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# TAOS REGIONAL GROUNDWATER FLOW MODEL

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ABSTRACT.— The New Mexico Office of the State Engineer Hydrology Bureau has developed a regional, 7-layer, groundwater flow model of the Taos Valley, New Mexico using MODFLOW-2000. This model was designed and developed together with the Taos Technical Committee, a team of experts in hydrology and geology, with many years of experience in the Taos area, and in conjunction with a U. S. Bureau of Reclamation (BOR) surface water model. Results from recent hydrogeologic investigations are incorporated, including deep drilling and hydrologic testing sponsored by the BOR, and the latest geologic mapping by the New Mexico Bureau of Geology and Mineral Resources. The model simulates groundwater flow in about 3000 ft of alluvial and volcanic materials, and is designed to estimate aquifer drawdowns and depletion effects to the Rio Grande, its tributaries and springs. The groundwater model serves two primary functions: first, as a tool to administer water rights, and second, to evaluate scenarios in settlement negotiations in an on-going water rights adjudication. This model simulates key hydrologic processes including natural recharge, irrigation seepage, evapotranspiration, and aquifer interaction with the Rio Grande and its tributaries and Buffalo Pasture Springs. Geologic strata represented in the model include Quaternary alluvial fan deposits, Tertiary Servilleta Basalt flows, and Tertiary Santa Fe Group sediments. The model simulates heads and groundwater discharges reasonably well, and captures major groundwater features such as large downward vertical gradients, thus allowing the interaction of the shallow and deep aquifer systems to be well simulated.

## INTRODUCTION

The Taos Valley stream system is fully appropriated with known shortages in surface water supply. Irrigated agriculture (approximately 12,000 acres) is an important part of the local culture and economy. As the agency responsible for administering the state's water resources, the New Mexico Office of the State Engineer is charged with the protection of existing water rights. This regional groundwater flow model for Taos is one tool the agency uses to meet this objective. Also, the model is being used within the context of water right adjudication negotiations to evaluate potential settlement scenarios.

The model is implemented in MODFLOW-2000 (Harbaugh and others, 2000), the U.S. Geological Survey's modular three-dimensional finite difference groundwater flow code. The model covers part of Taos County, which lies within the Rio Grande Underground Water Basin at the southern end of the San Luis Basin (Fig. 1). Whereas the Rio Grande Underground Water Basin is a declared Office of the State Engineer administrative basin, the San Luis Basin is structural. This model version uses long-term average annual input data. Although not described here, a seasonal model has also been developed. The seasonal model may be used in the future to investigate seasonal and climatic variations in water supply that are masked in the long-term average version.


FIGURE 1. Area simulated by the Taos regional groundwater flow model.

Model development has been a cooperative effort between and among multiple agencies and technical consultants. For example, a deep well drilling program conducted over the past few years sponsored by the U.S. Bureau of Reclamation (BOR) has improved our knowledge of hydrogeologic conditions at depth, and surface water modeling by the BOR has paralleled the groundwater model development process. Both have provided inputs to the groundwater model.

## GENERAL DISCUSSION OF GROUNDWATER SYSTEM

Groundwater in the Taos Valley moves primarily in a southwesterly direction from the mountain front and upper valley, eventually draining into the Rio Grande (Fig. 2). Water enters the aquifer through mechanisms including areal recharge of precipitation, mountain front recharge (underflow from the mountain block into the basin), and seepage from streams, acequias, irrigation ditches, and irrigated lands. Water leaves the aquifer via seepage to springs and surface water features, pumping, and evapotranspiration. There may be some underflow components to and from adjacent basins, but these are not well quantified, and have been neglected in the current analysis.

The model simulates a shallow unconfined alluvial aquifer system in the eastern part of the Taos Valley, underlying the Town of Taos and most of the irrigated lands, and deep, generally confined aquifers consisting of older Santa Fe Group deposits and layers of basalt which underlie the shallow system and extend westward to the Rio Grande. The sediments in the shallow alluvial

