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PRELIMINARY RESULTS OF MODELING THE SHALLOW AQUIFER, MORTANDAD CANYON, LOS ALAMOS NATIONAL LABORATORY, NEW MEXICO

DOE Oversight Program
Ground Water Protection and Remediation Bureau
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DOE Oversight Program

Remediation Section

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ABSTRACT

Mortandad Canyon receives effluent from Los Alamos National Laboratory's liquid radioactive-waste treatment facility at Technical Area 50 (TA-50). As the stream does not normally leave the canyon, the fate of the effluent is a concern. Although the hydrology of Mortandad Canyon has been fairly well studied, including some modeling, it is still not completely understood. Thus, a project to do additional modeling of the system was undertaken.

The first phase, reported here, consisted of a steady-state simulation of the shallow aquifer in one dimension for pre-TA-50 conditions. The model focused on the alluvium between wells MCO-1 and MCO-8, which was discretized as 1 layer, 1 column (scaled for valley cross-sectional dimensions) and 30 rows. MODFLOW, utilizing the recharge, evapotranspiration (ET) and streamflow-routing packages, was the code used. With ET maximized and no underflow or leakage to the underlying tuff allowed, the model showed that the stream flowed the entire length of the canyon. As this does not normally occur in nature and ET was maximized to a reasonable value for the vegetation present, the volume of water the model showed to be leaving the system via streamflow (0.177 cfs) must be dispersed either by leakage or underflowing ground water. Since no underflow has been detected in previous studies, the excess water must be lost through downward leakage.

This project showed the need for additional data on various parameters: runoff or interflow from slopes to the canyon floor; distribution, ET rates and extinction depths for vegetation types; and hydraulic conductivity of the alluvium. The next phase of the project, involving a fully three-dimensional simulation of the system, should eliminate the constraints placed on this model by using a single layer and column.

INTRODUCTION

Los Alamos National Laboratory (LANL) is located 40 mi northwest of Santa Fe, in Los Alamos County, NM (Figure 1). Since its inception in 1943, LANL has generated and disposed of radioactive waste in various forms. In order to protect the ground water in the region, it is essential that the hydrogeologic system(s) at LANL be fully understood.

Mortandad Canyon is one of numerous watercourses dissecting the Pajarito Plateau, the area of deeply dissected Quaternary volcanic deposits and Tertiary fill of the Espanola Basin situated between the Jemez Mountains and the Rio Grande (Figure 2). It lies between Sandia Canyon on the north and Canada del Buey on the south. Unlike some of the other drainages, it has its headwaters on the plateau itself, rather than in the mountains to the west. The area studied is that portion of the canyon in Sec 22, 23 and 24, T19N, R6E (Figure 3).

PROBLEM ADDRESSED

Since the 1960's, liquid radioactive waste generated at LANL has been collected and processed at the industrial-waste treatment plant located in Technical Area 50 (TA-50). This plant discharges more than 100,000 gal of treated effluent per week (in 26,000-gal batches) into Mortandad Canyon via an outfall in Effluent Canyon (Stone and others, 1993b). This contains plutonium 238, plutonium 239, americium 241, uranium and tritium (Koenig and McLin, 1992).

The fate of the effluent has long been a concern. It does not leave Mortandad Canyon as runoff, since the stream does not normally flow to, let alone beyond, the lab boundary. Rather, it soaks into the alluvium at various positions along the canyon, depending on season (Baltz and others, 1963). Larger runoff events apparently can occur, and must have in the past, as there is a recognizable channel all the way to the Rio Grande. Neither does it appear that the effluent leaves the canyon as underflowing ground water. Attempts to locate saturated alluvium down-canyon from the point where the stream normally dries up reportedly failed (Stoker and others, 1991). That leaves downward leakage into the tuff.

Various workers have called on leakage to account for apparent losses of water in the canyon. Purtymun (1974) included this as one of the processes responsible for the loss of tritium in a 1969 discharge from TA-50. Koenig and McLin (1992) concluded from modeling that most storm runoff and effluent entering the alluvium is lost by leakage. Geddis (1992) assumed leakage in modeling unsaturated flow in the tuff. Indeed, tritium has been encountered

at a depth of 195 ft below the canyon floor (Stoker and others, 1991). If tritium could move this deep, it seems possible that it (and possibly other radioactive contaminants from the effluent) could ultimately reach the main aquifer. Two questions remain: is leakage reasonable from a water-balance perspective and how much leakage is there?

PURPOSE OF STUDY

The hydrologic behavior of Mortandad Canyon has probably been more extensively studied than that of any other place at LANL. Yet, it is still incompletely understood. The New Mexico Environment Department (NMED) undertook a modeling project to learn more about the hydrologic system there. The purpose of this study was to simulate the hydrologic balance for Mortandad Canyon as a possible means of determining the fate of the effluent and quantifying what amount, if any, may be lost through downward leakage from the shallow aquifer. It also serves as a first step in constructing a fully three-dimensional model of the shallow and deep aquifers. This report describes the initial modeling effort and results.

ACKNOWLEDGEMENTS -- This study was undertaken as part of NMED's Department of Energy (DOE) Oversight Program. It was done in cooperation with the U.S. Geological Survey (USGS), Water Resources Division, Albuquerque District, and run on their computer system. Peter Frenzel of that agency provided invaluable assistance in applying MODFLOW to the problem, operating the system and useful review comments on this report. The USGS also drafted figures 3 - 10. Discussions with Alan Stoker, Steve McLin, Bruce Gallaher and Eric Koenig, of LANL, were also most helpful. Review comments by Dave Rogers (LANL) are appreciated.

MORTANDAD CANYON

Numerical models are only as good as the conceptual models upon which they are based. Thus, before any simulation of Mortandad Canyon is attempted, it is important to identify available data and formulate a sound hydrogeologic model of the area.

PREVIOUS WORK

Numerous studies have been done over the years on the hydrogeology and plant/water relationships at LANL. Some of these focus specifically on, or can be applied to, Mortandad Canyon. Baltz and

others (1963) did the preliminary study of the geology and hydrology of the canyon prior to construction of the industrial-waste treatment plant at TA-50. John and others (1966) compiled geologic and hydrologic data for the various wells at LANL, including those in Mortandad Canyon. Purtymun (1974) studied travel time for the effluent from the TA-50 outfall to reach its downstream limit. Lane and Barnes (1987) gave evapotranspiration values for juniper and ponderosa at locations in the Southwest, including Los Alamos. Tierney and Foxx (1987) presented rooting depths of various species at LANL. Stoker and others (1991) conducted various studies on the extent of saturation in Mortandad Canyon. Koenig and McLin (1992) characterized the water balance in Mortandad Canyon using a two-cell lumped-parameter model and the data collected from 1963 to 1965 by Purtymun (1967). Geddis (1992) modeled the movement of moisture to and beneath the shallow aquifer in a generalized cross section perpendicular to Mortandad Canyon. Stone and others (1993a) recommended further studies to test/improve the prevailing hydrogeologic conceptual model.

GEOLOGY

Mortandad Canyon is cut into the Bandelier Tuff (Pleistocene). More specifically, the canyon floor is formed in the basal part of the Tshirege Member of that unit. Baltz and others (1963) characterized this part of the Bandelier as pumiceous crystal-fragment tuff or pumiceous tuff breccia. Geologic logs for wells drilled along the canyon floor describe the tuff as "weathered" over much of the length penetrated, often in excess of 100 ft (Stoker and others, 1991).

Alluvium overlies the tuff throughout Mortandad Canyon. Its thickness generally increases down the canyon, ranging from <1 ft in the upper reaches (near the TA-50 outfall) to 61 ft at MCO-8 and at least 67 ft at MCO-9 (Figure 4). The total thickness of alluvium at MCO-9 is not known as drilling halted before the top of the tuff was reached. As might be expected from the source material, the texture is fairly fine: well logs commonly describe it as "silty sand" and even the sand is fine (Stoker and others, 1991). Since the material is derived strictly from the weathering and erosion of the Bandelier Tuff, it is also rather homogeneous in composition. Clasts reportedly consist predominantly of quartz and sanidine crystals or crystal fragments and small rock fragments of pumice or latite.

CLIMATE AND VEGETATION

The LANL area has a semiarid temperate mountain climate with an average annual precipitation of 19 inches (Dewart and Lyncoln-Kohen, 1993). Mean monthly temperature ranges from 28.5 F in January to 67.7 F in July, based on data compiled by Gabin and

Lesperance (1977). They also calculated an annual potential evaporation rate for Los Alamos of 31.22 inches using the method developed by Blaney and Criddle (1962) for irrigated crops.

