflect increasing ratio.

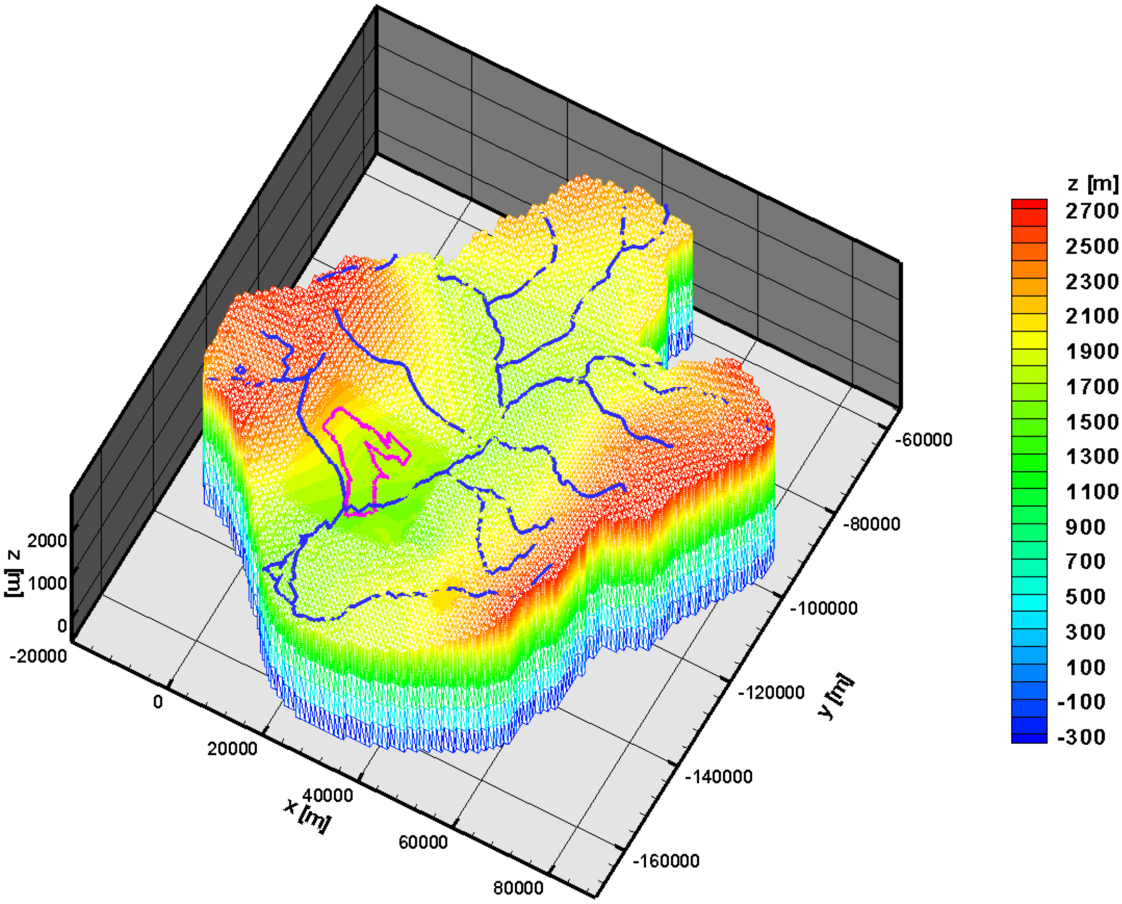


Figure 15. Computational grid of the Española basin model (z [m] is the elevation above the sea level).

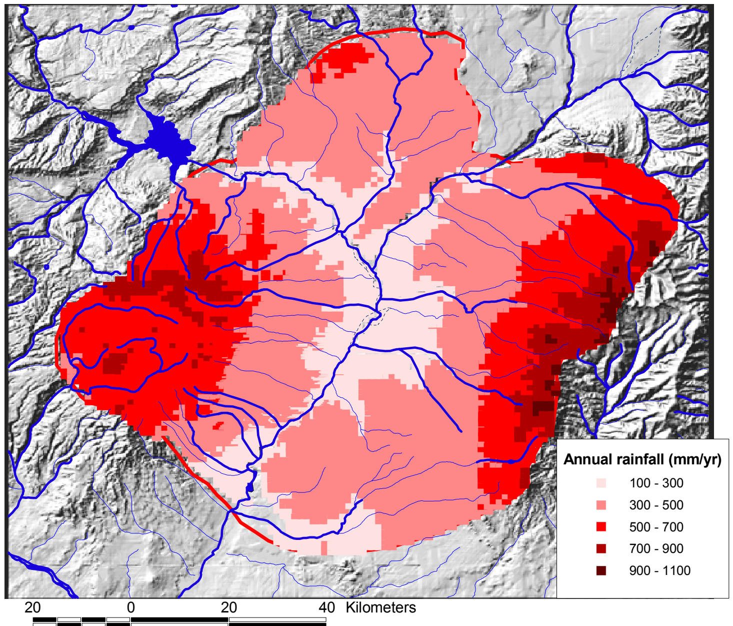


Figure 16. Estimated spatial distribution of precipitation [mm/yr].

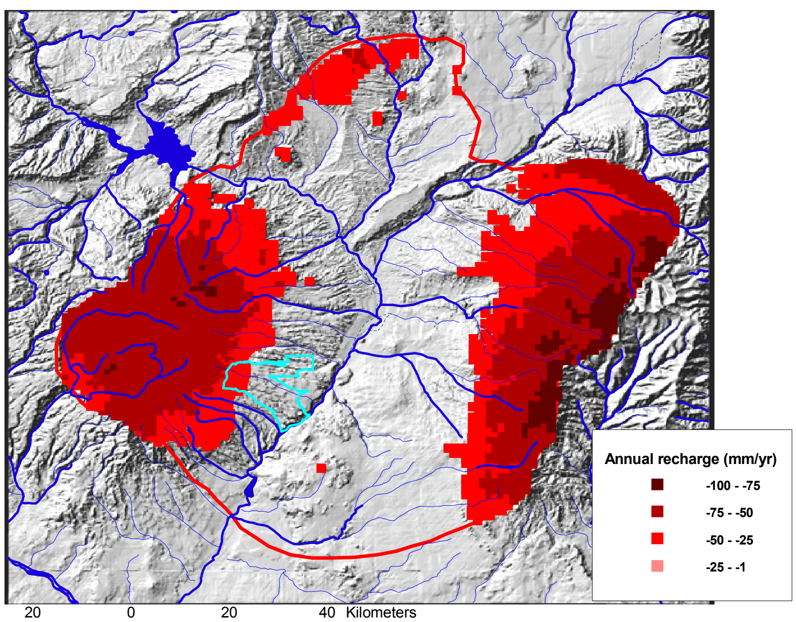


Figure 17. Estimated spatial distribution of groundwater recharge [mm/yr].