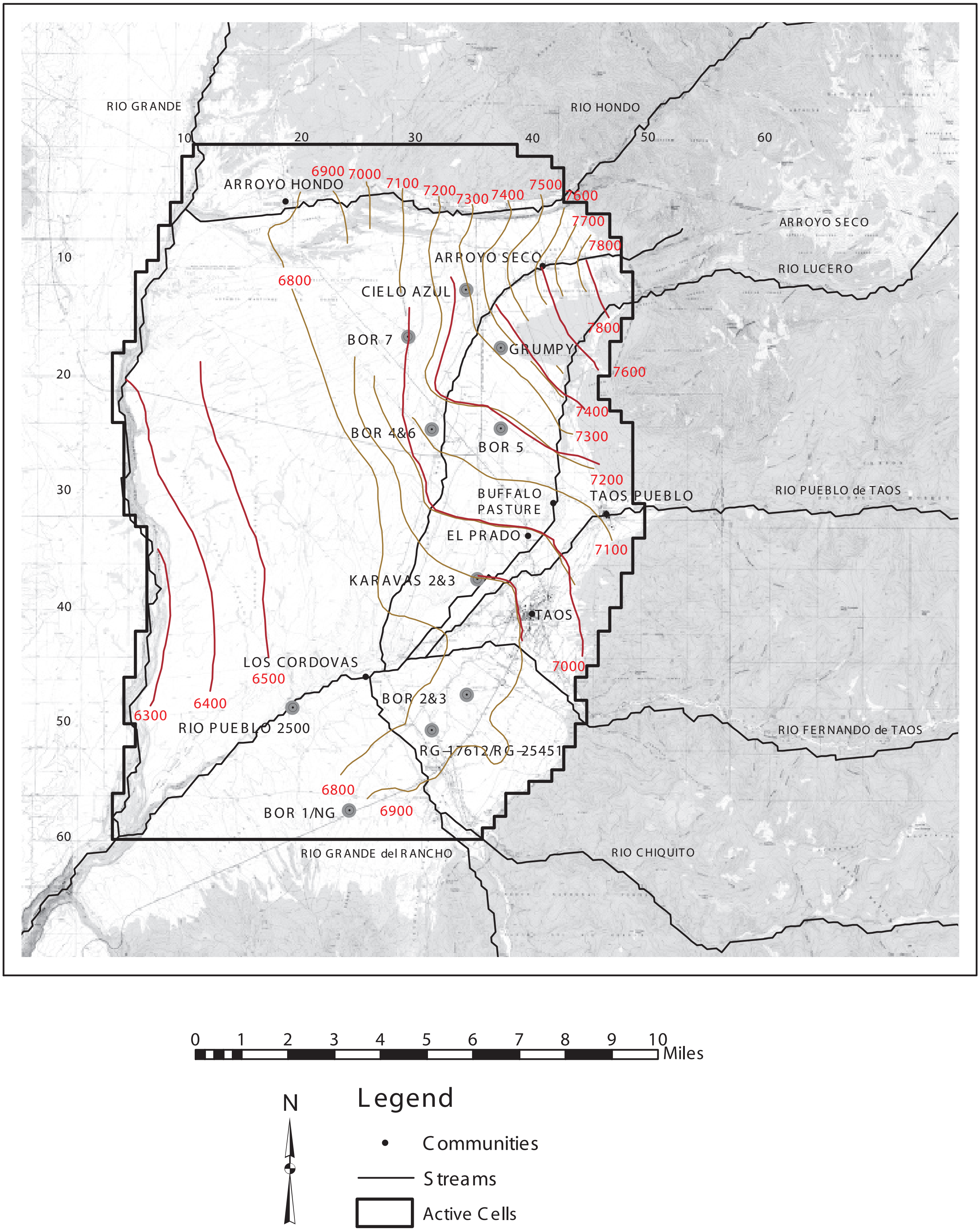


FIGURE 2. Observed water level contour map (after Spieel and Couse, 1969 and Purtyman, 1969) and critical well control for model.

aquifer system are derived from the Sangre de Cristo Mountains. The basin fill Santa Fe Group deposits consist of fluvial, lacustrine, and eolian sediments ranging in size from clays to gravels. Significant downward gradients are noted in data associated with BOR 1 deep, BOR 2C, and other wells, and reflect the drainage of the shallow aquifer system downward toward the deeply incised Rio Grande. Groundwater development in the Taos Valley has been minor. On the order of 2300 acre-feet per year (af/yr) of groundwater is pumped, and measured regional water levels have not shown a significant response to this production.