Vegetation in the area varies with elevation (Dewart and Lyncoln-Kohen, 1993). A pinyon-juniper community occupies south slopes of canyons at elevations of 6,200-6,900 ft and ponderosa pine is common at elevations of 6,900-7,500 ft. As the elevation of the canyon floor in the study area ranges from 6,700 to 7,100 ft, pinyon, juniper and ponderosa are the major trees present. According to Stoker and others (1991), Mortandad Canyon is characterized by underbrush and shrubs as well as pine, fir, box elder and oak trees in the upper part; thinner underbrush and pines on the canyon floor in the middle part; and a gradual replacement of the pines by a scattered pinyon-juniper community in the lower part.

HYDROLOGY

Prior to the construction of the treatment plant and effluent discharge at TA-50, the stream flowed mainly during the spring in response to snowmelt. It eventually soaked into the alluvium before leaving the laboratory property. Baltz and others (1963) reported the extent of flow at various times in 1961. The stream flowed the farthest, and was still advancing, on 14 April, when it was just beyond the position of TW-8A (Figure 5), but was receding by 21 April. By May the water level was well below the channel surface and the stream was not flowing below well MCO-4.

The alluvium is saturated below various depths where ground water is apparently perched atop the less permeable tuff. Thus, the alluvium is often referred to in LANL reports as the "alluvial perched aquifer" or the "shallow perched aquifer". The depth to water ranges from 1 ft in the upper reach studied near well MCO-1 (actually in Effluent Canyon near its confluence with Mortandad Canyon) to 61.5 ft in the lower reaches (well MCO-8). The next well downstream (MCO-9) not only did not reach the tuff, it did not encounter the saturated zone either. At this site the water table is deeper than 67 ft. Thus, ground-water flow in the shallow aquifer of Mortandad Canyon is generally eastward. Recharge apparently occurs along the canyon.

The water table may not always lie within the alluvium. Some water levels reported upon completion of the wells fall within the tuff (Table 1 and Figure 6). However, the wells may not have recovered from drilling when these measurements were made and these values may not be reliable. Based on observations by Baltz and others (1963), there is apparently a seasonal leveling off of water table. That is, as the water level falls below the stream channel in the upper reaches, it rises in the lower reaches.

MODELING

Numerical models are important tools in characterizing and studying ground-water systems. They are not "cure-alls", but rather provide nonunique scenarios of the hydrology, as limited by the code used, the assumptions made about hydrologic conditions and the parameters specified. Nonetheless, models show basic hydrologic relationships and are a good way to test the conceptualized hydrogeologic setting as well as learn what additional data are needed.

The model described herein is simple and preliminary. It was constructed as a pilot for more sophisticated simulation to follow. This being the case, no attempt was made to introduce lateral variations in parameters throughout the simple grid. The numerical model was intended to test the conceptual model of the shallow aquifer in Mortandad Canyon, simulate the water budget based on this conceptualization and evaluate the adequacy of the available data.

RATIONALE

Models are idealized representations of reality, used to demonstrate some property of it. The reality being demonstrated or tested here is the water balance in Mortandad Canyon. In simplest terms this may be expressed as

$$P = RO + ET + R,$$

where P = average annual precipitation (rain and snow), RO = average annual runoff (streamflow), ET = average annual evapotranspiration and R = average annual recharge (downward leakage that escapes ET). In other words, precipitation in an area is dispersed by means of the other three processes.

One may visualize two steady-state scenarios for Mortandad Canyon: pre- and post-TA-50. In this study, pre-TA-50 streamflow and water-level conditions, as reported by Baltz and others (1963), were considered steady-state. It was reasoned that if leakage was found to occur under pre-TA-50 conditions, it would certainly occur under post-TA-50 conditions, with the added input of the effluent. Prior to TA-50, a specific relationship existed between the natural input and output components of the water balance for Mortandad Canyon. Input is envisioned to have included precipitation, runoff (or interflow) from slopes, and streamflow into the canyon. Output would have been accomplished by some combination of streamflow, ET, leakage, and underflow.

Since the amount of ground-water leakage into the tuff is the least known hydrologic parameter in Mortandad Canyon, and that of most

concern, modeling was designed to investigate this parameter. More specifically, it was reasoned that if no downward leakage or underflow were allowed and ET was maximized, any excess water identified in the model as streamflow must represent leakage or underflow. The model was set up so that no downward leakage was allowed and there was no constant head at the downstream end. Thus, the only way for water to leave the model would be by streamflow. The various assumptions made in this modeling effort are discussed below and summarized in Table 2.

CODE USED

MODFLOW, developed by the U.S. Geological Survey (McDonald and Harbaugh, 1988), was selected for the study because of its widespread use and versatility. It is a modular, finite-difference model, capable of simulating ground-water flow in one, two and three dimensions. The FORTRAN program is divided into independent subroutines or modules which are grouped into packages (some required, some optional), each representing a specific hydrologic feature or process. The Basic and Block-Centered Flow packages are required. However, it is the optional stress packages that make MODFLOW so versatile. Stress packages used in this project include those for recharge, evapotranspiration and a stream. The solver used was Preconditioned Conjugate-Gradient 2 (PCG2) prepared for MODFLOW by Hill (1990).

Parameters used with the various packages are given below. Brief descriptions of the packages are also offered for those readers unfamiliar with the code. However, these are very general and the reader should consult the original reference on MODFLOW (McDonald and Harbaugh, 1988) for detailed information on their construction and operation.

BASIC PACKAGE -- Various administrative tasks for MODFLOW are handled by the Basic Package. This is where the number (but not dimensions) of layers, rows, columns, stress periods as well as the initial and boundary conditions are specified. The Basic Package also allocates memory space for arrays, establishes time discretization, calculates overall water budget and controls output.

For this preliminary look at the water balance in Mortandad Canyon, the system was simulated as simply as possible. There was 1 layer, 1 column, 1 stress period and the time units used were seconds. The column was divided into 30 rows. A constant-head condition was specified at the upper end of the model and variable heads everywhere else. Initial (start) heads for each cell are as given in Appendix A. In this configuration, the model is one-dimensional (down canyon).

BLOCK-CENTERED FLOW PACKAGE -- In MODFLOW, ground-water flow is assumed to occur in the center (node) of each cell. The Block-Centered Flow Package calculates hydraulic heads and flow rates required for balancing the finite-difference equation. It specifies aquifer type (confined/unconfined), simulation type (steady-state/transient), anisotropy, row width, column width, hydraulic conductivity and elevation of the aquifer bottom.

In this study, the aquifer was specified as unconfined, simulation type was steady-state (storage was set at zero in the flow equation), the aquifer was isotropic, row width was 400 ft, column width was 50 ft, hydraulic conductivity (K) was assumed to be that of silty sand (0.0015 ft/sec; Freeze and Cherry, 1979, Table 2.2). The bottom of the aquifer was set at 15 ft below the bottom of the alluvium. This was done so that water level would not drop out of the model and dry up cells where the alluvium is thin, as in the upper end of the model. The weathered tuff was assigned the same hydraulic conductivity as the alluvium (K = 0.0015 ft/sec). These decisions seem reasonable in view of the facts that, according to Baltz and others (1963), the water table was within the tuff in some wells and weathered tuff probably differs little from alluvium derived from weathered tuff.

SCALING -- The model covers the area of the canyon for which there were pre-TA-50 water-level data: from well MCO-1 (in Effluent Canyon) to MCO-8 in lower Mortandad Canyon (Figure 3). The shallow aquifer in this area was modeled as a straight, wedge-like box, in spite of curves and junctions with tributaries.

Although the canyon was discretized as a single column, input parameters were scaled for the cross-sectional dimensions of the canyon to provide realism. The width of the column was set at 50 ft, the canyon width in the upper reaches. Precipitation and evapotranspiration in each cell were scaled to the single column by multiplying them times a factor for the number of 50-ft increments making up the canyon (alluvium) width there (Figure 7).

Stream characteristics had to be scaled as well. For example, stream width varies relative to the model grid width so was scaled as shown in column M of Appendix A. A V-shaped channel was assumed for scaling hydraulic conductivity. More specifically, half of the area of a rectangle formed by the wetted width and saturated thickness of the alluvium was used (Figure 8). The model of the canyon is shown schematically in Figure 9 and input data are given in Appendix A.

RECHARGE PACKAGE -- The recharge package simulates areally distributed recharge to the ground-water system. Such recharge is assumed to be accomplished by the percolation of precipitation to the water table.