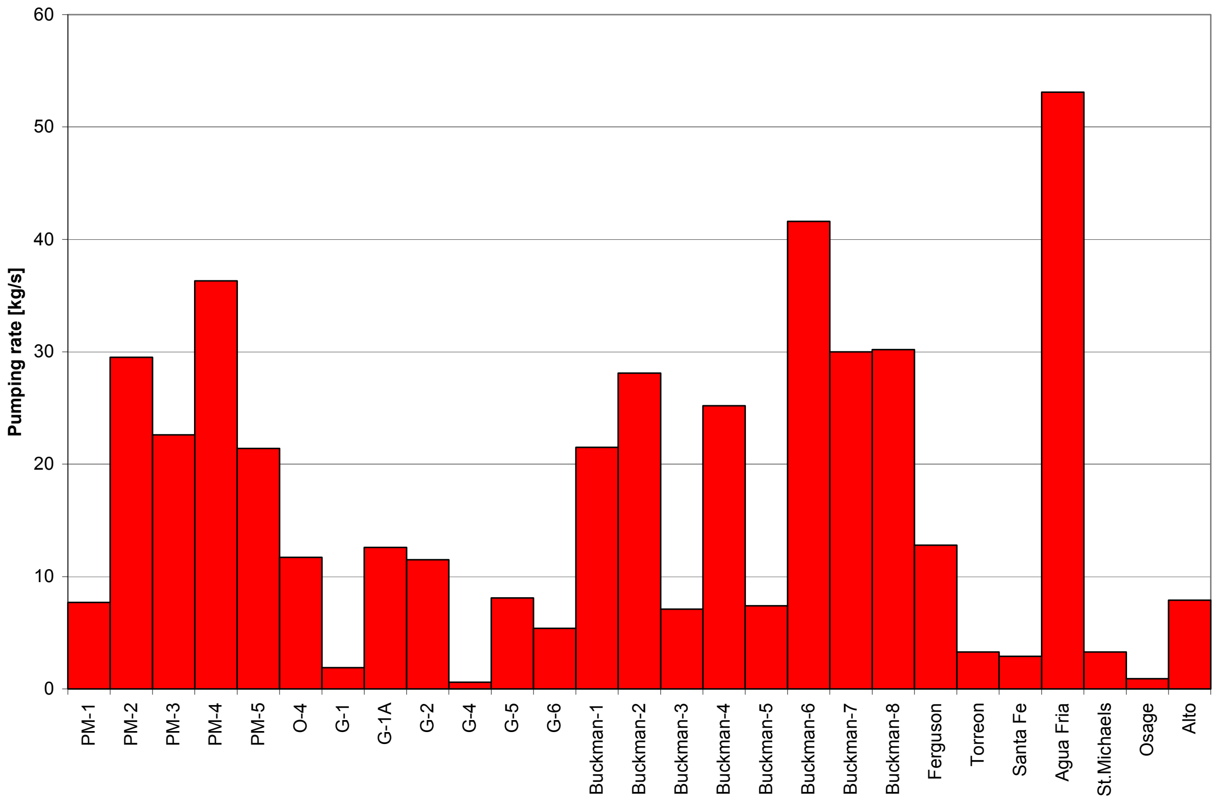
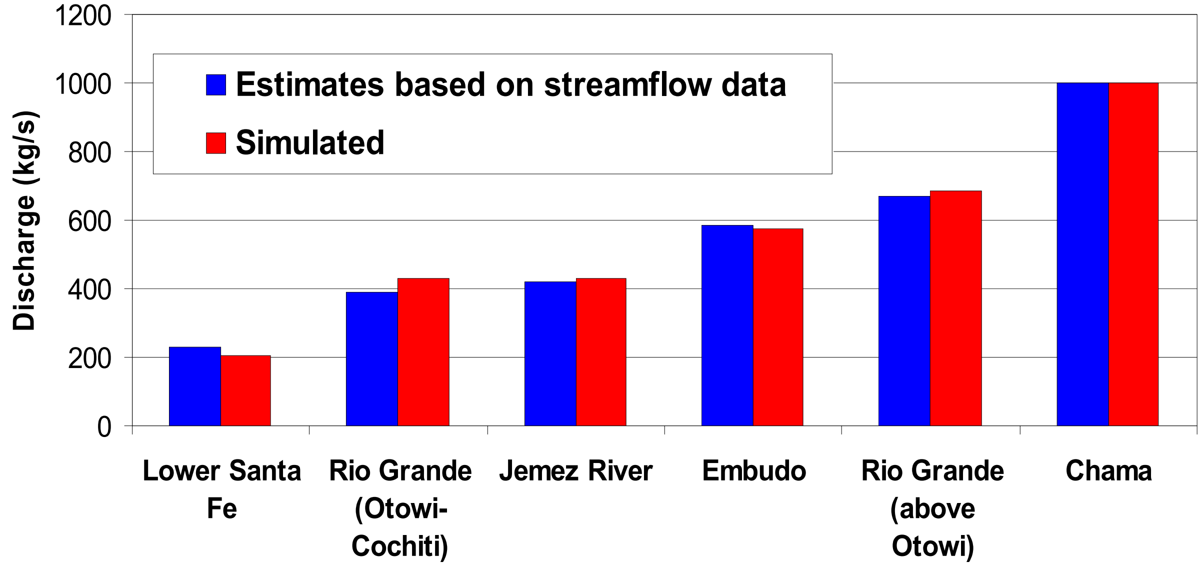
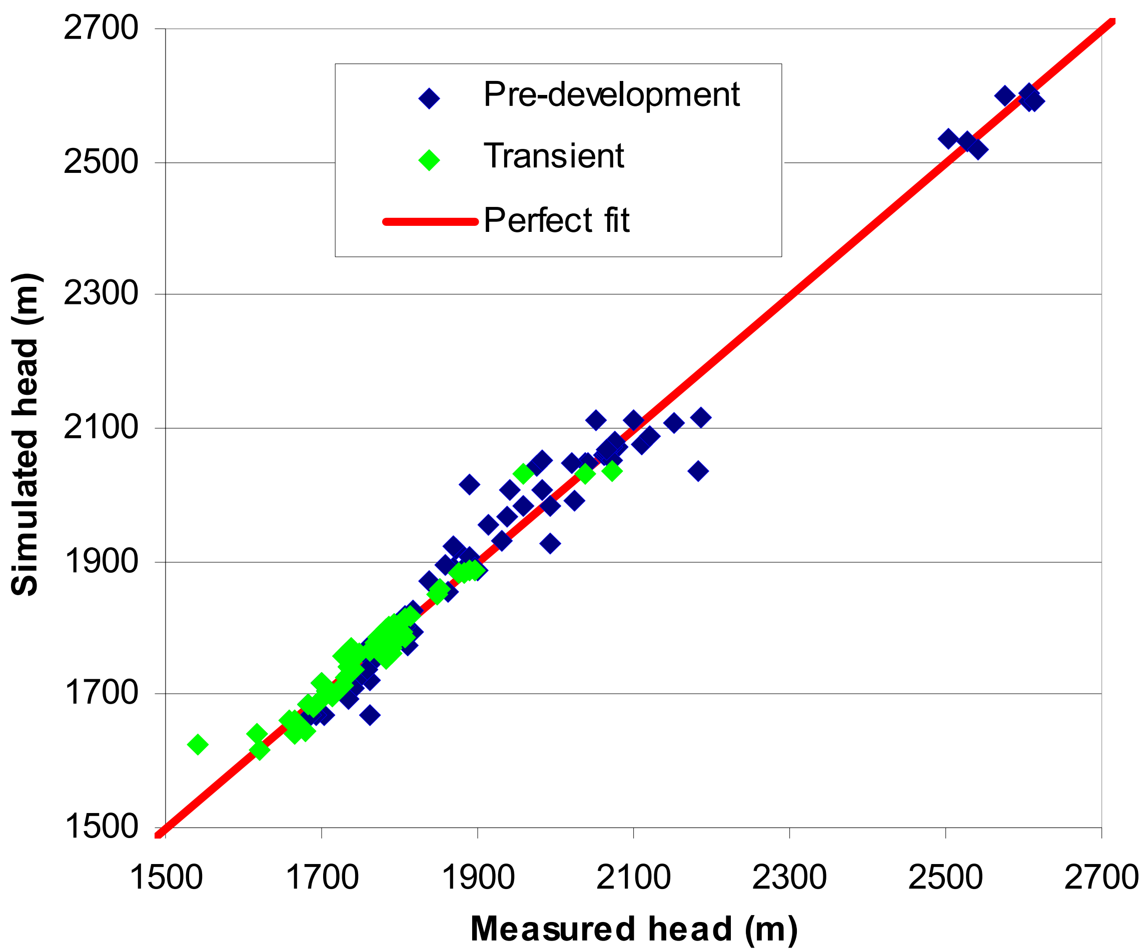


Figure 18. Pumping rates of the wells used in the post-development steady-state simulations.



(a)



(b)

Figure 19. Comparison between measured and simulated groundwater flux (a) and head (b) data.

