Calibration of a Flow Model and Optimal Pumping Strategies To Capture TCE Plume at Travis AFB, California

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Systems Simulation/Optimization Laboratory
Dept. of Biological and Irrigation Engineering
Utah State University
Logan, Utah

Consultant Operations Division
Environmental Restoration Directorate
Air Force Center for Environmental Excellence
Brooks AFB, Texas

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EXECUTIVE SUMMARY

The objective of this study was to develop a ground-water model that can be used in conjunction with an optimization model to optimize the containment and remediation of ground water contaminated with organic compounds at Travis AFB, California (TAFB). Based on studies by WESTON (Roy F. Weston, Inc.), RADIAN (Radian Corporation), and others, the major ground-water quality problem is a plume of TCE that originates at the Oil Spill Area (OSA) and has migrated to the south and east under the runway. The immediate remediation objective is to stop the movement of the plume.

To simulate the movement of ground water carrying the TCE, a computer model has been constructed for a large portion of TAFB. The model addresses the area of the plume and extends in all directions well beyond the plume. The flow model subsequently is used with a computer optimization model (REMAX) to select the best arrangement of pumping wells to stop the movement of a TCE plume that has formed downgradient of the OSA.

Shallow ground water beneath TAFB occurs in the Overburden and Bedrock Aquifers. The Overburden Aquifer is thin, ranging from zero to about 50 feet in thickness. Alluvial materials range from clays to sands and some gravel. Clays and silts predominate, making Overburden Aquifer hydraulic conductivity typically low. Sands and gravels tend to occur as ancient stream-bed deposits that trend from northwest to southeast, creating preferred ground-water flow paths in this direction. The Bedrock Aquifer consists of folded and weathered sandstone and shale. Typically, the sandstones form predominant bedrock ridges, and the shales underlie the alluvium-filled valleys. The Bedrock Aquifer characteristically is significantly less permeable than the Overburden Aquifer.

A three-dimensional finite-difference flow model, MODFLOW, was used for the simulation. MODFLOW is a widely used computer model developed by the US Geological Survey to simulate ground-water flow. For the TAFB study, the model comprises a rectangular array of cells that cover an area 13,600 feet (north-south) by 12,600 feet (east-west). It was discretized into 5040 cells per layer, with horizontal cell dimensions ranging from 100x100 feet at the center of the area to 300x300 feet at the boundaries of the area. The Overburden and shallow Bedrock Aquifers were modeled using a total of four discrete 15-foot-thick layers to represent three-dimensional ground-water flow underlying TAFB.

The model was calibrated by adjusting hydrologic parameters and boundary conditions in a physically realistic way to reproduce observed ground-water elevations measured in approximately 130 monitoring wells.

Optimal pumping strategies are developed to capture the TCE plume. One of the developed strategies prevent the plume from further spreading for a range of hydraulic conductivity values.

INTRODUCTION

Travis Air Force Base (TAFB) occupies approximately 5,000 acres in Solano County, California, and is located approximately three miles east of the City of Fairfield. TAFB lies midway between San Francisco and Sacramento in an area dominated by agricultural and livestock activities with minor amounts of light industry (Fig. 1).

TAFB was founded in May 1943 and became the West Coast's largest aerial port by 1945. Military Air Transport Services (MATS) assumed jurisdiction of TAFB in 1948, and control of TAFB was transferred soon thereafter to the Strategic Air Command (SAC). TAFB was home for SAC bombers until 1958, when MATS resumed control. In 1962, C-135 and KC-135 Stratotankers arrived. In the early 196Os, MATS was renamed the Military Airlift Command (MAC). Currently, TAFB is the largest and busiest Air Materiel Command (AMC) base, operating one-half of AMC's C-5 Galaxy force and one-sixth of the C-141 force.

Generation of hazardous wastes at TAFB has been associated with industrial operations, fuels management, fire protection training, pesticide/herbicide use, etc. (ESI, 1983). Prior to 1960, waste materials, such as used oils, contaminated fuels, used hydraulic fluid, spent solvents, and spent paint thinners, were landfilled, burned in a fire training area, or discharged either to the sewage treatment plant or to the surface drainage system.

Of particular interest is a TCE plume that originates at an area designated the Oil Spill Area (OSA). The plume has spread and migrated to the south and east and is now moving beneath the runway (Fig. 2). It appears to be the single largest area of contaminated ground water on TAFB.