In this study, average annual precipitation was assumed to be 19 inches, based on the published average for the LANL area (Dewart and Lyncoln-Kohen, 1993). Recharge was defined as 100% of the precipitation falling on the canyon floor plus 50% of the precipitation falling on the sunny, relatively barren north slopes of the canyon. In reality, the water from the north slope would enter the system as runoff and/or interflow along the top of the tuff. However, for modeling purposes, it is simply added to the precipitation falling on the canyon floor. No recharge was allowed from the shady south slopes, where it is more moist, soils are better developed and the thicker vegetation is assumed to get rid of the available precipitation through ET.

EVAPOTRANSPIRATION PACKAGE -- The evapotranspiration (ET) package simulates the removal of water from the system through direct evaporation and transpiration by plants. Several variables must be specified:

1. ET rate - average annual ET value,
2. ET surface - elevation which water table must equal or exceed to maximize ET at the rate specified and
3. Extinction depth - water-table depth below which ET ceases.

In this study ET rate was set at 17 inches. This was based on 1) the average of ET values determined in Arizona for the same kind of vegetation as occurring in Mortandad Canyon and 2) a modeled estimate of ET for Los Alamos, both as reported by Lane and Barnes (1987). The ET surface was set at the initial heads in order to maximize ET. Extinction depth is essentially the maximum rooting depth for the area. Tierney and Foxx (1987) studied root lengths for plant species at LANL and compared them with those cited in the literature. In their study the roots often broke so they had to estimate total lengths. This was done using a standard equation relating root radius to length developed from observations made on roots that hadn't broken. For the main species in Mortandad Canyon (pinyon, juniper and ponderosa) the reported root lengths range from 3.9 to 5.6 ft. As this is considerably less than the range of literature values they cited (15 - 80 ft), an intermediate value of 10 ft, was used as a conservative estimate of extinction depth in the model.

STREAM PACKAGE -- Stream/aquifer interaction was simulated by means of a stream package. That used was the streamflow-routing package developed by Prudic (1989) to account for flow in streams and simulate the interaction of surface and ground water. The advantage of that package, over the River package incorporated in the original MODFLOW code, is that it allows the stream to go dry and is thus more appropriate for semiarid regions of the Southwest like the study area.

In addition to various flags specifying output instructions, input for this package includes several things:

1. Streamflow into the first segment,
2. Stream stage (elevation),
3. Streambed conductance (= KLW/M, where K is hydraulic conductivity of streambed, L is length of reach, W is width of stream and M is streambed thickness),
4. Elevation of the stream bed bottom and
5. Elevation of the stream bed top.

Streamflow into the model is not known. Reportedly some discharge data were collected at the upper end of the canyon years ago, but they could not be located. A value of 0.001 cfs was used in the model. The stream stage was set at an elevation of 0.1 ft above the channel bottom. This applies only if the stream package determines that the stream is flowing. The package assumes there is some streambed material that differs from the modeled layer. In this study, both are alluvium and probably indistinguishable. Nonetheless, a K of 0.0015 ft/s (same as for the alluvium) and a thickness of 1 ft were prescribed for the model.

RESULTS

Criteria for accepting the model included

1. no dry cells,
2. convergence to within 0.001 ft of change between iterations and
3. low discrepancy between input and output.

For the run using the parameters described under "packages" above and as shown in Figure 9, there were no dry cells and the model converged. Results are shown schematically in Figure 10 and the volumetric water-budget calculation from MODFLOW is given in Appendix B. Input to the shallow aquifer included a constant head at the upper end of the model (0.0014514 cfs), areal recharge (0.25183 cfs) and leakage from the stream (0.0087891 cfs) for a total of 0.26207 cfs. Output from the system included ET (0.089282 cfs) and leakage to the stream (0.18480 cfs) for a total of 0.27409 cfs. Input - output = 0.012016 cfs or a -4.48% discrepancy (the minus sign indicates there was more output than input).

Although this discrepancy is large, it is the best obtained with the USGS computer. Other runs were made, specifying recharge on north slopes of the canyon as 0%, 12.5% and 25%. However, these gave larger discrepancies. A discrepancy of only -2.45% was obtained for a run with a constant head at the lower end of the model, but this is inconsistent with the assumption of no underflow and was rejected. It is interesting to note that for some reason, a water-budget discrepancy of only 0.23% is obtained when running

the model with the USGS's PC version of MODFLOW.

DISCUSSION

It is instructive to compare this project with previous modeling efforts. At first glance, the model reported on here might seem similar to the lumped-parameter model of Koenig and McLin (1992), differing only in that it had 30 cells instead of two. However, it actually differed in more significant ways. First, it dealt with pre-TA-50 conditions. Also, it attempted to allow for dimensional variability of the canyon where possible. Although it was a simple series of cells, they were scaled to reflect variation of input in the natural aquifer. Finally, unlike their model, it included recharge to the canyon floor from slope runoff.

This model also differed from that of Geddis (1992). The model described here looked solely at saturated conditions near the alluvium/tuff contact, whereas that of Geddis included unsaturated conditions and deeper movement of water in the tuff. Furthermore, this model treated a portion of the actual system along a longitudinal profile, whereas that of Geddis focused on a theoretical transverse section.

The simple model described herein is by no means the last word on Mortandad Canyon hydrogeology. It was intended to test the general conceptual hydrogeologic model, provide a feel for the water balance there, based on such a conceptualization, and evaluate the adequacy of the data set. In short, it was a pilot model, preliminary to more sophisticated efforts to follow.

Nonetheless, the preliminary model makes some contributions of its own. Since the stream flowed over the entire length of the model, and this seldom occurs, the water this represents must be dispersed in other ways. If the parameters used in the model are reasonable, and based on available data they seem to be, the water ascribed to streamflow by the model is actually that being lost through leakage and/or underflow. Since underflow has not been previously detected in the lower reaches of the study area (Stoker and others, 1991), the volume would seem to be wholly attributable to leakage.

However, the reader is reminded that ground-water models are inescapably nonunique. That is to say, various combinations of hydrologic parameters, model grid, boundary conditions and code may give the same results. Also, model results are approximations, applicable only to the assumptions made. Thus, while the model suggests that leakage of water from the shallow aquifer in Mortandad Canyon into the underlying Bandelier Tuff can occur, the

amount of water indicated is not absolute. It is subject to change as input parameters become better defined.

The preliminary MODFLOW simulation met with a few problems. Some may be overcome by expanding the model to a fully three-dimensional mode. The difficulty in balancing the water budget may be a result of the constraints placed on the model by scaling everything to a single column and layer. Other problems may have arisen because of the lack of some specific input data. For example, there were no data for either streamflow or slope runoff (additional recharge) and values for these parameters had to be assumed. A recently installed stream gage may provide the needed streamflow input data. However, studies to quantify slope runoff/interflow and underflow in the alluvium should be conducted. Detailed vegetation maps and site-specific ET observations for the major types would also be useful.