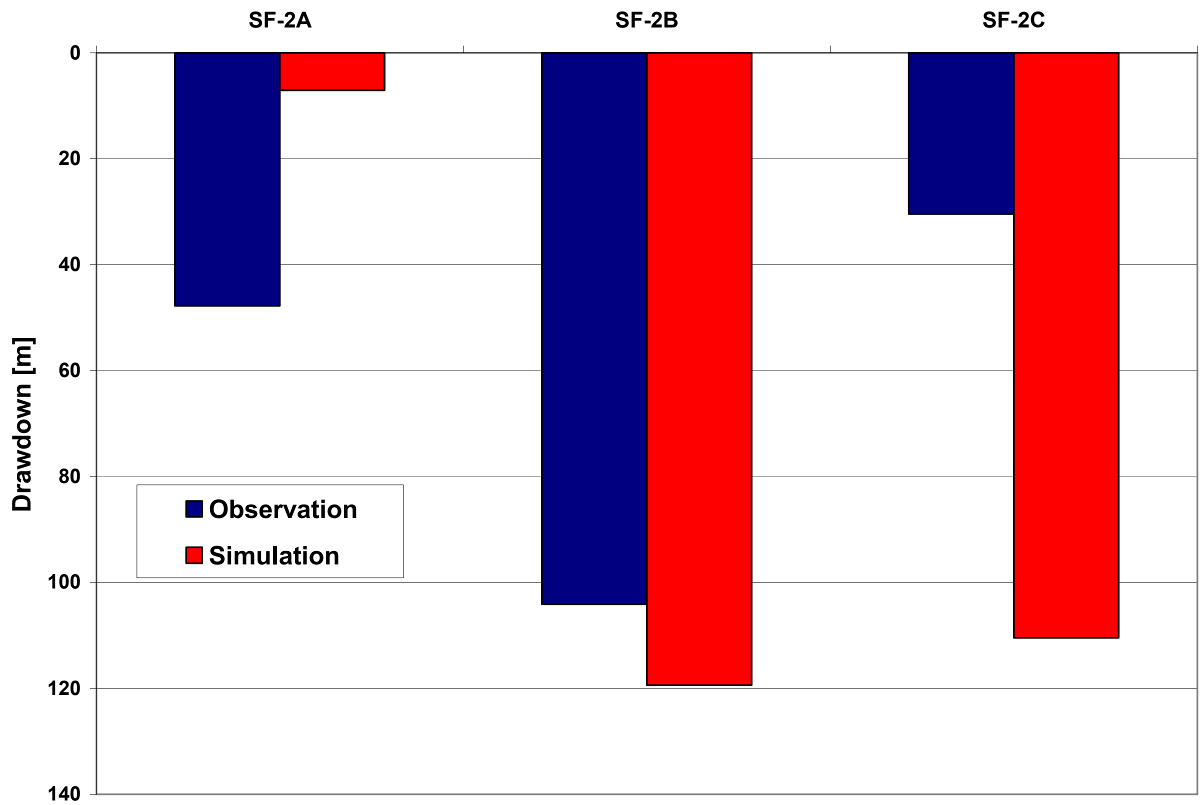


Figure 20. Comparison between observed and simulated drawdowns at piezometer nest SF-2 (A, B and C are respectively bottom, middle, top observation intervals).

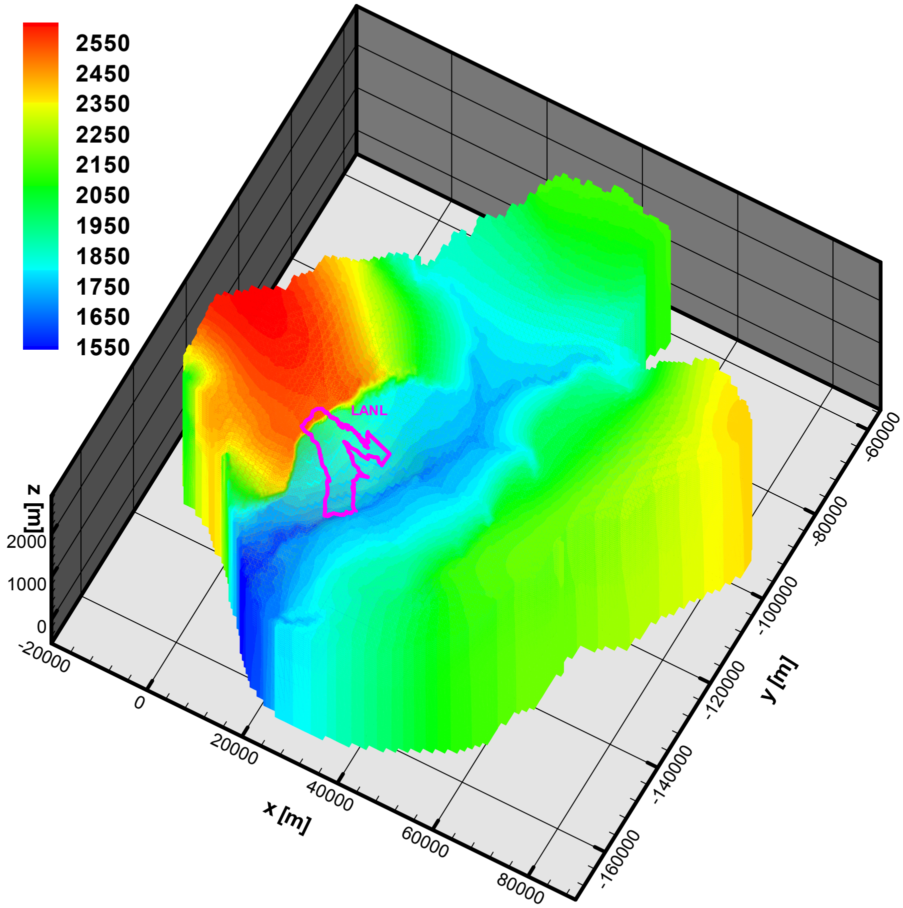


Figure 21. Simulated pre-development steady-state hydraulic heads [m].

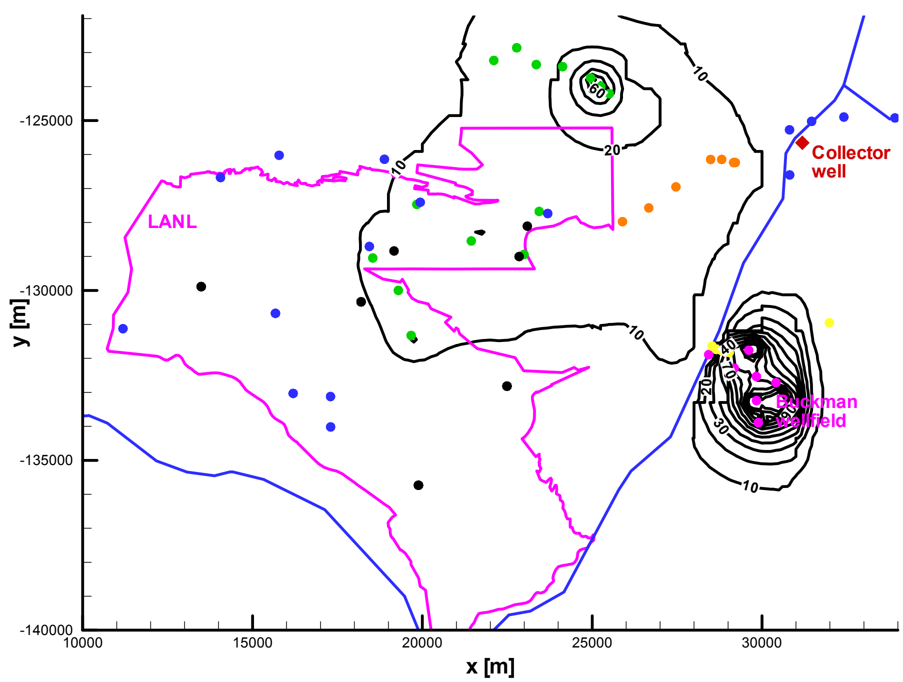


Figure 22. Simulated present transient water-table drawdowns [m].