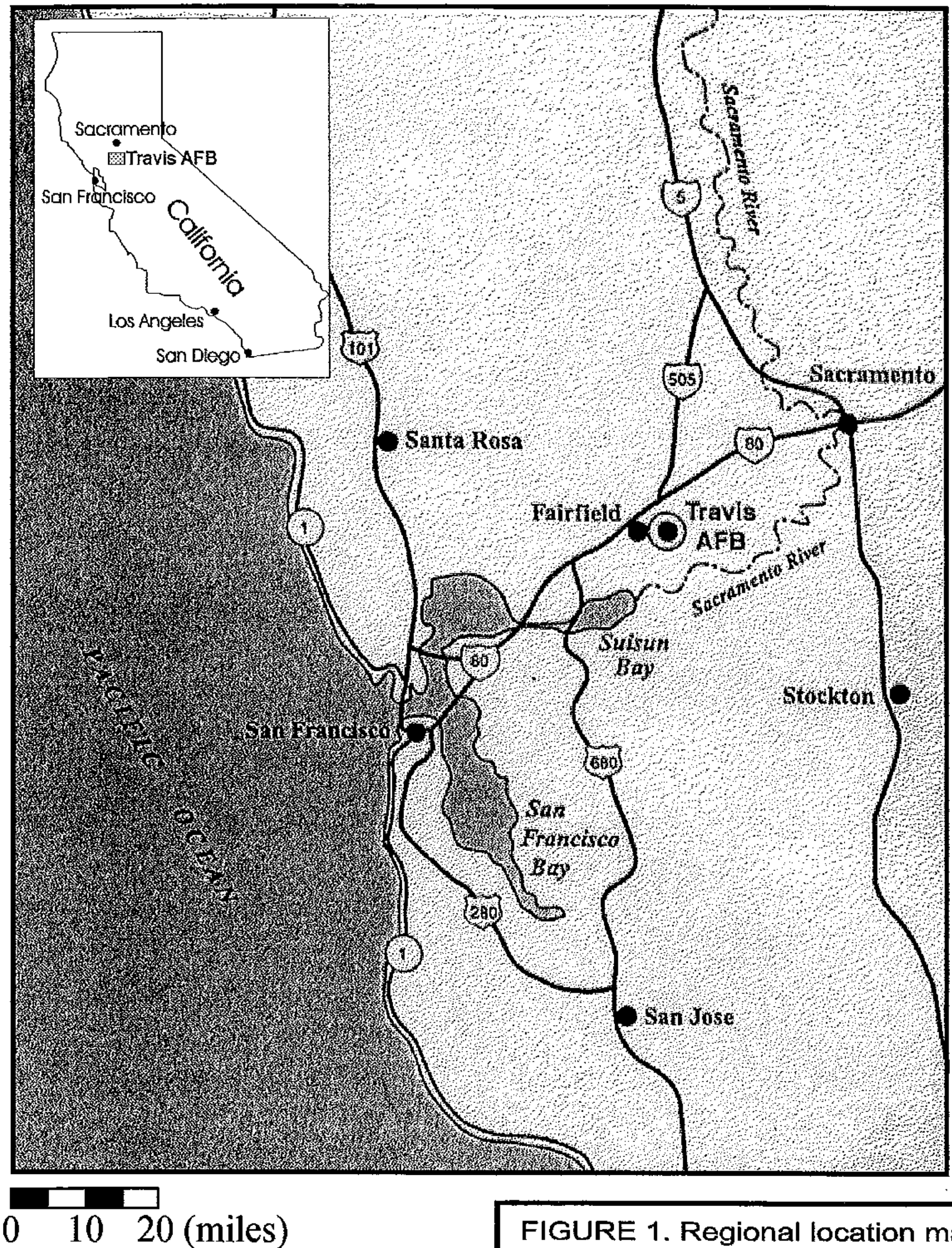

FIGURE 1. Regional location map Travis AFB.

Travis AFB, CA

Modified from RADIAN (1995).