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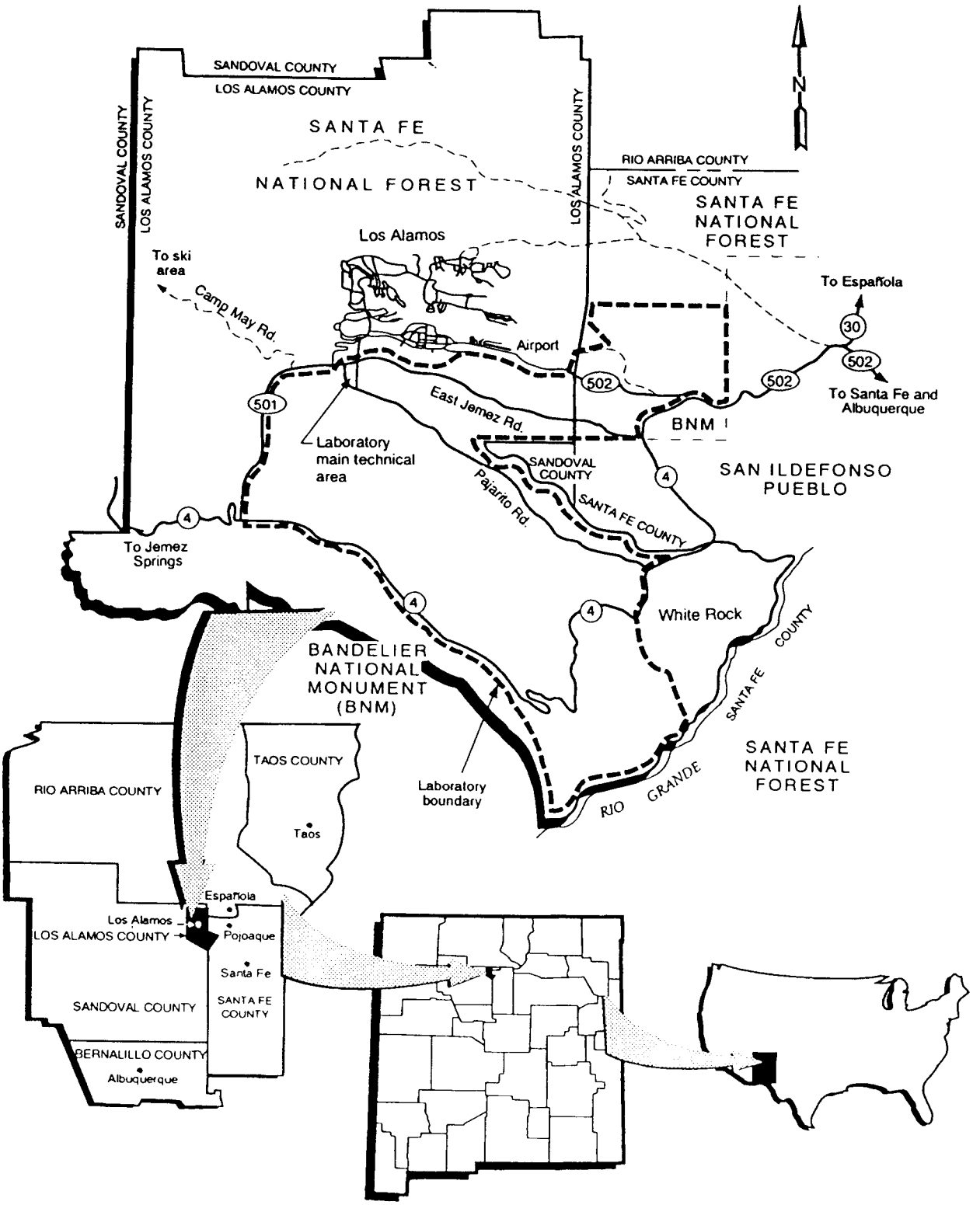


Figure 1. Location of Los Alamos National Laboratory (Dewart and Lyncoln-Kohen, 1991, Fig. II-2).

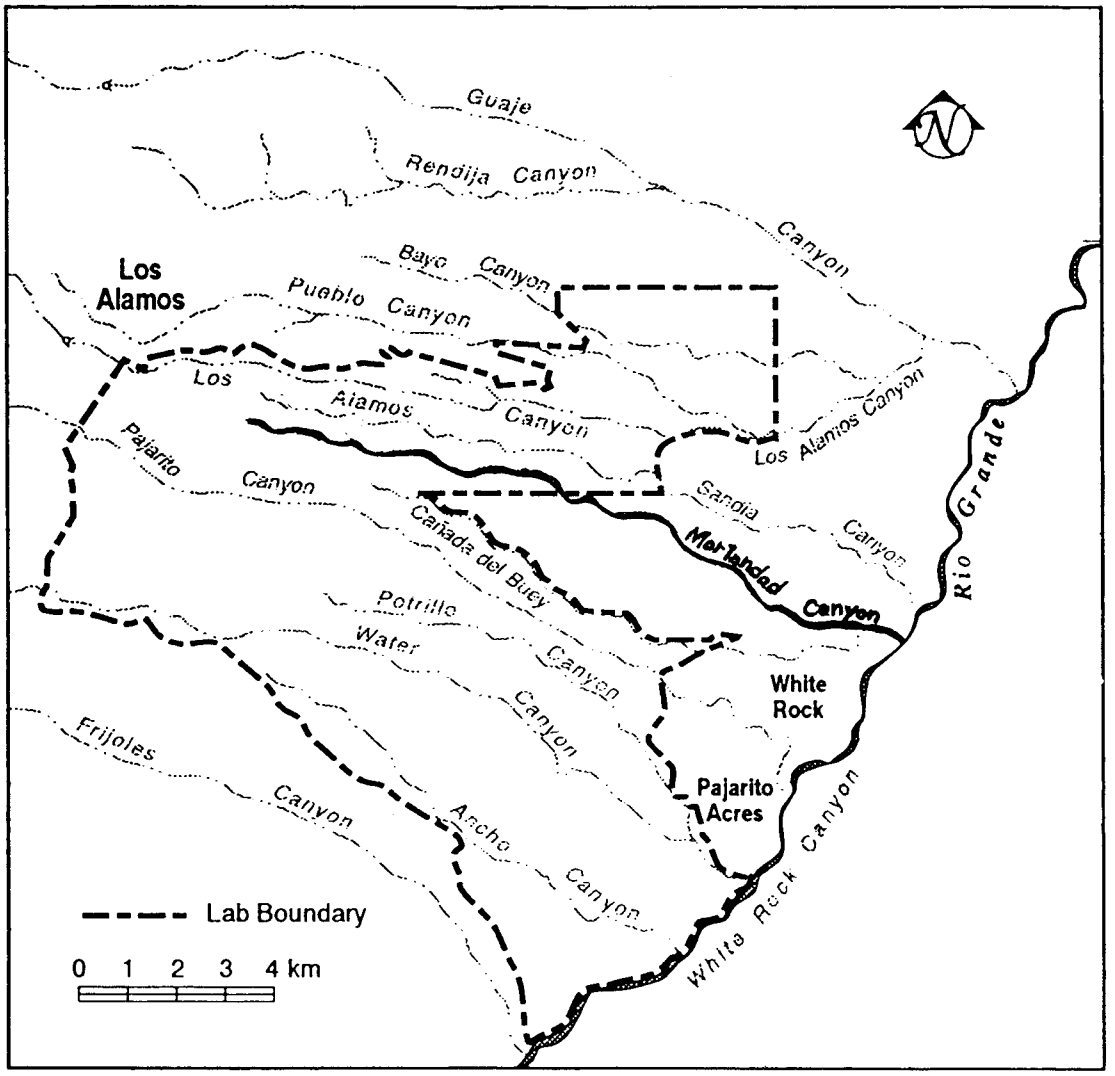


Figure 2. Location of Mortandad Canyon (modified from Dewart and Lyncoln-Kohen, 1991, Fig. IV-24).

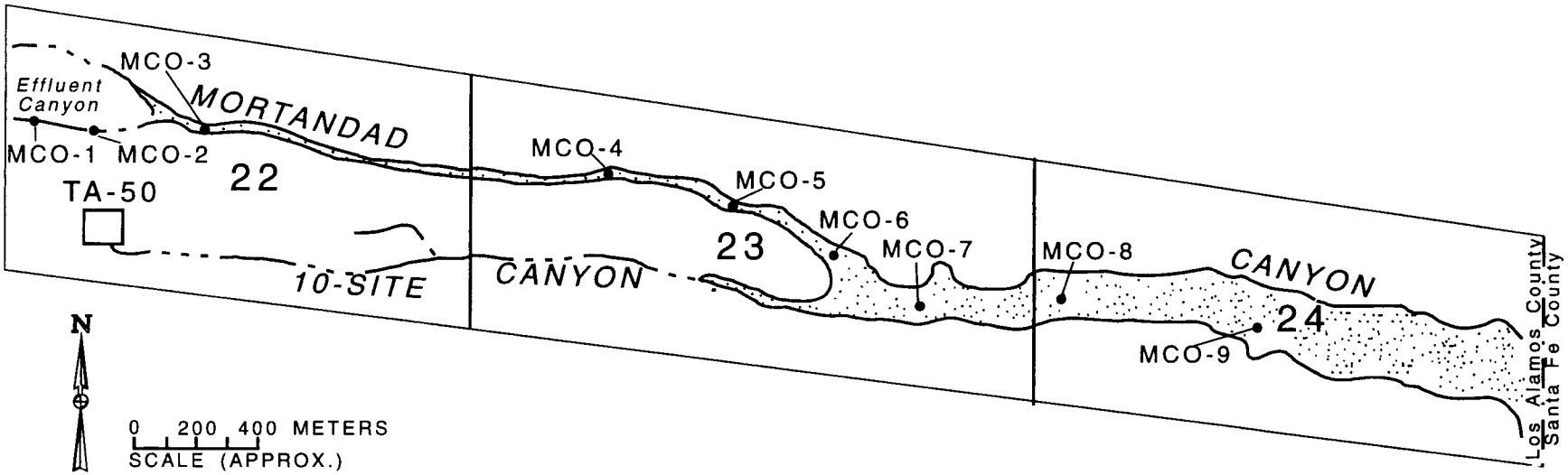


Figure 3. Location of Technical Area 50 (TA-50) and wells used in Mortandad Canyon modeling (modified from Stoker and others, 1991, Fig. 3-3).