## MODEL EXTENT AND LAYERING

The model grid (Fig. 3) encompasses a 225-square mile area from the Rio Grande to the Taos Range of the Sangre de Cristo Mountains and from the Rio Hondo to the confluence of the Rio Grande with the Rio Pueblo de Taos. The model area measures 15 miles by 15 miles and has 60 rows, 60 columns, and 7 layers. Rows and columns are evenly spaced and measure 1320 ft (1/4 of a mile) on each side. The southwest corner of the model grid is tied to the southwest corner of sec. 2, T24N, R11E, Public Land Survey System, New Mexico Prime Meridian (NMPM). The grid is oriented north-south and east-west.

Figure 3 shows the active extent of the model grid and selected model boundary conditions. The cells representing mountain areas to the east and the area west of the Rio Grande are inactive. Mountain front recharge is applied along the base of the Sangre de Cristo Mountains as shown in Figure 3 and is described in more detail in the next section. The northern and southern boundaries, apart from where mountain front recharge occurs, are no-flow (inactive) boundaries. There is also a no-flow model boundary immediately west of the Rio Grande. These no-flow boundaries allow us to simulate the system conservatively given our lack of hydrologic information about how, or even whether, the Taos Valley aquifers extend beyond the boundaries here defined. Using no-flow boundaries in these locations will help ensure that this model does not underestimate drawdowns or stream impacts caused by proposed changes in water management.

The model is a simplified representation of complex regional hydrogeologic conditions of the Taos Valley described in Bauer et al. (1999). The surficial and subsurface geologic materials are represented in seven model layers as depicted in a schematic geologic cross-section (Fig. 4). Layer descriptions and nominal thickness are given in Table 1. The total model thickness is more than 3000 ft. Land surface elevations range from about 6100 ft above mean sea level (amsl) in the southwest to just under 8000 ft amsl in the northeast. Upper layers (1 – 4) thin and pinch out toward the west. Consequently, rivers and streams cut down from higher to lower layers as they flow west.

## BOUNDARY CONDITIONS

The model boundaries are designed to simulate inflows from recharge and irrigation return flow, interaction between the aquifer and the Rio Grande tributaries, and discharge to the Rio Grande.

### Areal and Mountain Front Recharge

Areal recharge is estimated at 4% of the average annual precipitation (12.55 in./yr, Garrabrant, 1993) or 0.5 in. Areal recharge totaling 1820 af/yr is simulated with the MODFLOW recharge package and is distributed over the uppermost active cells in model layers 1 through 4, where the water table is relatively shallow.

Mountain front recharge of about 5310 af/yr is applied using specified flux cells (injection wells) along the mountain front on the eastern and part of the southern boundary. The amount and distribution of mountain front recharge in the model area is based primarily on calibration requirements, but is consistent with the results of previous mass balance studies involving seven watersheds (Johnson, 2003). Mountain front recharge is applied in model layers 1 through 4.

### Groundwater Accretions

Groundwater accretions consist of recharge from acequia/ditch/lateral seepage and on-farm deep percolation. The groundwater accretion values are derived from the U.S. Bureau of Reclamation's Taos Valley surface water model and represent about 30% of the surface water diverted for irrigation (additional irrigation return flows are routed directly to downstream nodes in the surface water model for potential reapplication in surface water irrigation). Groundwater accretions were applied in zones defined using GIS coverage showing irrigated lands. Specified flux cells (injection wells) were used to simulate this process. Groundwater accretions account for a total of about 11,590 af/yr.

### Surface Water Features

The tributaries are simulated in layers 1 through 5 with the MODFLOW stream-routing (STR) package (Prudic, 1989). Long-term average stream flow values are applied to the upper end of these features, derived from USGS stream gage measure-

TABLE 1. Model layer descriptions

| Layer | Geologic Description | Nominal Thickness(ft) |
|---|---|---|
| 1, 2 | Youngest alluvial fan deposits derived from Sangre de Cristo Mtns. | 20, 30 |
| 3 | Youngest alluvial fan deposits derived from Sangre de Cristo Mtns. | 50 |
| | (Northern Basin: Reworked alluvial fan materials) | (up to 700) |
| 4 | Reworked alluvial fan materials and other basin fill deposits including poorly to well sorted silts, sands, and gravels | <100 to 550 |
| 5 | Pliocene Servilleta Basalt flows and interbedded sediments | 400 |
| 6, 7 | Miocene Santa Fe Group sediments composed of fluvial, eolian, and lacustrine clays, silts, sands, and gravels | 500, 1700 |