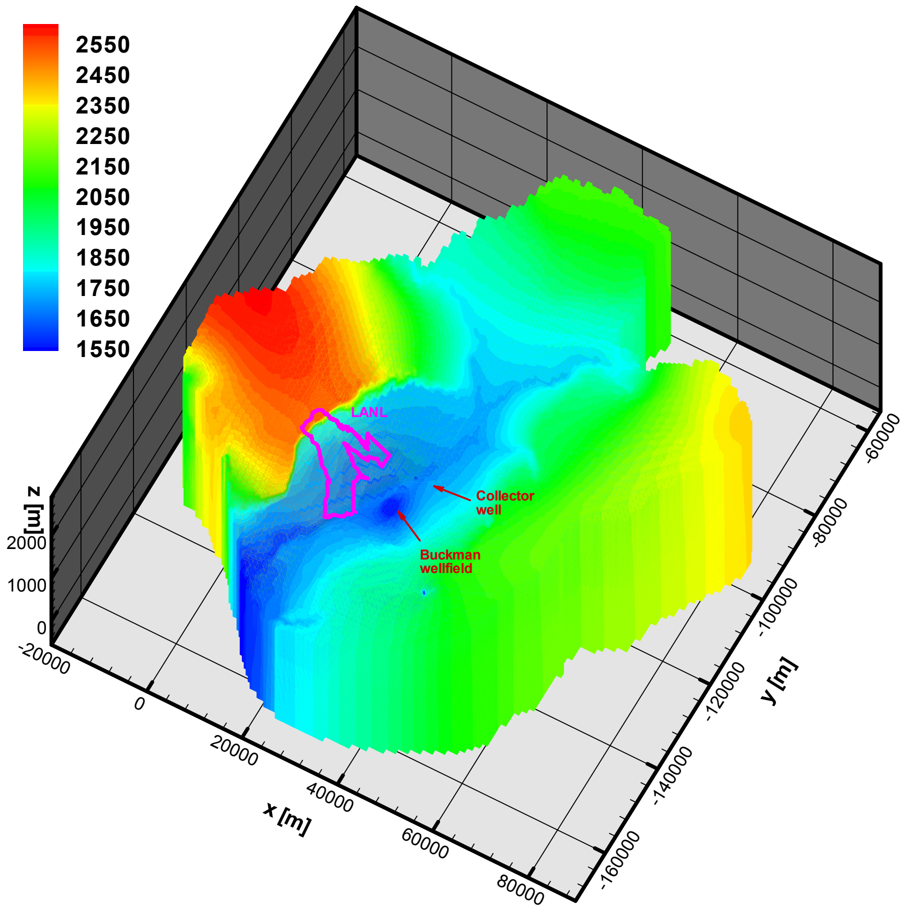
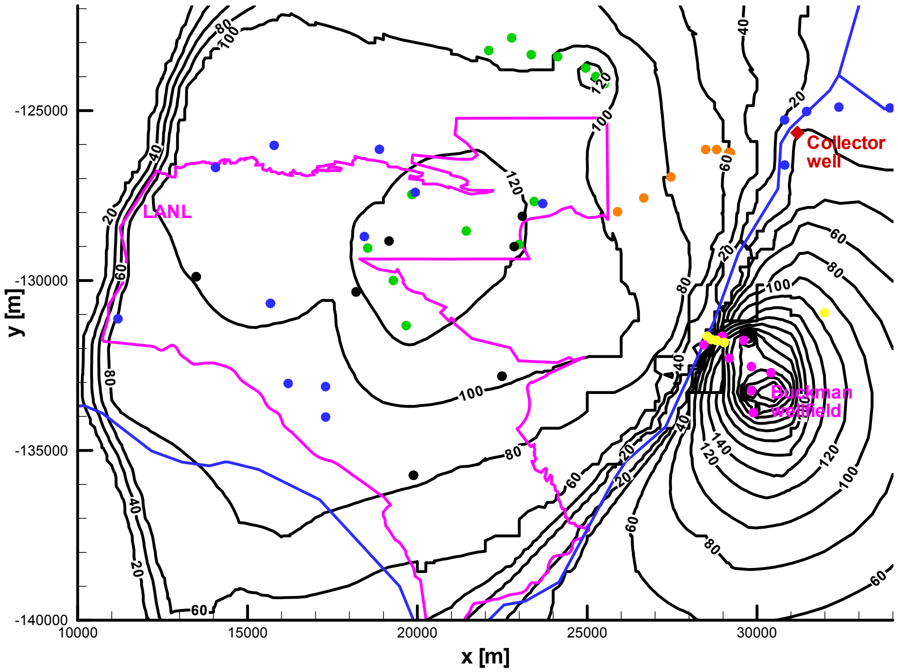
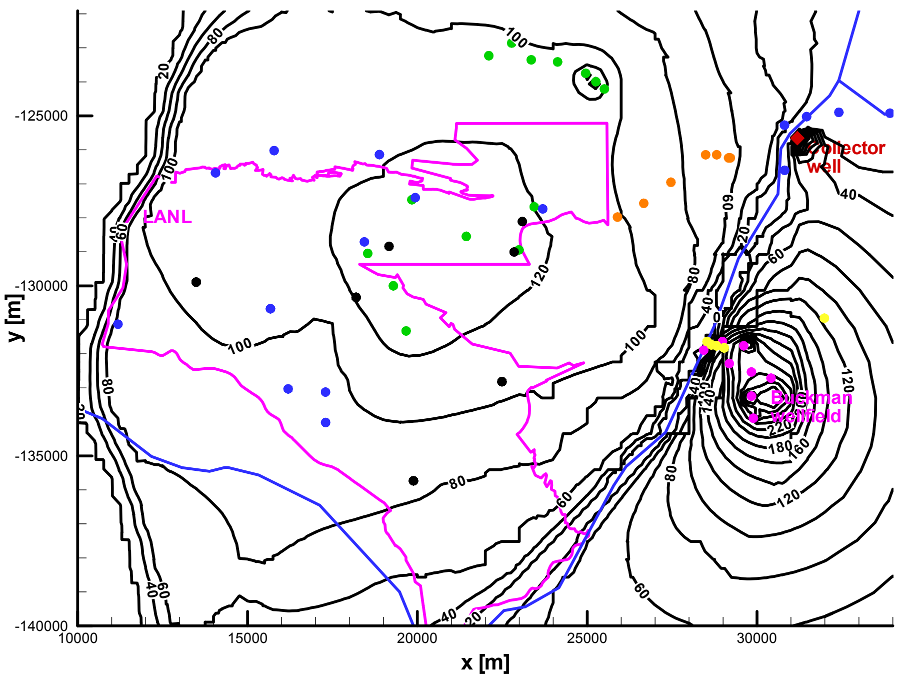


Figure 23. Simulated post-development (future) steady-state hydraulic heads [m] (with the collector well).



(a)



(b)

Figure 24. Simulated post-development (future) steady-state water-table drawdowns [m] without (a) and with (b) the proposed collector well.