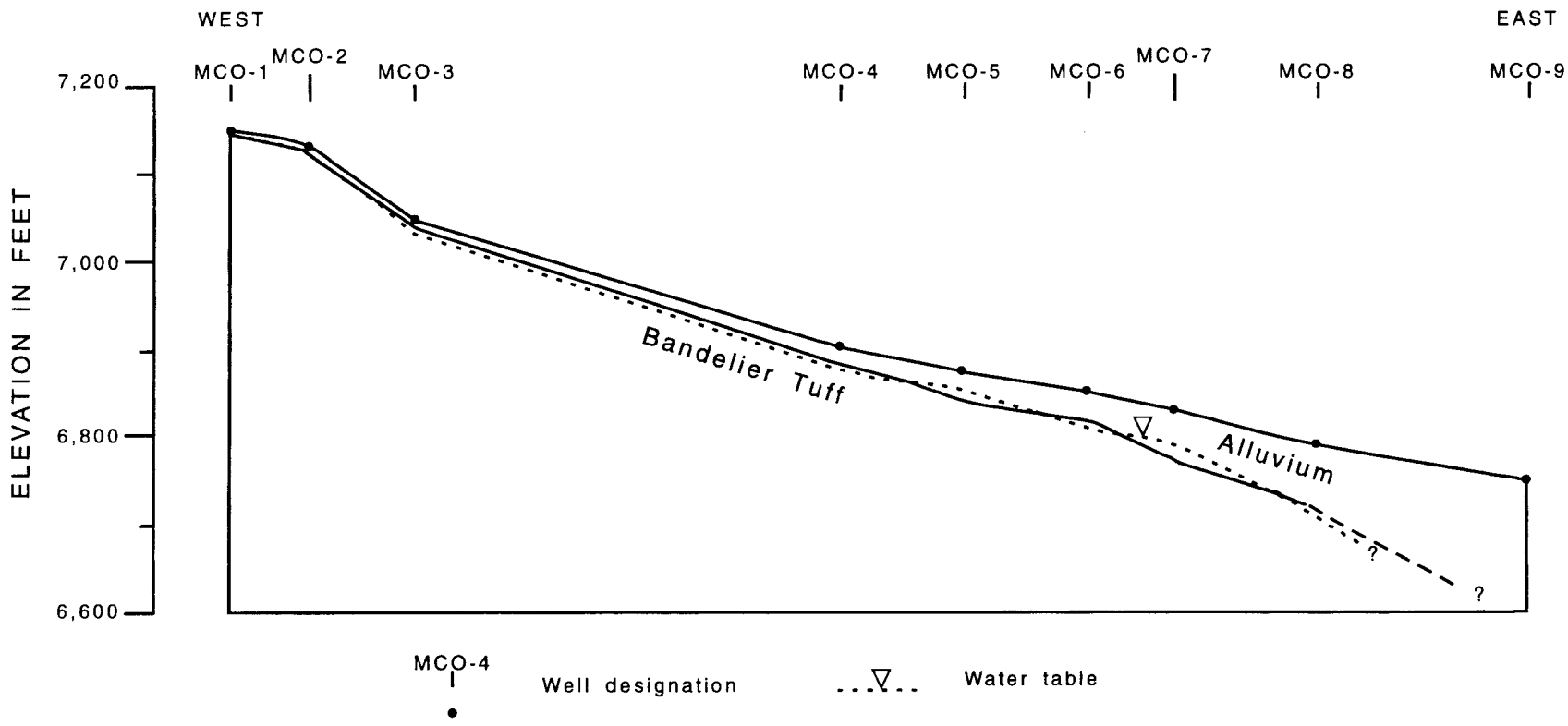


Figure 4. Hydrogeologic cross section of Mortandad Canyon, drawn from well to well (data from Baltz and others, 1963). For location of wells see Figure 3; for details of wells see FIgure 6.

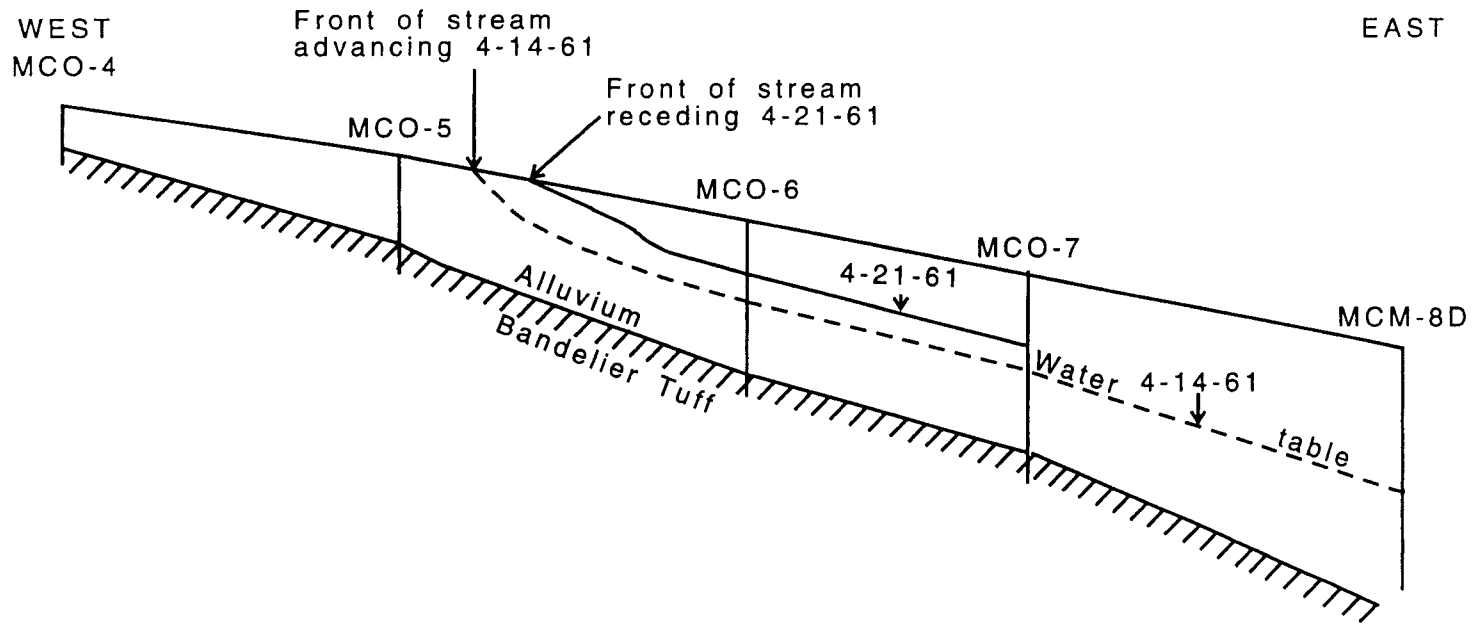


Figure 5. Extent of streamflow, Mortandad Canyon, 9161 (modified from Baltz and others, 1963).