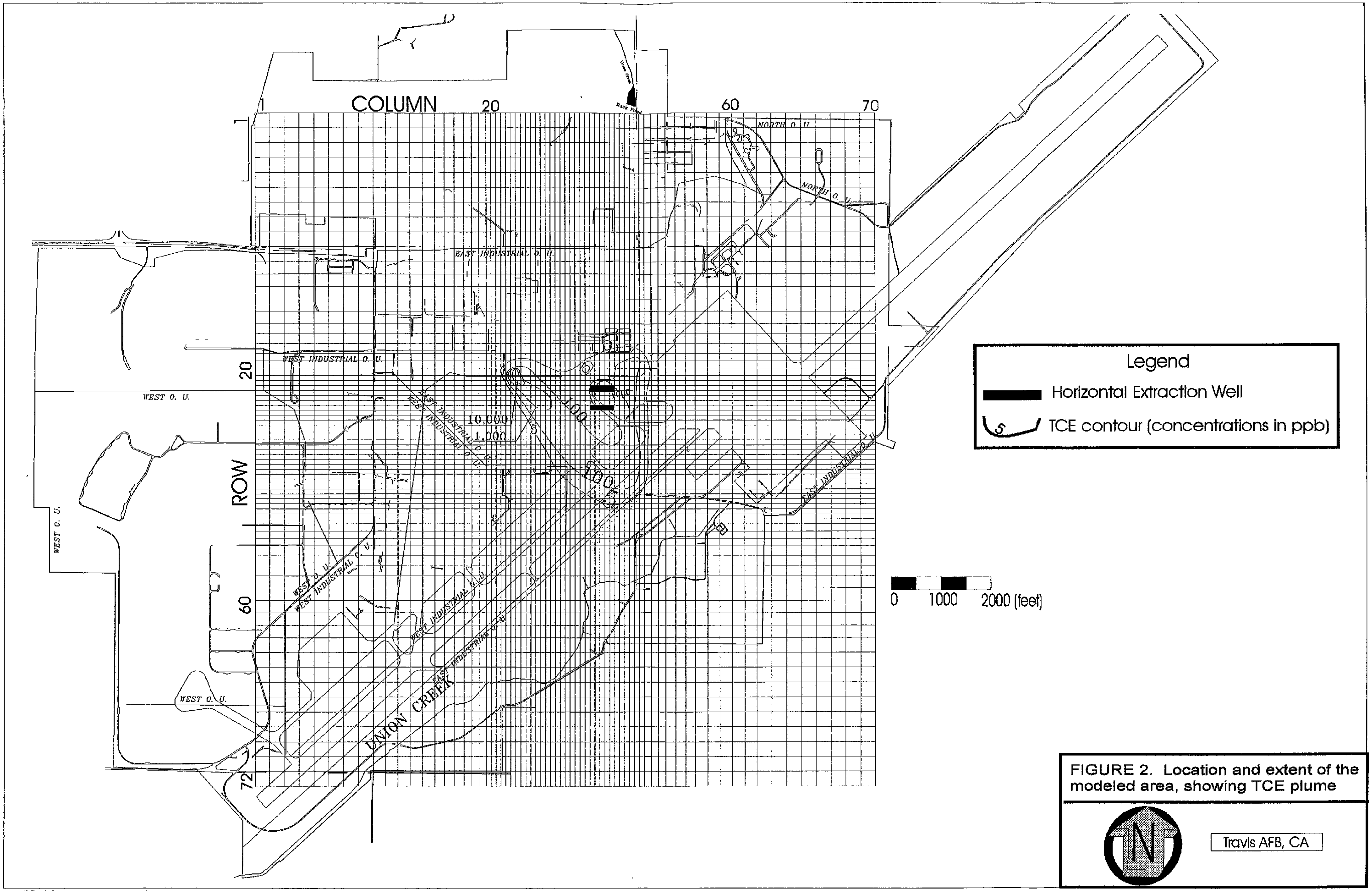

FIGURE 2. Location and extent of the modeled area, showing TCE plume

Modified from RADIAN (1995).

STUDY OBJECTIVES

The objective of this study was to develop a ground-water model that can be used in conjunction with an optimization model (REMAX) to optimize the containment and cleanup of TCE-contaminated ground water at the OSA. Based on studies by WESTON, RADIAN, and others, the major area of ground-water contamination is a plume of TCE that originates at the Solvent Spill Area and has migrated to the south and east under the runway.

The ground-water model provides a tool to evaluate the effectiveness of different control and cleanup options for the TCE plume. One immediate remedial action might be to install a well or wells to stop the migration of the plume and ensure that it does not move beyond TAFB boundaries. A longer term action might be to clean up the plume by pumping from wells, treating the contaminated water above ground, and reinjecting the treated water at the plume fringes.

ENVIRONMENTAL SETTING

The environmental setting of TAFB is described in the following sections. These sections provide the information needed to build a computer representation of the physical system that accurately reflects (models) the real world.

TOPOGRAPHY

Topography in the vicinity of TAFB ranges in elevation from approximately 20 feet above mean sea level (MSL) on TAFB to over 170 feet MSL in the hills located immediately north, and reaches sea level in the marshlands to the south. TAFB lies on an alluvial surface with some bedrock outcrops. Base topography is gently sloping to nearly flat, with elevation variations of up to 50 feet.

CLIMATE/METEOROLOGY

The mean annual temperature for the period of record is 60° F. Monthly mean temperatures have ranged from 46° F during December and January to 72° F during July, August, and September. Mean annual precipitation for the period of record is 17.5 inches. Approximately 85% of the precipitation occurs between November and March. Potential evaporation averages 47 inches per year, giving an annual net precipitation deficit of 29.5 inches per year. The average wind direction is variable throughout the year; the most common wind direction is from the southwest to the northeast. Mean annual wind speed for the period of record is eight knots. Monthly relative humidity for the period of record has ranged from a low of 50% during June to a high of 77% during January.

WETLANDS

An 85,000-acre tidal marsh is located southwest of TAFB. It is the largest contiguous estuarine marsh in the continental United States and is the largest wetlands area in the western United States. Union Creek, which discharges to the marsh, has headwaters north of TAFB, transects TAFB, and flows into the marsh beyond the southwestern TAFB boundary. Most of TAFB drains to Union Creek.

GEOLOGY

The sedimentary units found in the TAFB area represent a near-shore to deeper marine depositional cycle. The oldest formation exposed on the Base is the Eocene (Tertiary)-age Domengine Sandstone, which is conformably overlain by the Nortonville Shale and the Markley Sandstone. The fine-grained, consolidated Tertiary marine strata have low permeabilities and are generally not considered useful for ground-water supply (WESTON, 1992).

The Tehama Formation was deposited in the Pliocene and Pleistocene. The Tehama Formation is composed of terrestrial alluvial fan and floodplain deposits originating from the Coast Ranges (WESTON, 1992).

A geologic map of TAFB and vicinity is presented on Figure 3 (RADIAN, 1994), and a representative cross section. of the geology underlying TAFB is illustrated on Figure 4.

The Domengine Sandstone is a light-brownish-gray to yellowish-brown, coarse-grained sandstone with interbedded siltstones and shales. The Nortonville Shale conformably overlies the Domengine Sandstone. The Nortonville Shale underlies the majority of TAFB but is poorly exposed because it is less resistant to erosion than the other bedrock formations. In general, the Nortonville is a dark-gray to chocolate-brown mudstone, shale, and siltstone, interbedded with lesser amounts of light-gray to buff-tan sandstone. The Tehama Formation unconformably overlies the older Tertiary rocks and consists of poorly stratified, unconsolidated to moderately cemented deposits of silt, clay, sand, and gravel, often of volcanic origin. Quaternary alluvium covers most of the Base, except for a few isolated resistant sandstone outcrops, to depths of 5 to 50 feet below ground surface. Although bay mud is not exposed on the surface at TAFB, it was identified in some borings.