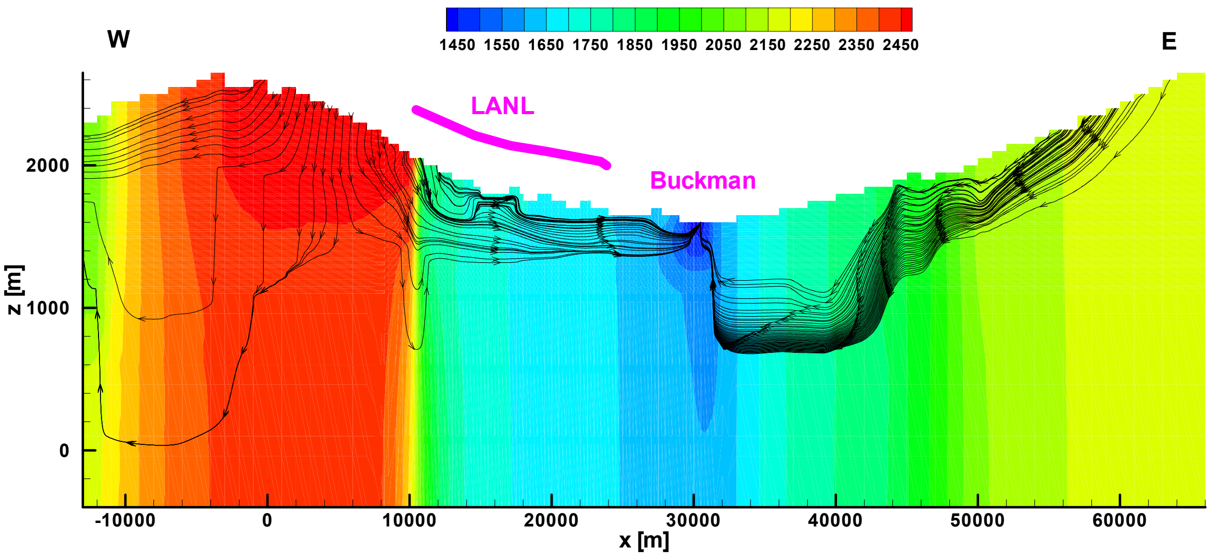
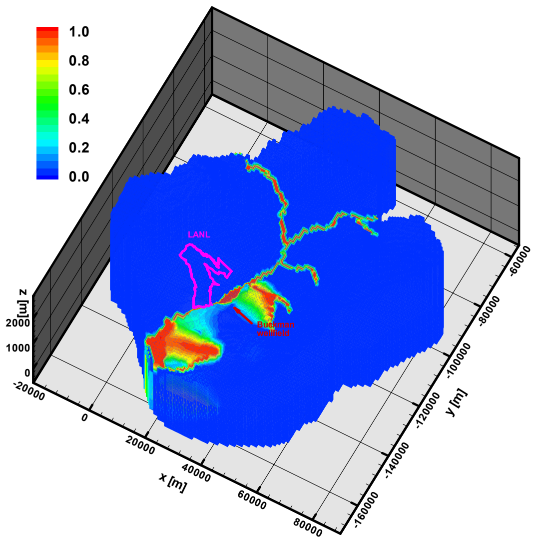
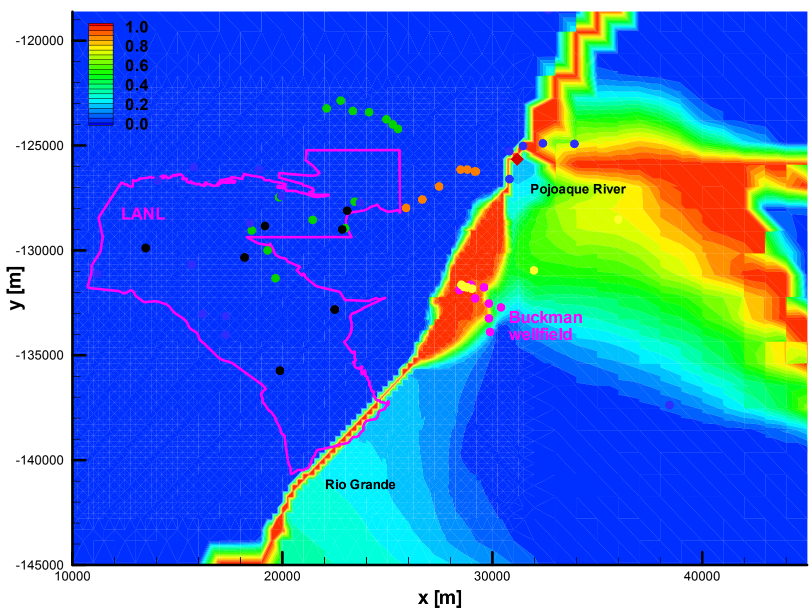


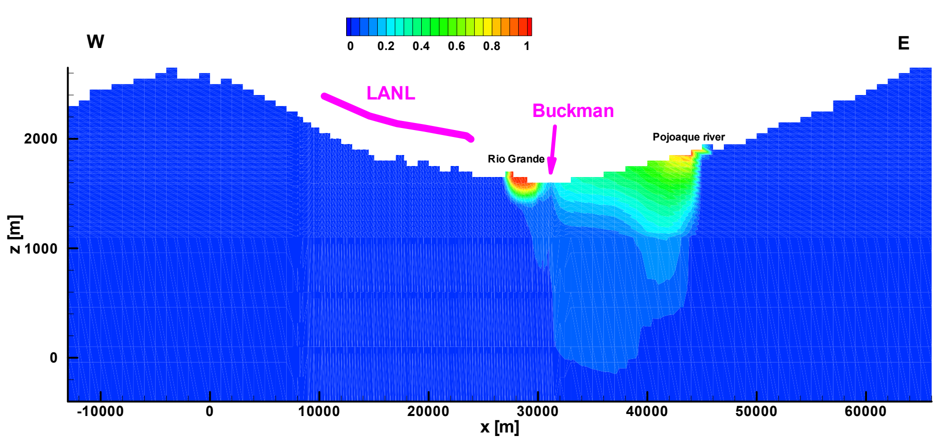
Figure 25. Vertical cross-section through post-development steady-state hydraulic head [m] field at y = –133,000 m (10 times vertical exaggeration); the flowpaths represent the directions of the groundwater from the west and east recharge areas.



(a)



(b)



(c)

Figure 26. Model prediction of the ratio of groundwater originated from recharge of surface water (the Rio Grande and its tributaries): 3D (a), plan (b) and cross-section (c) views.

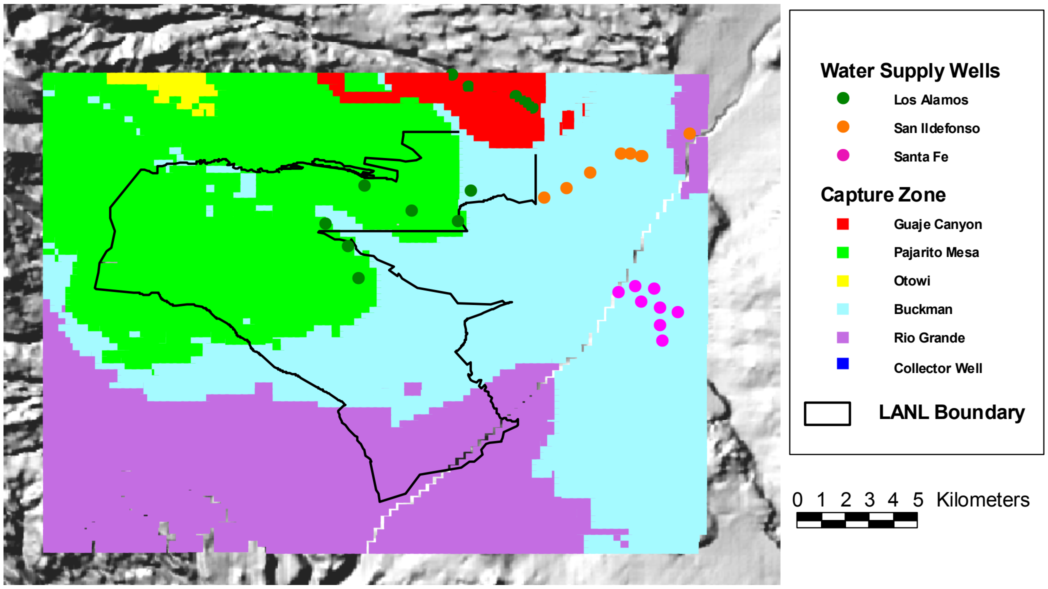


Figure 27. Planar representation of the three-dimensional capture zones of the water-supply systems (without the collector well) at the water table.