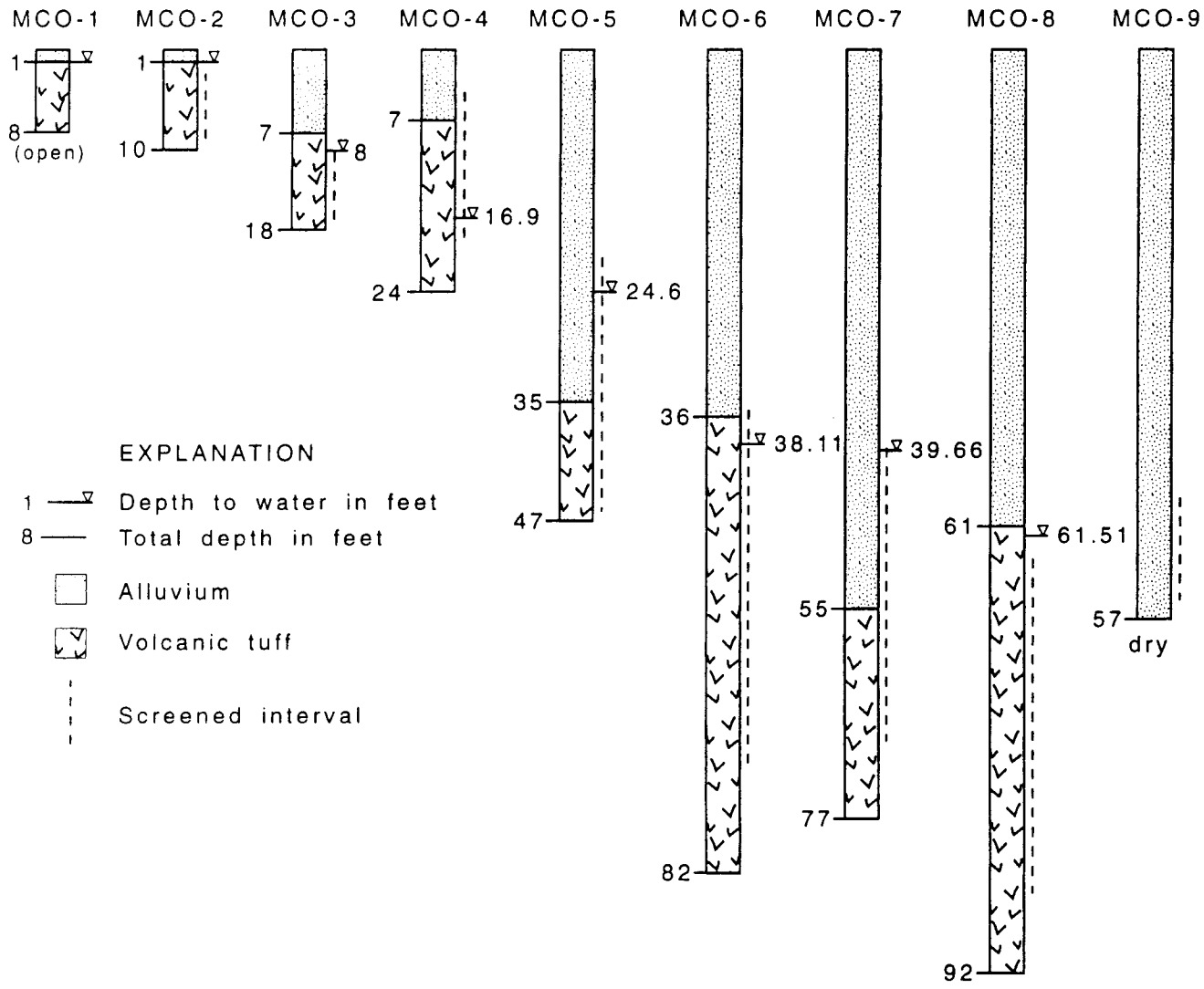


Figure 6. Logs of wells used in Mortandad Canyon modeling, 1961 (data from Baltz and others, 1963).

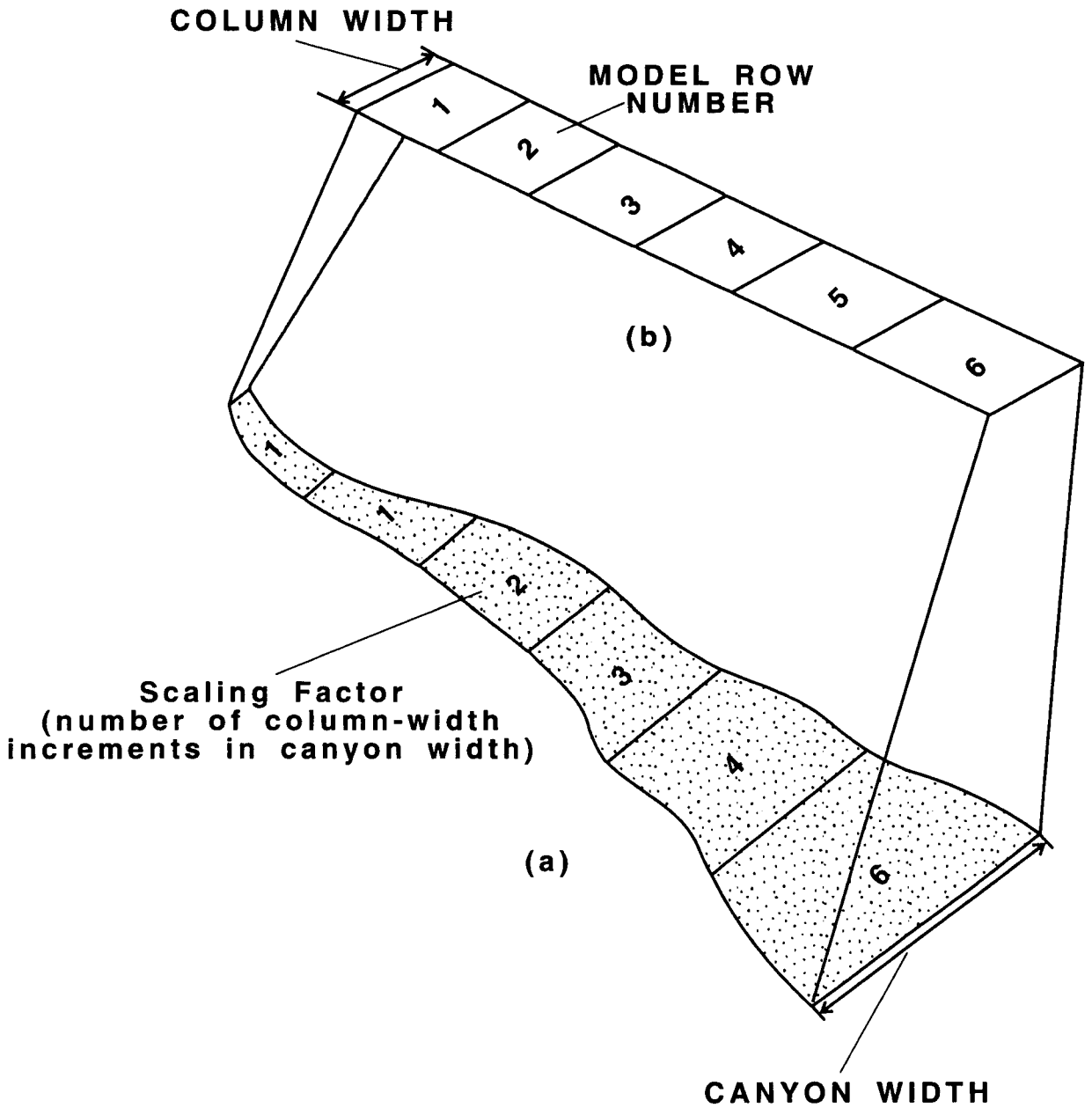


Figure 7. Approach to scaling precipitation and evapotranspiration in 1-column model; a) actual canyon floor, b) modeled canyon floor.

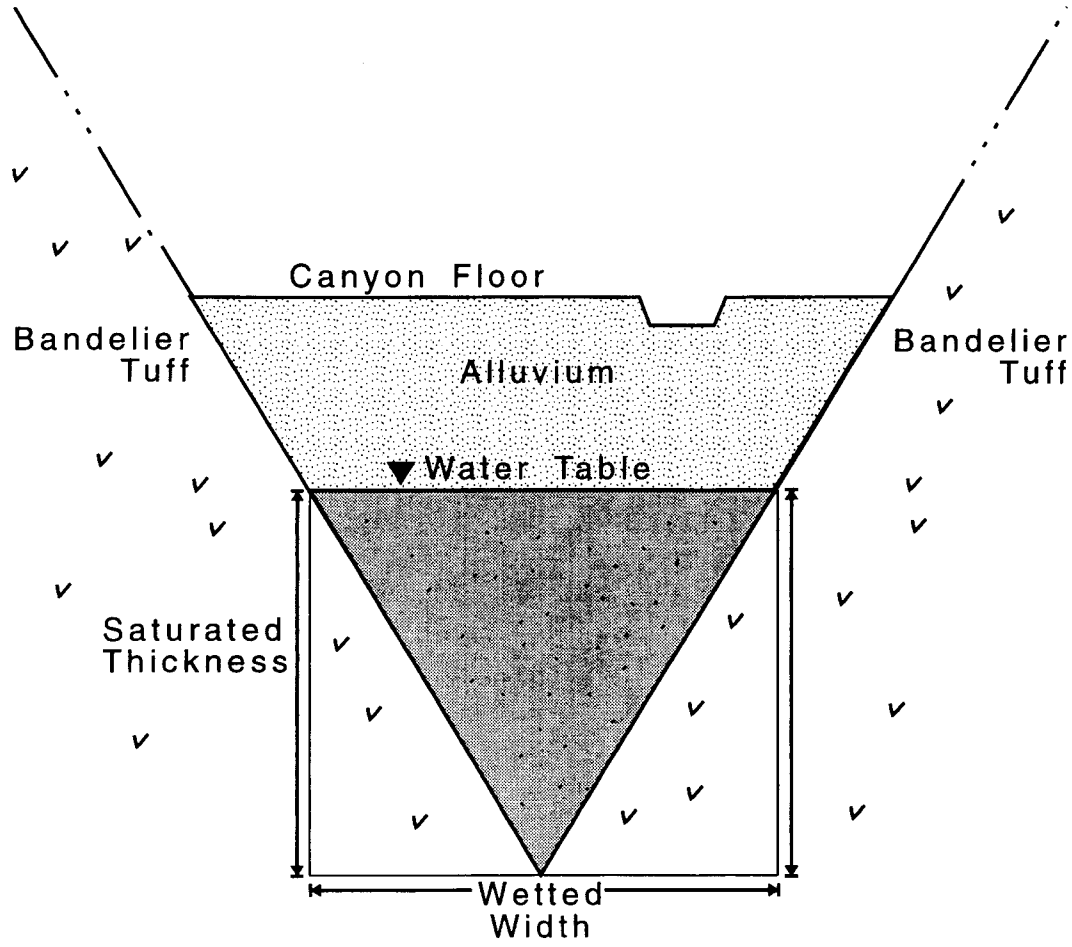


Figure 8. Approach to scaling hydraulic conductivity in 1-column model.