The Domengine Sandstone crops out along the fold axis, forming the core of an anticline. The Markley Sandstone crops out on the east side of the Base and along the outer limbs of the anticline. The Nortonville Shale underlies the intervening basins where Quaternary alluvium has been deposited to observed thicknesses of 50 feet and less.

On the west side of TAFB the Tehama Formation crops out at the surface or is covered by a thin veneer of Quaternary alluvium. In the central part of TAFB thicker sequences of Quaternary alluvium are underlain by Nortonville Shale.

A significant geologic feature on TAFB is the Vaca Fault, which roughly coincides with the crest of the plunging anticline in the center of TAFB. An exposure of the fault plane in a cut along the Southern Pacific Railroad north of TAFB and along a cut south of Facility 363 indicate an orientation subparallel to bedding with a northwest strike and northeast dip (WESTON, 1992). The Domengine Sandstone is present on both sides of the fault in these two locations.

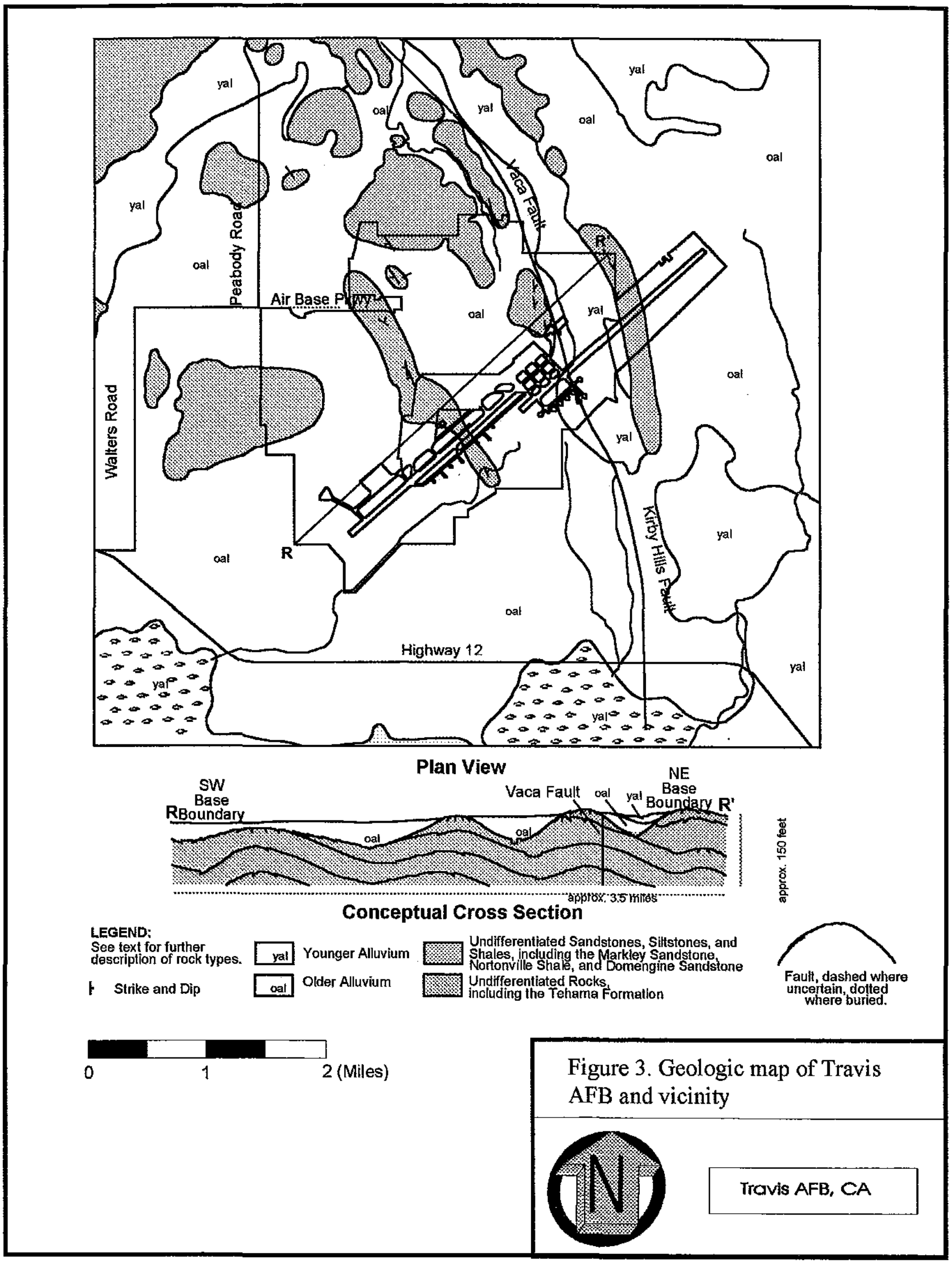

Figure 3. Geologic map of Travis AFB and vicinity

Modified from USGS map by Olmsted, et al. (1950, 1951). Strike and dip information from Radian field data.