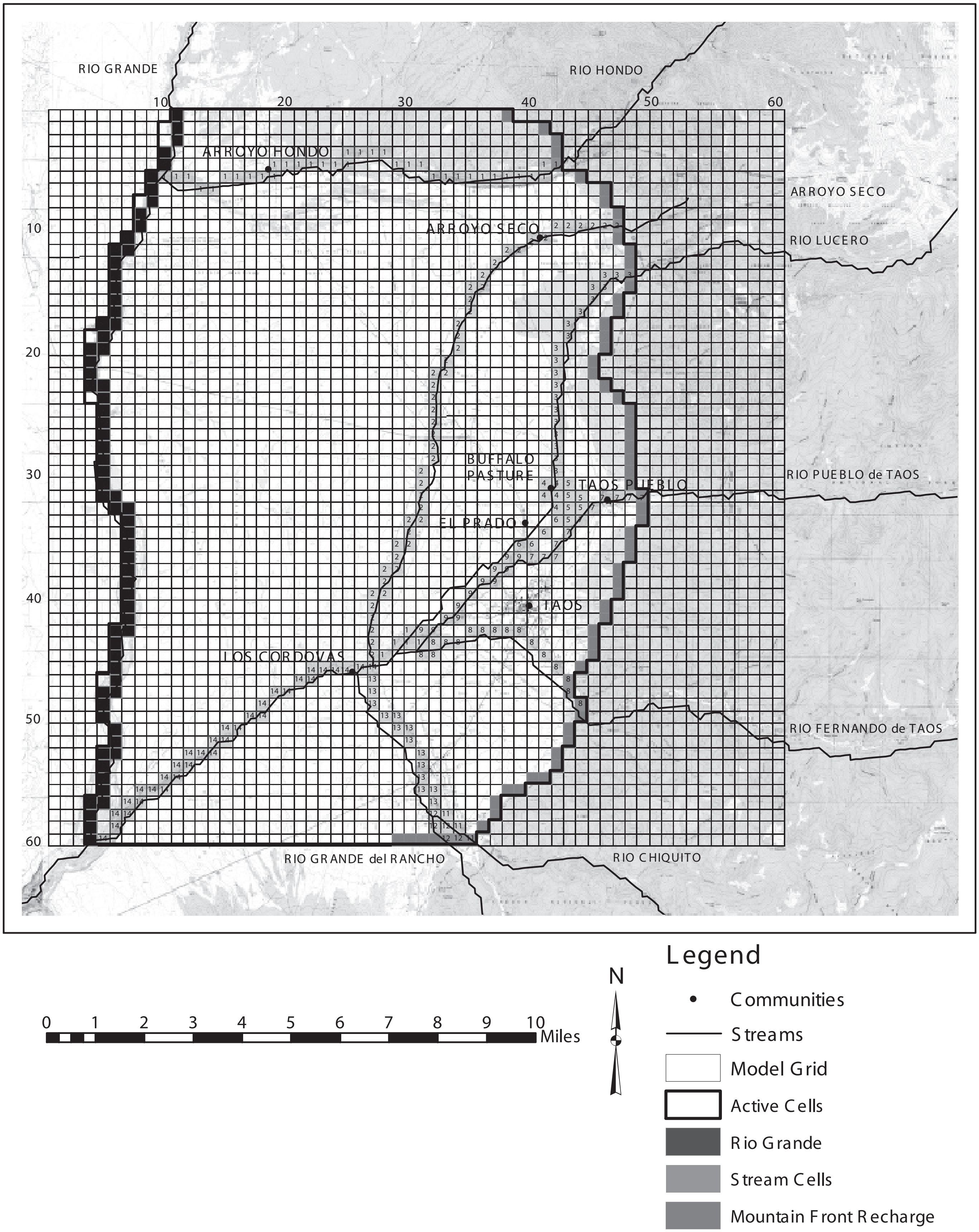


FIGURE 3. Model grid and selected model boundary conditions.