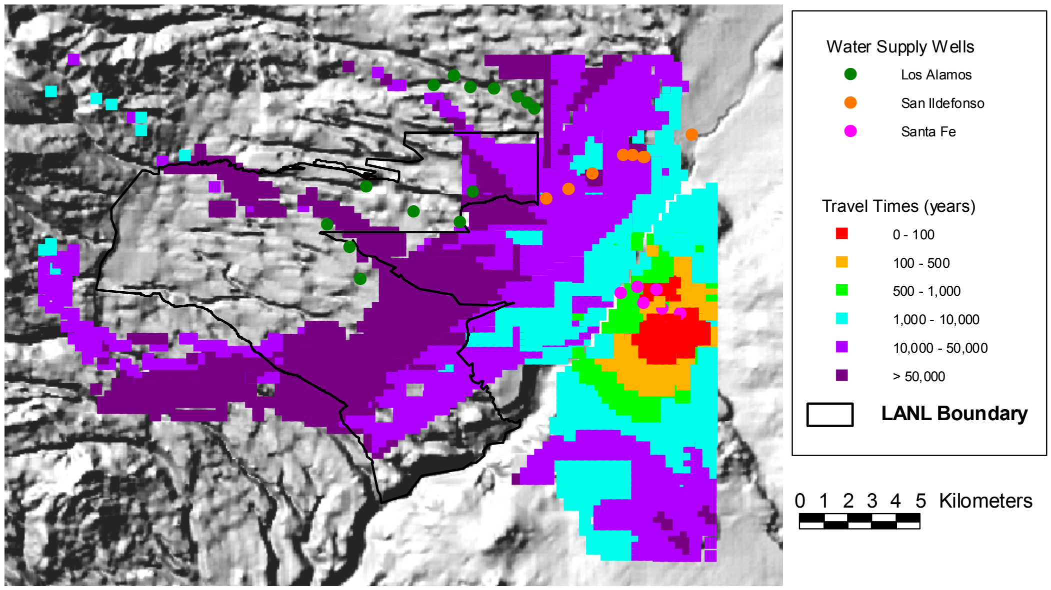


Figure 28. Travel times (in years) to Buckman from the water-table.

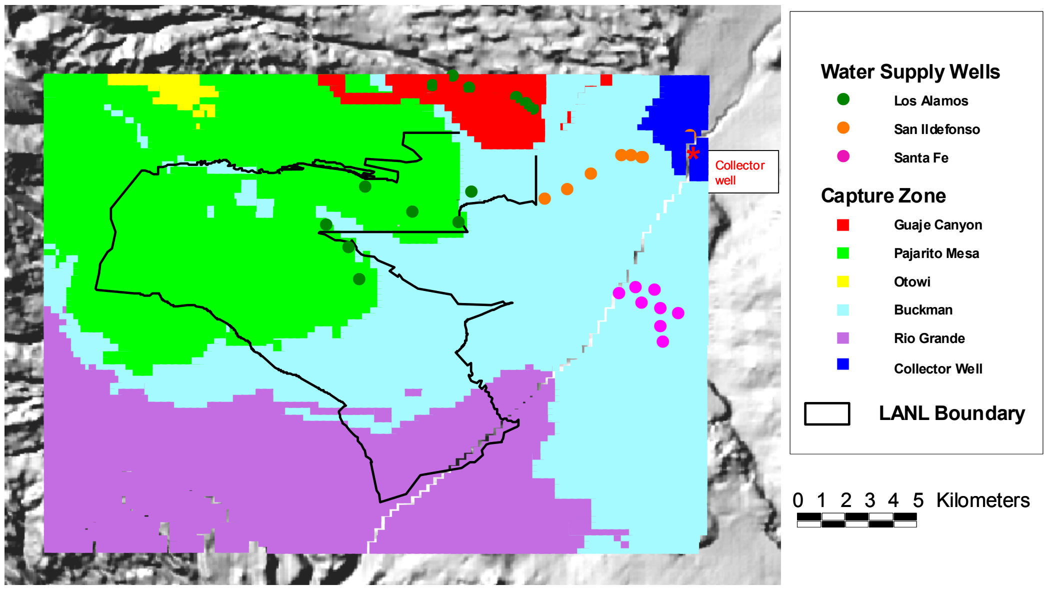


Figure 29. Planar representation of the three-dimensional capture zones of the water-supply systems (with the collector well) at the water table.

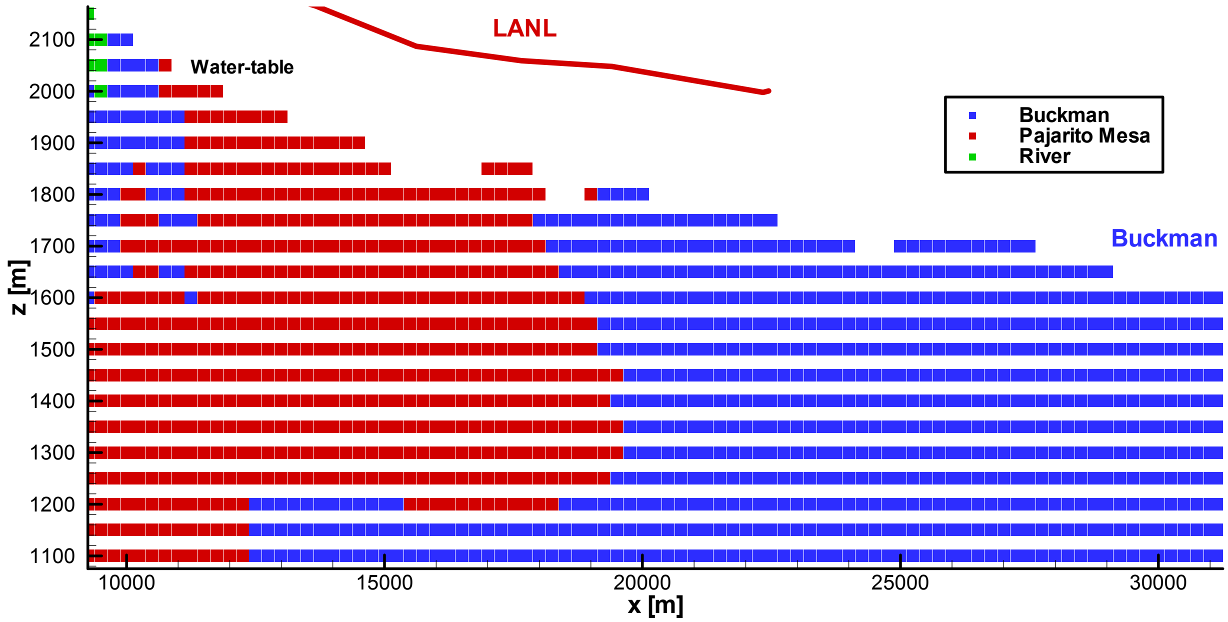


Figure 30. Vertical cross-section through the three-dimensional capture zones; the cross-section trace passes through Buckman at y=–133,295 m.