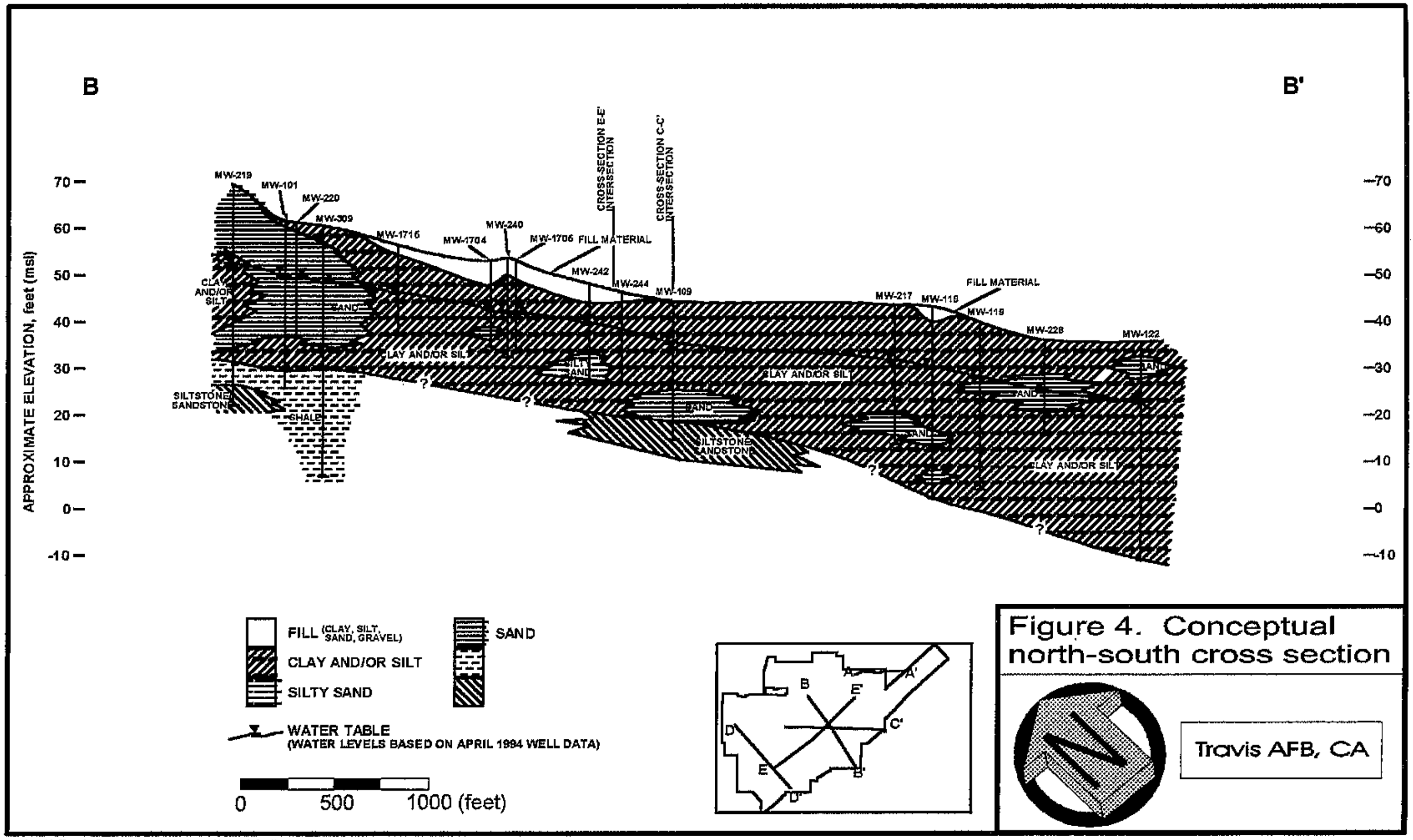

Figure 4. Conceptual north-south cross section

Modified from RADIAN (1995).

HYDROGEOLOGY

The depositional history in the TAFB area makes delineation of discrete hydrogeologic units difficult. Unconsolidated Quaternary alluvial deposits and colluvium overlie Tertiary bedrock units over most of TAFB. The alluvium consists of clays, silts, and sands of low permeability. Coarser sands and occasional gravels occur as relatively thin discontinuous lenses within the clays and silts. These coarser units are channel deposits, which are generally more permeable than the surrounding finer grained material. The sediments exhibit a high degree of lateral and vertical variability typical of alluvial environments. The hydraulic conductivity of these sediments is low, limiting their potential for ground-water production. The underlying bedrock is relatively impermeable except where it is fractured or weathered.

Of primary hydrogeologic interest at the Base are the water-saturated Quaternary alluvial sediments and colluvium overlying the Tertiary section. In a report by WESTON (1995) and in this report, these saturated unconsolidated deposits collectively are referred to as the Overburden Aquifer. Thickness of the Overburden Aquifer ranges from zero feet in most of the northern portion of the Base to more than 40 feet in the extreme southcentral portion in a buried bedrock valley (Fig. 5).