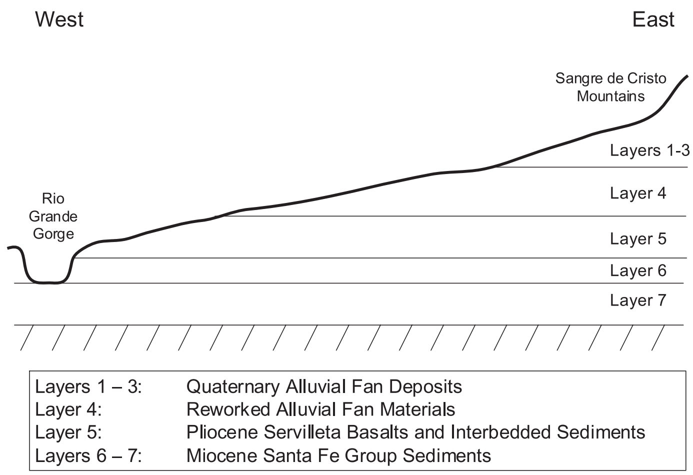


FIGURE 4. Schematic cross-section of Taos Valley showing geologic layers represented in the model. See Table 1 for layer thicknesses.

ments (typically 1935 to 1988). The Rio Grande, which occurs in model layers 5 and 6, is represented using the MODFLOW river (RIV) package.

Buffalo Pasture Springs cover a roughly 600-acre marshy area on both sides of the Rio Lucero. Of critical importance to Taos Pueblo, these springs are modeled by stream-routing package cells. Observed flows from the springs reportedly range from 2 to 15 cubic feet per second (cfs). Seasonal variation of spring discharge is likely, but as yet not quantified.

### Evapotranspiration

Non-crop evapotranspiration is simulated with the MODFLOW Evapotranspiration package (Harbaugh et al., 2000). In most cells, evapotranspiration is active over the entire model in the highest active layer with a maximum rate of 2.2 ft/yr and an extinction depth of 6 ft below land surface. In stream cells the maximum evapotranspiration rate is reduced to one-fifth of that in other cells. Evapotranspiration from groundwater is reduced in stream cells to account for the fact that much of the water consumed by streamside vegetation is probably intercepted surface water, a phenomenon that is treated in the surface water model. Total evapotranspiration from the groundwater model is about 5370 af/yr, which, although not well constrained by measurement, is a reasonable value based on earlier unpublished water balance calculations in the valley. A comparison of spatial locations of model cells experiencing evapotranspiration with GIS coverage of soggy soils/wet meadows (U.S. Department of Agriculture, 2000) shows relatively good agreement.

### Groundwater Diversions

Groundwater pumping from a variety of sources is represented. The model simulates Town of Taos municipal wells (840 af/yr), about one dozen mutual domestic water users associations (460 af/yr), 1900 private domestic wells pumping a total of 560 af/yr, multiple household domestic wells pumping a total of 300 af/yr, and commercial wells using 190 af/yr.

## HYDRAULIC PROPERTIES

Geologic deposits simulated by the model include Quaternary alluvial fan materials, some of which are reworked, derived from the Taos Range of the Sangre de Cristo Mountains (Layers 1 through 4), Pliocene Servilleta Basalt flows and interbedded sediments (Layer 5), and Miocene Santa Fe Group sediments consisting of clay, silt, sand, and gravel of fluvial, eolian, and lacustrine origin (Layers 6 and 7). Several faults are represented using the MODFLOW horizontal flow barrier package. These normal faults – Los Cordovas, Town Yard, and other unnamed faults – generally trend north and are typically downthrown to the west.

The model defines zones of hydraulic conductivity, which are then multiplied by layer saturated thicknesses to generate transmissivity. Model hydraulic conductivities were determined in part based upon the results of 46 aquifer tests, as well as by model calibration (especially for zones where no aquifer test data are available). Transmissivity values from aquifer tests in the shallow system range from 250 to 8000 feet squared per day ($ft^2/d$). Transmissivity in the lower aquifer system tends to be lower, ranging from 100 to 1400 $ft^2/d$. Model hydraulic conductivities in the shallow system range from 1.0 to 90.0 feet per day (ft/d), and in the deeper layers from 0.1 to 10 ft/d.

There are few data on aquifer storage for the Taos area, and therefore it was decided to use typical values for alluvial aquifers. For reasons of stability, the model simulates all layers as "Type 0", or confined layers, with specific storage set so as to generate the appropriate storage (0.15) for areas that are actually unconfined. Specific storage for confined areas is set at $2 \times 10^{-6}$ per foot. This configuration introduces some error because modeled transmissivity does not change as drawdowns change the thickness of unconfined layers. However, since historical drawdowns have been very small and future drawdowns in the shallow unconfined system are anticipated to remain small, this error is negligible for the proposed use of the model.