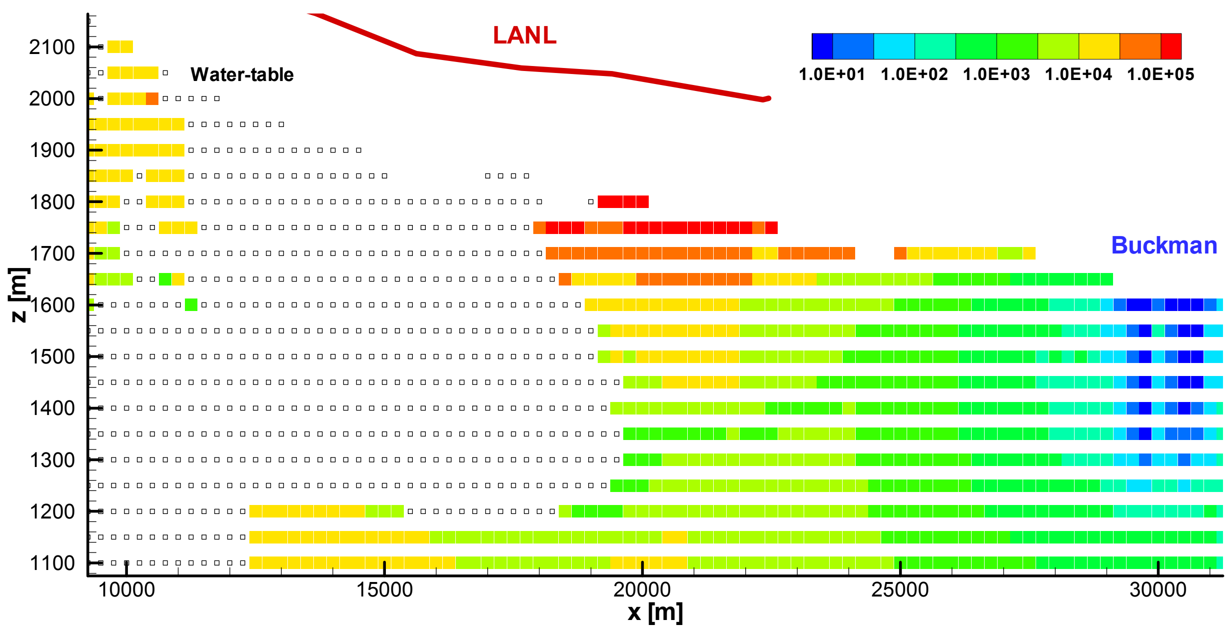


Figure 31. Travel times (in years) to Buckman along the vertical cross-section through three-dimensional capture zones; the cross-section trace passes through Buckman at y=–133,295 m.

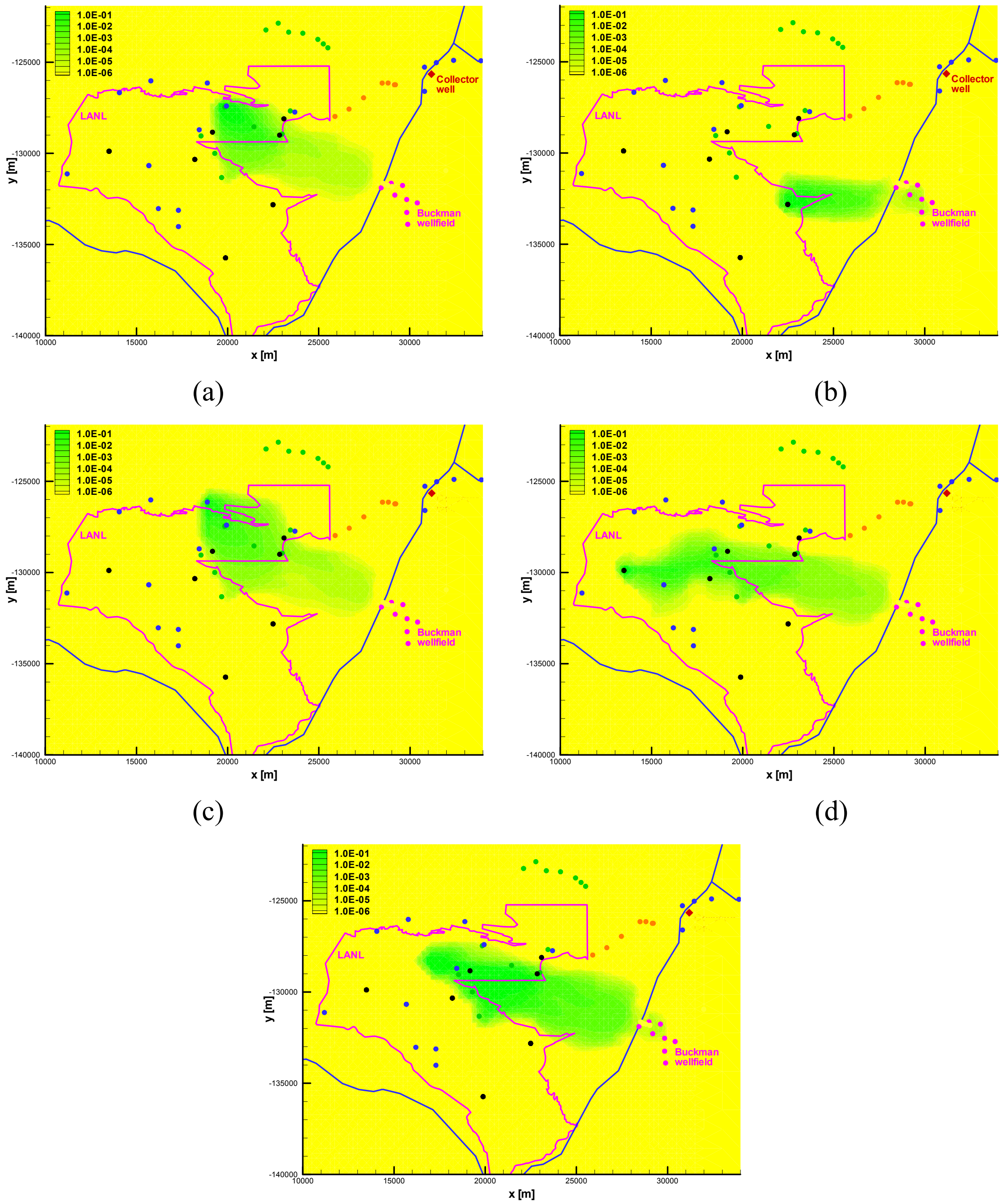


Figure 32. Predicted relative concentrations at the water table assuming steady-state regime and hypothetical water-table sources at (a) the confluence of Los Alamos and Pueblo Canyons, (b) R-22 (Area G), (c) County Sewage Water-Treatment Plant, (d) R-25 (TA-16), and (e) Mortandad Canyon; colors correspond to concentrations relative to permanent-source concentration.