For the purposes of this report and the associated ground-water flow modeling, the uppermost portion of the bedrock section, ranging from zero to 60 feet thick and consisting typically of weathered and fractured sandstone or shale, comprises the Bedrock Aquifer. From the perspective of a conceptual hydrogeologic model, the Overburden Aquifer and the upper, fractured and weathered Bedrock Aquifer generally act as one unconfined ground-water flow system (WESTON, 1995).

Configuration of the water table in June 1996 is shown on Figure 6. This configuration mirrors the ground-surface topography. Ground water flows to the south and southeast beneath TAFB, with localized easterly and westerly flow components. The flow direction is essentially the same during all seasons of the year. The ground-water flow direction in the deep portions of the Overburden and Bedrock Aquifers is generally the same as the upper portions of these aquifers -- flowing to the south with localized easterly and westerly flow components.

Depth to ground water across TAFB varies spatially and seasonally. Throughout much of TAFB, ground water is present at depths ranging from eight to 12 feet (WESTON, 1995). Water levels decline during the dry summer season and rise in response to recharge by rainfall during the rainy winter season. In addition, ground-water levels in most wells have declined in recent years due to a prolonged drought.

Based on six rounds of water-level measurement and the resulting water-level contour maps for the period March 1985 through August 1994, generalized horizontal gradients were calculated for the eastern and western portions of TAFB. Gradients range from 0.0035 to 0.0042 in the eastern half of TAFB, and from 0.0032 to 0.0048 in the western half (RADIAN, 1994). Hydraulic gradients are influenced by bedrock topography and the storm-sewer system (WESTON, 1995). Many greater horizontal gradients are associated with bedrock highs and the lower permeability of the bedrock in these areas (e.g., the ground-water high in the extreme northeastern corner of TAFB).

Vertical hydraulic gradients have been calculated for at least 20 well pairs (shallow and deep wells located side by side) across TAFB (RADIAN, 1994; WESTON, 1995). These vertical gradient calculations reveal a spatially variable combination of downward and upward flow potentials. WESTON (1995) reports that four well pairs exhibited a seasonally fluctuating gradient. Available vertical gradient data document a complex pattern of vertical flow between the Overburden and Bedrock Aquifers as well as intra-aquifer flow. Most likely, the absence of any thick or areally extensive confining units within the vertical interval penetrated by TAFB monitoring wells accounts for the relatively small vertical gradients and the observed complex vertical flow pattern.