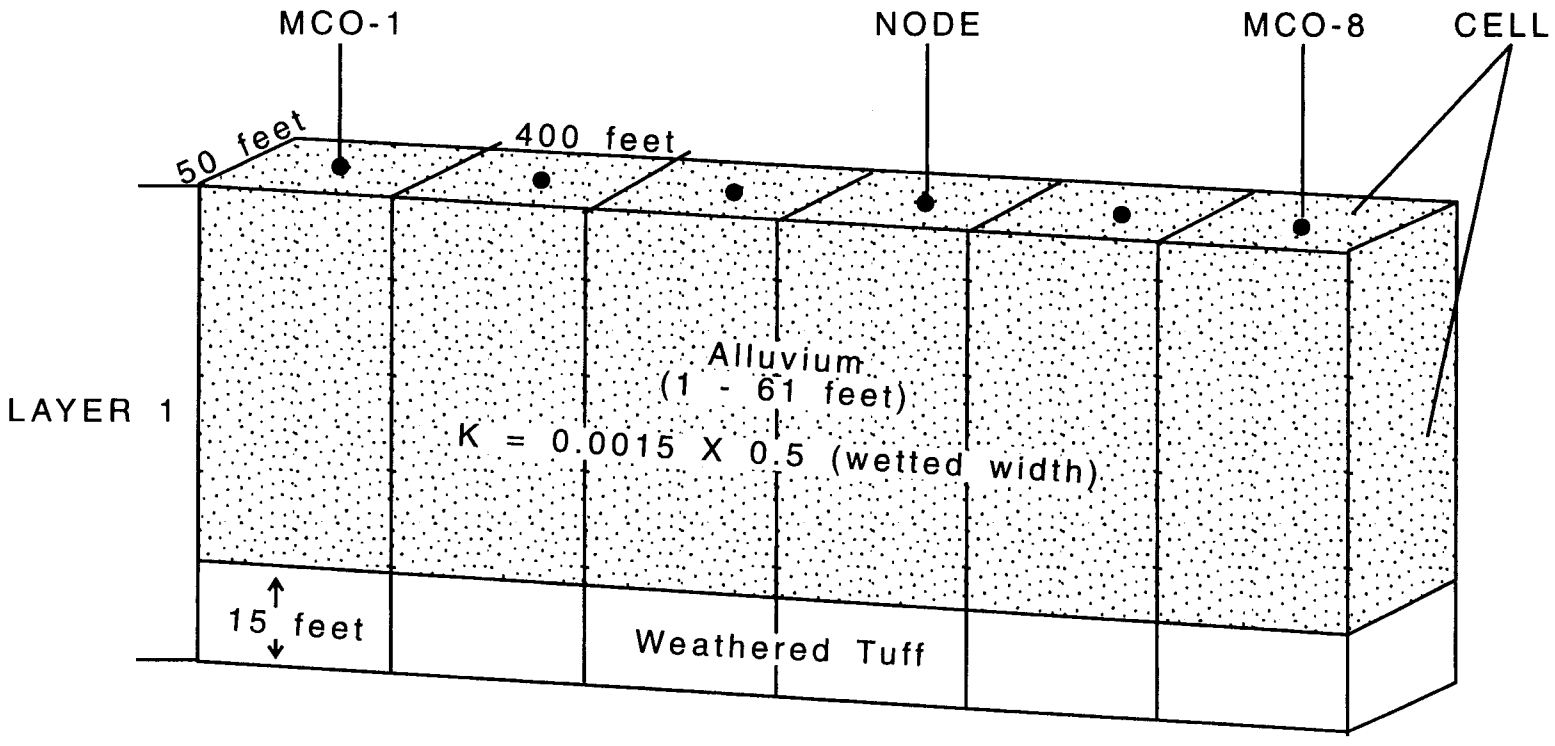
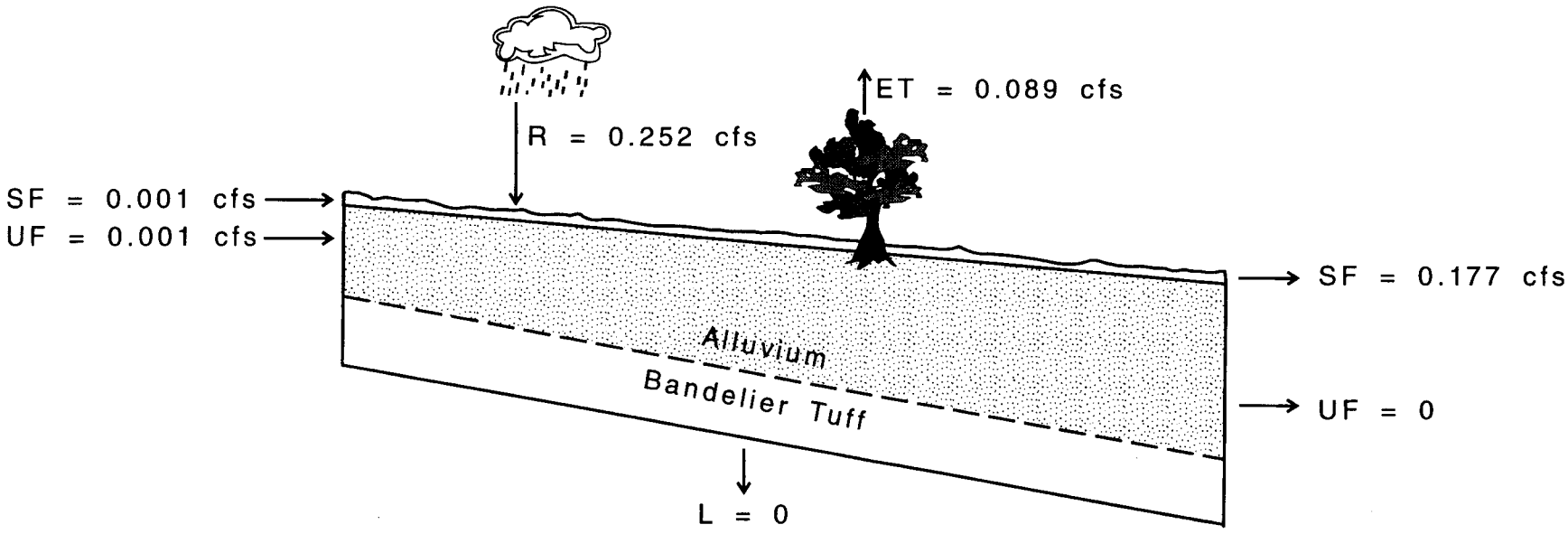


Figure 9. Schematic diagram of 1-column model (not to scale).



$$SF + UF + R = ET + L + SF + UF$$

$$0.262 \text{ cfs} \neq 0.274 \text{ cfs}$$

Figure 10. Model results (cfs); SF = streamflow, R = recharge, L = leakage, ET = evapotranspiration, UF = underflow. See Appendix B for detailed water budget.

Table 1. Records of wells used, Mortandad Canyon; WL = water level, Elev = elevation. Values are to nearest ft; depths are below ground surface.