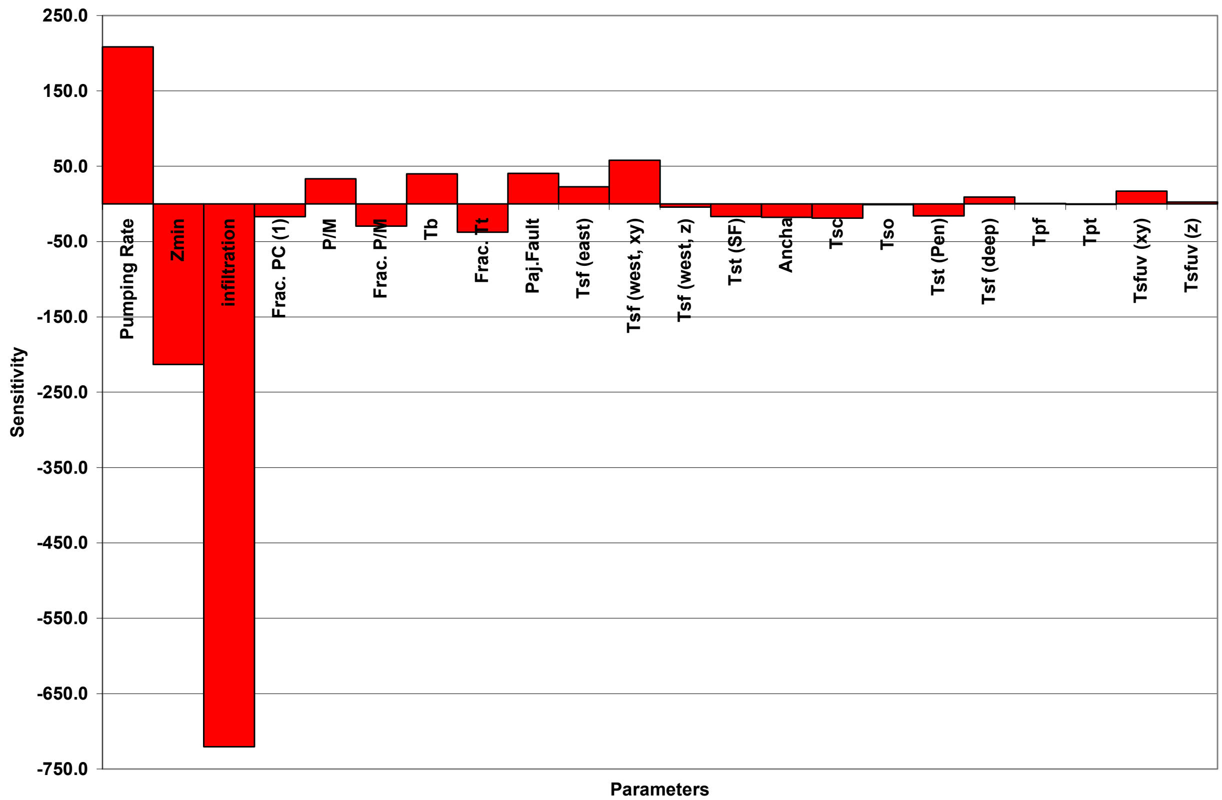


Figure 33. Sensitivity coefficients of model parameters to the predicted portion of Buckman water originating in the western part of the basin (see Table 3 for explanation of symbols).

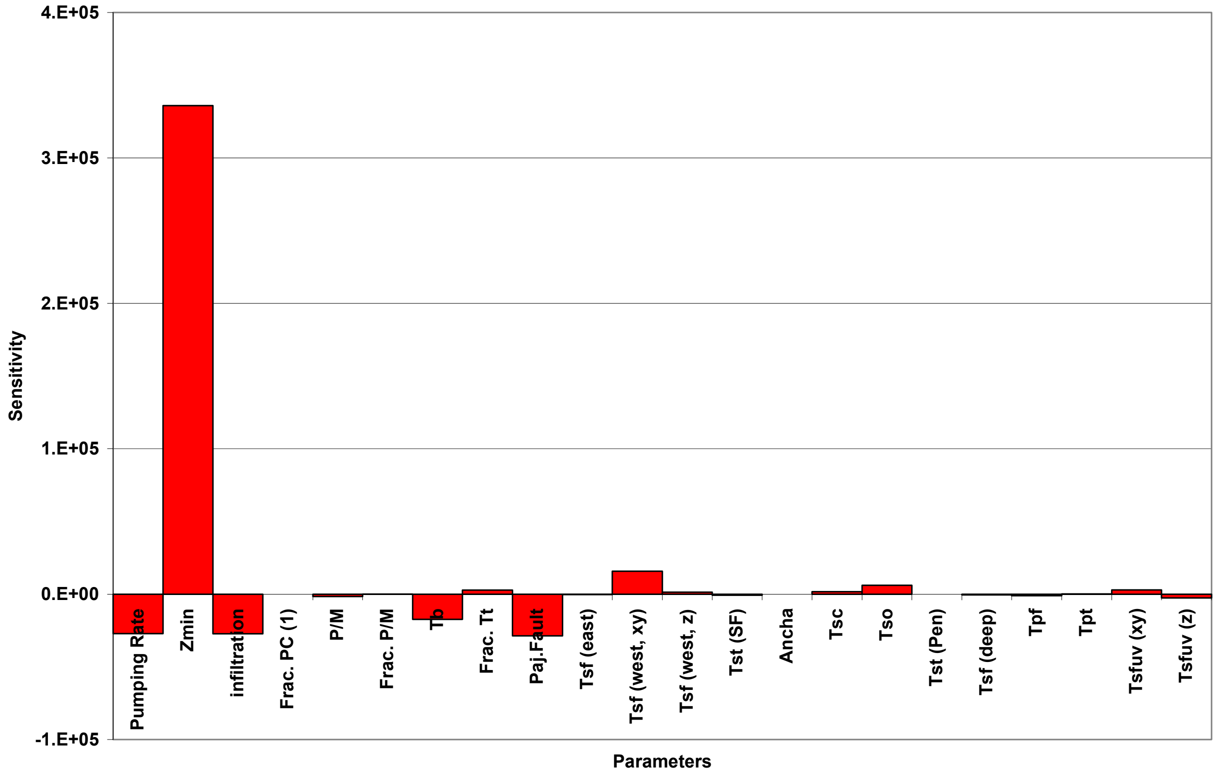


Figure 34. Sensitivity coefficients of model parameters to the predicted minimum travel times for advective groundwater transport from the western part of the basin to Buckman (see Table 3 for explanation of symbols).

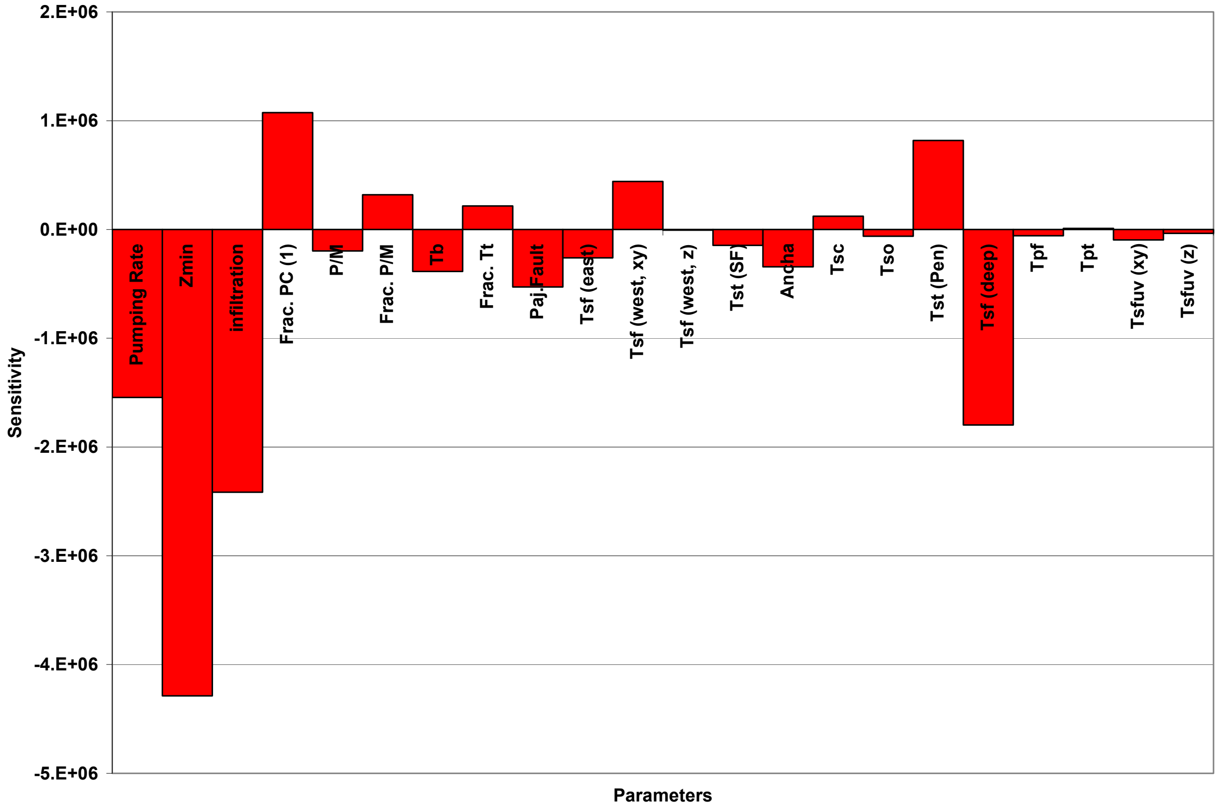


Figure 35. Sensitivity coefficients of model parameters to the predicted average travel times for advective groundwater transport from the western part of the basin to Buckman (see Table 3 for explanation of symbols).