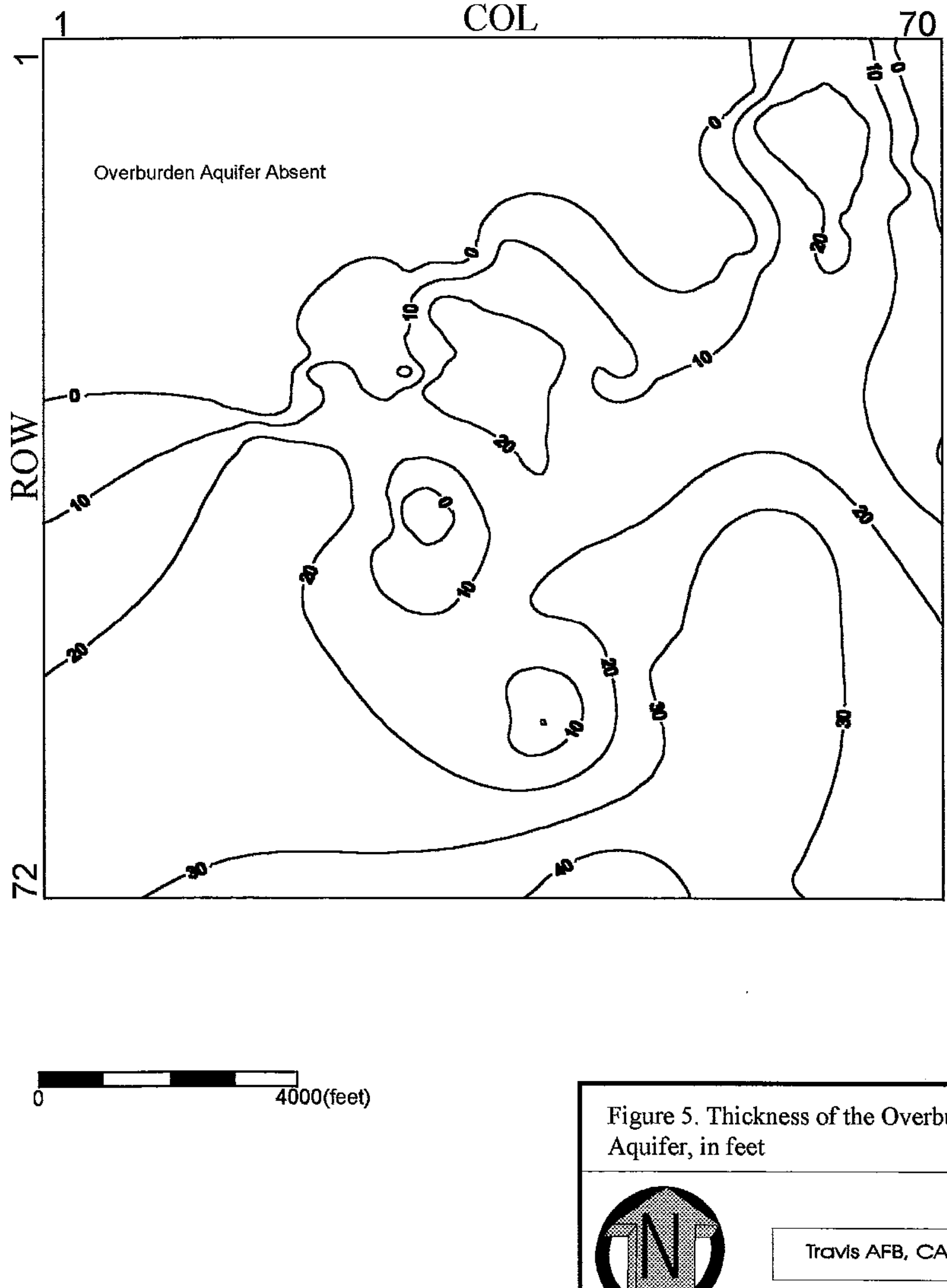

Figure 5. Thickness of the Overburden Aquifer, in feet

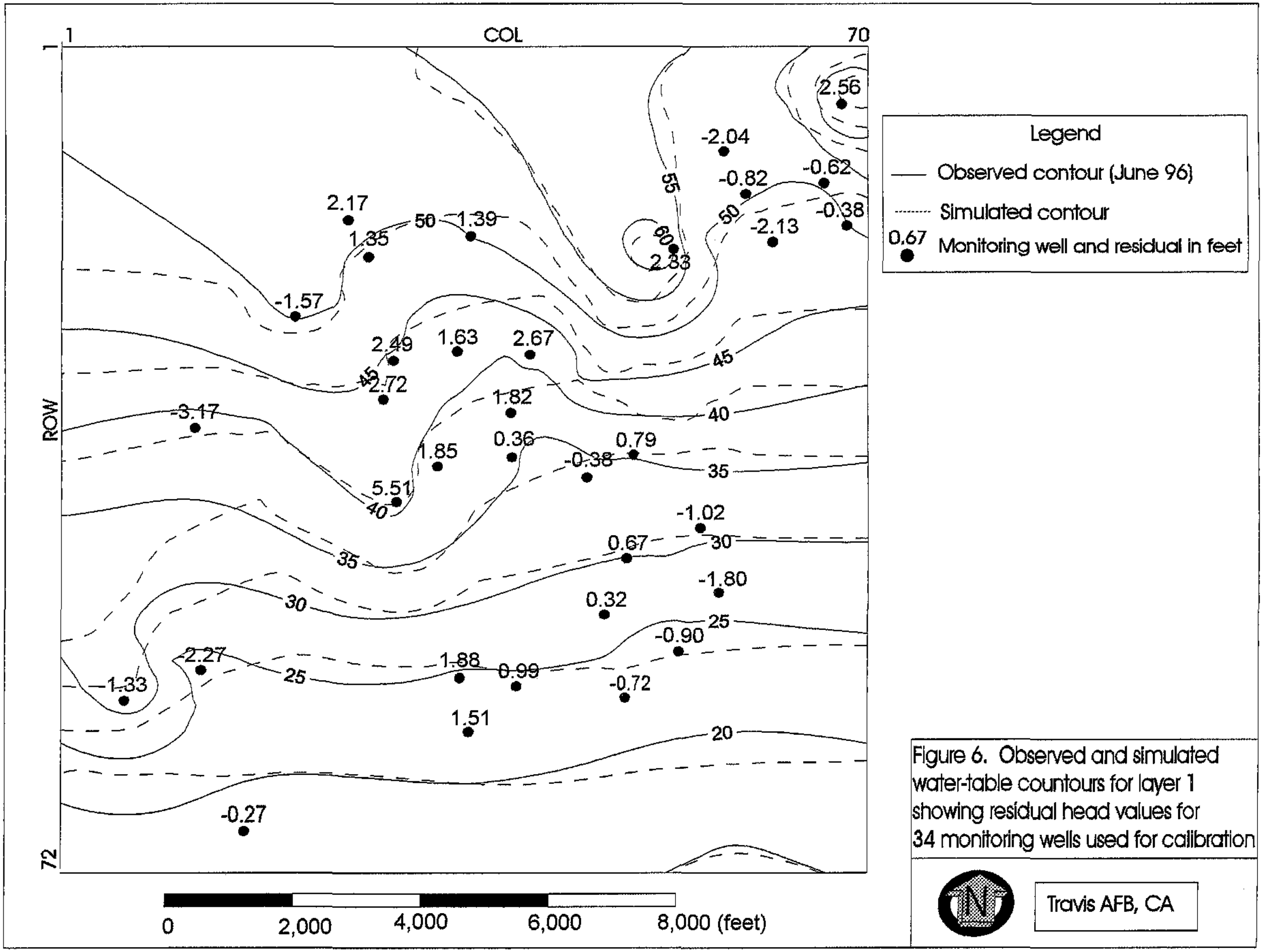

Figure 6. Observed and simulated water-table countours for layer 1 showing residual head values for 34 monitoring wells used for calibration

AQUIFER TESTING

In 1991, 27 slug tests and three long-term (greater than 24 hours) constant-rate pumping tests were performed. In 1988, seven single-well recovery tests and 11 gravity injection well tests were performed. Based on these tests, horizontal hydraulic conductivity was calculated to range from 0.0001 to 0.06 ft per minute (0.14-86 ft/d). Transmissivity was calculated to range from 3.83 to 883 ft^2/day (WESTON, 1992).