Well	Depth Drilled	WL Depth	WL Elev	Depth to Tuff	Elevation, Top of Tuff
MCO-1	8	1	7152	1	7152
MCO-2	10	1	7132	1	7132
MCO-3	17	8	7038	7	7039
MCO-4	24	17	6883	7	6893
MCO-5	47	25	6852	35	6842
MCO-6	82	38	6811	36	6813
MCO-7	77	40	6788	55	6773
MCO-8	92	61	6736	61	6736
MCO-9	67	>67	<6683	>67	<6683

Table 2. Summary of assumptions made in the modeling.

Discretization
- 1 column (50 ft wide, scaled for actual valley dimensions)
- 1 layer (alluvium + 15 ft of weathered tuff)
- 30 rows (400 ft wide)
- 1 stress period
- time units = seconds

Miscellaneous
- initial heads from Baltz and others (1963)
- aquifer = silty sand
- aquifer volume from V-shaped valley (scaled as in text)
- K, aquifer = 0.0015 ft/s (Freeze and Cherry, 1979)
- stream bed = silty sand
- stream bed thickness = 1 ft
- K, streambed = 0.0015 ft/s (same as aquifer)
- simulation = steady-state

Input
- constant head at upper end of model
- variable head elsewhere
- P = 19 inches (scaled as in text)
  - 50% of P from north slopes
  - 0 from south slopes

Output
- ET = 17 inches
- ET surface set at initial heads
- extinction depth set at 10 ft
- leakage from bottom of model = 0
- underflow = 0

APPENDIX A

Spreadsheet With Input Data

EXPLANATION

The first two lines show whether the value was calculated or assigned. If calculated, there is a formula in which numbers are parameters and letters refer to other columns. If assigned, the specified value

K(Qal) = value for hydraulic conductivity of the alluvium (ft/s)

Precip = value input for precipitation (ft) assuming 100% of that falling on the canyon floor plus 0% of that falling on the south canyon wall and 50% of that falling on the north canyon wall

Precip2 NSlope*0 = like Precip, but no input from the north slope

Precip3 NSlop.25 = like Precip, but 0.25 % from north slope

Precip4 NSlop125 = like Precip, but 0.125 % from north slope

Layer 1 Bottom = elevation (ft) of the bottom of layer 1

Qal Bottom = elevation (ft) of the bottom of the alluvium

ET Surf = elevation (ft) of the evapotranspiration surface

ET = average annual evapotranspiration (ft) rate x scaling factor

Start Heads = initial heads or water-level elevations (ft)

Model ro = model row (1 - 30); corresponding wells shown at left

ET scale = scaling factor for evapotranspiration (number of 50-ft increments in canyon width)

Wet.widt = wetted width or width (ft) of canyon at water table

Wet.dept = wetted depth or saturated thickness of alluvium (ft)

NSlop.wd = width (ft) of north slope or canyon wall receiving precipitation (horizontal width as viewed from overhead)

Qal K = hydraulic conductivity of the alluvium (ft/s)

Tuff K = hydraulic conductivity of the tuff (ft/s)

ET ft.H2O = average annual ET rate (ft)

Precip ft.H2O = average annual precipitation (ft)

Valley Area = area of the canyon floor in each cell (ft2)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
0015*.5M	1.583(L+.5o	1.583L	1.583(L+0.25o)	1.583(L+0.125o)	G-15	Specified	Specified	1.46L	Specified	Specified	Specified	Specified	Specified	Blank		Specified	Specified	Specified	Specified	50*400*L
K(Gal)	Precip	Precip2	Precip3	Precip4	Layer 1	Gal	ET	ET	Start		Scaling factors for various model features assuming 50-ft wide model column					Values of simulated aquifer characteristics				
Input	Input	NSlope*0	NSlop.25	NSlop125	Bottom	Bottom	Surf	Input	Heads	Model ro	ET scale	Wet.widt	Wet.dept	NSlope.wd		Gal K	Tuff K	ET ft.H2O	Precip ft.H2O	Valley Area
0.00075	5.5405	1.583	3.56175	2.572375	7146	7161	7161	1.46	7161	1	1	1	1	5		0.0015	0.00006	1.46	1.583	20000
0.00075	6.332	1.583	3.9575	2.77025	7135	7150	7151	1.46	7151	Well.1 2	1	1	1	6						20000
0.00075	6.332	1.583	3.9575	2.77025	7124	7139	7140	1.46	7140	Well.2 3	1	1	1	6						20000
0.00075	6.332	1.583	3.9575	2.77025	7099	7114	7118	1.46	7118	4	1	1	1	6						20000
0.00075	22.162	1.583	11.8725	6.72775	7069	7084	7089	1.46	7089	5	1	1	1	26						20000
0.00075	11.081	1.583	6.332	3.9575	7037	7052	7060	1.46	7060	Well.3 6	1	1	1	12						20000
0.00075	10.68525	1.583	6.134125	3.858563	7016	7031	7040	1.46	7039	7	1	1	1	11.5						20000
0.00075	9.498	1.583	5.5405	3.56175	6999	7014	7026	1.46	7024	8	1	1	1	10						20000
0.00075	8.7065	1.583	5.14475	3.363875	6985	7000	7012	1.46	7008	9	1	1	1	9						20000
0.00075	8.7065	1.583	5.14475	3.363875	6969	6984	6997	1.46	6993	10	1	1	1	9						20000
0.00075	8.7065	1.583	5.14475	3.363875	6953	6968	6982	1.46	6978	11	1	1	1	9						20000
0.00075	7.915	1.583	4.749	3.166	6938	6953	6969	1.46	6963	12	1	1	1	8						20000
0.00075	7.915	1.583	4.749	3.166	6923	6938	6955	1.46	6948	13	1	1	1	8						20000
0.00075	7.51925	1.583	4.551125	3.067063	6908	6923	6940	1.46	6933	14	1	1	1	7.5						20000
0.00075	7.1235	1.583	4.35325	2.968125	6893	6908	6926	1.46	6918	15	1	1	1	7						20000
0.00075	7.1235	1.583	4.35325	2.968125	6877	6892	6912	1.46	6903	16	1	1	1	7						20000
0.00075	6.332	1.583	3.9575	2.77025	6863	6878	6899	1.46	6888	Well.417	1	1	10	6						20000
0.00075	7.1235	1.583	4.35325	2.968125	6850	6865	6892	1.46	6879	18	1	1	12	7						20000
0.001125	8.7065	2.3745	5.5405	3.9575	6838	6853	6885	2.19	6870	19	1.5	1.5	14	8						30000
0.001125	9.498	2.3745	5.93625	4.155375	6825	6840	6878	2.19	6862	Well.520	1.5	1.5	16	9						30000
0.0015	11.081	3.166	7.1235	5.14475	6808	6823	6870	2.92	6850	21	2	2	21	10						40000
0.0015	13.4555	3.9575	8.7065	6.332	6794	6809	6861	3.65	6835	22	2.5	2	26	12						50000
0.0015	15.0385	4.749	9.89375	7.321375	6777	6792	6852	4.38	6822	Well.623	3	2	32	13						60000
0.00525	30.077	20.579	25.328	22.9535	6763	6778	6844	18.98	6810	24	13	7	33	12						260000
0.003	28.494	14.247	21.3705	17.80875	6752	6767	6835	13.14	6799	25	9	4	34	18						180000
0.003	26.911	15.83	21.3705	18.60025	6741	6756	6827	14.6	6789	Well.726	10	4	35	14						200000
0.003	27.7025	15.83	21.76625	18.79813	6721	6736	6818	14.6	6771	27	10	4	37.5	15						200000
0.003	27.7025	12.664	20.18325	16.42363	6703	6718	6810	11.68	6757	28	8	4	40	19						160000
0.003	28.494	15.83	22.162	18.996	6683	6700	6800	14.6	6742	29	10	4	42.5	16						200000
0.003	20.579	14.247	17.413	15.83	6663	6680	6792	13.14	6726	Well.830	9	4	45	8						180000

APPENDIX B

Volumetric Water-Budget

(as generated by MODFLOW)

```
VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP  1 IN STRESS PERIOD  1
-------------------------------------------------------------------------------

                IN:
                ---
                  STORAGE =   0.00000E+00
            CONSTANT HEAD =   0.14514E-02
                 RECHARGE =   0.25183
                       ET =   0.00000E+00
           STREAM LEAKAGE =   0.87891E-02

                 TOTAL IN =   0.26207

               OUT:
               ----
                  STORAGE =   0.00000E+00
            CONSTANT HEAD =   0.00000E+00
                 RECHARGE =   0.00000E+00
                       ET =   0.89282E-01
           STREAM LEAKAGE =   0.18480

                TOTAL OUT =   0.27409

                 IN - OUT =  -0.12016E-01

      PERCENT DISCREPANCY =                -4.48
```