Vertical anisotropy (the ratio of horizontal hydraulic conductivity to vertical) is known to be significant, both from large observed vertical hydraulic gradients, and from the presence of horizontal structures, including thick horizontal basalt layers. Model anisotropy was determined during calibration, in order to accurately simulate the observed vertical gradients, and ranges from 25:1 near the edges of certain alluvial layers, to 1400:1 in the basalt layer.

## MODEL CALIBRATION

The model run was divided into two parts: an initial steady-state simulation representing conditions before much groundwater development, followed by a transient historical period of 40 years in which estimated groundwater pumping rates were applied. The model was calibrated to observed water level data,

TABLE 2. Model calibration statistics

| Parameter | All Layers |
|---|---|
| Number of Observations | 354 |
| Residual Mean (ft) | 3.13 |
| Residual Standard Deviation (ft) | 44.9 |
| Sum of Squared Residuals (ft2) | 714,109 |
| Absolute Residual Mean (ft) | 30.7 |
| Minimum Residual (ft) | -143 |
| Maximum Residual (ft) | 232 |
| Observed Head Range (ft) | 1267 |
| Minimum Observed Head (ft) | 6452 |
| Maximum Observed Head (ft) | 7719 |
| Std. Deviation/Head Range | 3.5 % |
| Percent of Residuals within 100 ft | 95 % |
| Percent of Residuals within 50 ft | 82 % |
| Percent of Residuals within 30 ft | 64 % |
| Percent of Residuals within 20 ft | 50 % |
| Percent of Residuals within 10 ft | 29 % |

discharge from Buffalo Pasture Springs and discharge to the Rio Grande. There was very little change in modeled water levels or discharges during the simulation period throughout most of the model, which is consistent with the available observational data. Calibration was done using trial and error methods.

Water level data used to calibrate the model were obtained from various sources including U.S. Geological Survey Ground-water Site Inventory, state well records (WATERS database), consultant and contractor reports, and a Bureau of Indian Affairs well database of Taos Pueblo wells. The range of water levels is similar to the range in land surface elevation in the model, from about 6100 ft amsl at the Rio Grande to nearly 8000 ft amsl at the mountain front. There is considerable scatter in the observed water level data due to issues of hydrogeologic complexity, the presence of large hydrologic gradients, and variable data quality. The match of simulated water levels and observed water levels reflects this scatter, but is considered adequate. In general, the shallow system is simulated more accurately than the deep system. Model calibration statistics are given in Table 2. Fifty percent of simulated

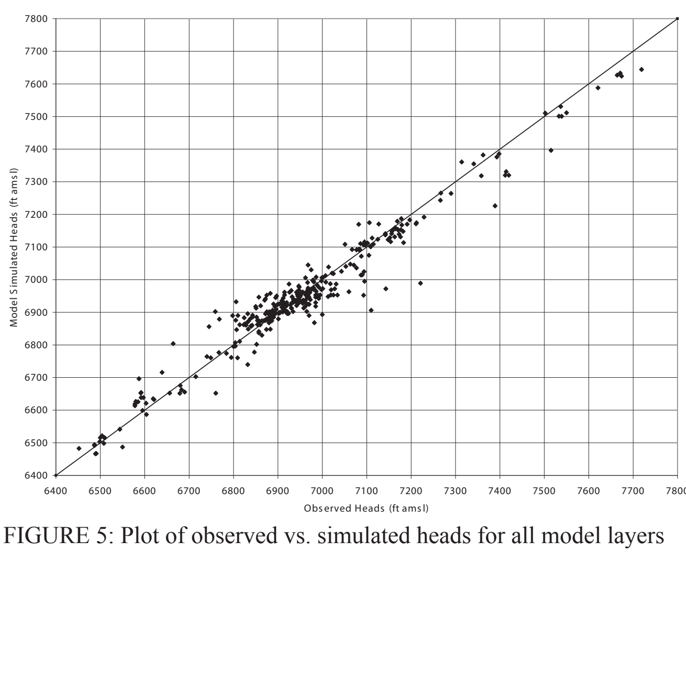


FIGURE 5: Plot of observed vs. simulated heads for all model layers

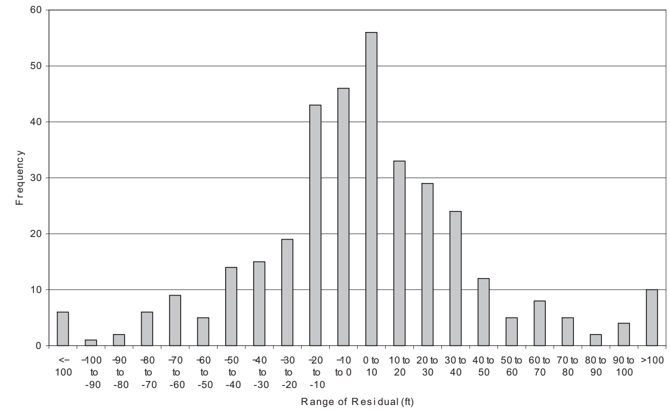


FIGURE 6: Bar chart of head residuals for all model layers.

water levels are within 20 ft of observed values, and 82% are within 50 ft, which is acceptable given the scatter in the data and the large range of observed water levels across the model area (1267 ft). Most large residuals are associated with wells at the edge of the basin, or wells of suspect location or screening (we did not attempt to eliminate such outliers). Figure 5 shows observed versus modeled water level elevations, and Figure 6 is a chart of the distribution of residuals. The residual value equals observed head minus model-simulated head, and the values shown represent a reasonable distribution of residuals, centered on zero.

This model closely simulates the large vertical gradients observed between the shallow and deep aquifer system in the area. Observed differences in water level between deep and shallow wells at the same location range from 100 to over 400 ft (the deeper well having the lower water level), and this phenomenon is well simulated by the model (see Table 3). These gradients constrained model vertical anisotropy, which in many models is a highly uncertain and unconstrained parameter.

Analysis of recorded flows in the Rio Grande from the confluence of the Rio Grande and Rio Hondo to the Taos Junction stream gage shows a gain of about 20 cfs (or about 1 cfs per mile). The model simulates approximately 21 cfs discharge from groundwater in this reach. At Buffalo Pasture, modeled discharge from groundwater is about 5 cfs or 3800 af/yr, compared with

TABLE 3. Observed and simulated vertical head difference between shallow and deep wells at a single location.

| Well | Observed Difference(ft) | Simulated Difference(ft) |
|---|---|---|
| BOR 1/ National Guard | 62 | 104 |
| BOR 2 and 3 | 218 | 211 |
| BOR 4 and 6 | 424 | 400 |
| BOR 5 | 132 | 103 |
| BOR 7 | 253 | 258 |
| Cielo Azul | 208 | 214 |
| Grumpy | 137 (?) | 465 |
| Karavas 2 and 3 | 255 | 260 |
| RG-17612/RG-25451 | 41 | 47 |
| Rio Pueblo 2500 | 131 | 117 |

TABLE 4. Model water budget

| Recharge | af/yr | Discharge | af/yr |
|---|---|---|---|
| Areal recharge from precipitation | 1,820 | Discharge at Buffalo Pasture Springs | 3,800 |
| Mountain front recharge | 5,310 | Evapotranspiration | 5,370 |
| Irrigation seepage | 11,590 | Groundwater pumping | 2,340 |
| Tributary recharge (to aquifer) | 18,770 | Discharge to tributaries | 10,970 |
| | | Discharge to Rio Grande | 14,900 |
| Total | 37,490 | | -37,380 |
| Difference | +110<br>0.3% | | |

2-15 cfs observed discharge (which may contain a direct surface water return component not simulated here). The water budget for the model is provided in Table 4.

## CONCLUSION

Given the hydrogeologic complexity of the Taos area, this groundwater flow model does a relatively good job matching observed water levels, the discharge from the springs at Buffalo Pasture, and the observed large downward vertical gradients. Simulation of the large vertical gradients constrains model vertical anisotropy, and should make this model quite reliable in its simulation of the interaction between the deep and shallow aquifer systems. This model should provide reasonable and useful predictions of the impacts of changes in water management, although the applicability and limitations of the model should be evaluated on a case-by-case basis.

## ACKNOWLEDGMENTS

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