Slug tests on 26 newly installed wells and one previously installed well were performed in the fall of 1991. Hydraulic conductivity ranged from 0.002 to 0.097 ft/min (2.9-140 ft/d) (WESTON, 1992).

Long-term pumping tests were performed at the OSA and several nearby Installation Restoration Program (IRP) sites during 1991. Transmissivity values ranged from 0.008 to 0.731 ft^2/min (11.5-1050 ft^2/d). Storage coefficient values ranged from 0.054 to 0.336. Horizontal hydraulic conductivity values ranged from 0.003 to 0.071 ft/min (4.3-102 ft/d), while vertical hydraulic conductivity values ranged from 0.000121 to 0.00229 ft/min (0.17-3.3 ft/d) (WESTON, 1992a).

A twenty-four hours pumping test was conducted at monitor well 269 near the South Base Boundary in 1993. The horizontal hydraulic conductivities at and near this well (observation wells P-13 through P-16) ranged from 4.3 to 24 ft/d. Vertical hydraulic conductivities ranged from 0.17 ft/d to 1.02 ft/d. In September 1994, Engineering Science, Inc. (ESI) conducted two short-term (less than 24 hrs) pumping tests at two monitoring wells in the northcentral part of TAFB. The horizontal hydraulic conductivities for monitoring wells 202 and 208 were 9.8 and 2.0 ft/d, respectively (WESTON, 1995).

The range of ground-water flow velocities was estimated by WESTON (1995) for the Overburden Aquifer based on the average hydraulic gradient values during 1993 and 1994 (0.0022-0.0045), the range of hydraulic conductivity values (0.4-114 ft/d), and the range of effective porosity based on storage coefficient values (0.05-0.34). The resulting minimum, average, and maximum Overburden Aquifer ground-water flow velocities were estimated at 0.003, 0.3, and 10 ft/d, respectively.

GROUND-WATER USE

Given that productivity of the aquifers in the vicinity of TAFB is typically low, ground-water use in this area is restricted almost entirely to domestic, livestock watering, and small-scale (e.g., garden) irrigation uses. The Fairfield public water-supply well field is located more than three miles west of TAFB, where the Overburden Aquifer is thicker and more permeable. This is the only public water-supply well field in the TAFB area (WESTON, 1995).

No on-base wells are used for potable water production. Several wells located four miles north of TAFB at the golf course annex produce 400-500 million gallons of water per year. Their well water is mixed with surface water purchased from the City of Vallejo to supply potable water to TAFB (RADIAN, 1995).

SURFACE-WATER HYDROLOGY

Natural surface-water drainage patterns in the TAFB area are generally southward toward marshes and sloughs. Local drainage patterns have been substantially altered at TAFB by the rerouting of Union Creek; aircraft runway and apron construction; installation of storm sewers and ditches; and general development including industrial shops, maintenance yards, roads, and housing. The surface-water collection system has divided TAFB into eight independent drainage systems. These systems discharge to Union Creek.

Union Creek splits into two branches north of TAFB. The main branch enters TAFB from the north and is impounded to form Duck Pond. The creek is then routed through TAFB in a storm sewer. It again forms an open creek along the southeastern installation boundary. The western branch enters TAFB on its northwestern boundary. An open ditch along the western boundary routes flow through the housing area and on through TAFB. Flow proceeds under the runway through a storm sewer and reenters the main channel of Union Creek.

Because ground water occurs at shallow depth, the location and elevations of the ditches and storm-sewer drains affect ground-water movement on TAFB. To the extent possible, these effects have been simulated in the ground-water flow model.

Vernal pools occur throughout TAFB, notably in the northern portion. These vernal pools result from depressions in the surface topography and from relatively low-permeability soils in these depressions.

THE GROUND-WATER FLOW MODEL

A modular finite-difference, three-dimensional ground-water model, MODFLOW, developed by the U.S. Geological Survey (McDonald and Harbaugh, 1988), was selected to simulate ground-water flow at the Base. MODFLOW was selected because: (1) it has been verified and is widely accepted and used by ground-water scientists; (2) its output files can be directly imported into REMAX, Utah State University's optimization model; and (3) it has a number of pre- and post-processing packages that make entry of data and model output presentation reasonably easy. The primary output is calculated water levels at the center (node) of each grid cell.

MODEL SETUP

The modeled area centers around a TCE plume originating in the OSA and extending to the south and east under the runway. This plume is carrying TCE to shallow ground-water discharge points along storm-sewer drains under the runway and along Union Creek that flows south of the runway.

A north-south orientation was chosen for the MODFLOW grid. Three factors led to this choice. First, ground-water flow at the Base is generally in a north-south direction which allows model boundary conditions such as no-flow or constant head to be easily represented in the grid. Second, no predominant direction of Overburden or Bedrock Aquifer isotropy has been determined. Finally, much of the data are keyed to the State Plane Coordinate System and can be easily input to a grid with the same orientation.

The modeled area is a rectangle of 13,600 (north-south) by 12,600 feet centered over the major TCE plume at the Base. The rectangle extends well beyond the area of the TCE plume in all directions to eliminate model boundary effects. The modeled area is comprised of 70 columns and 72 rows of grid cells. The grid-cell horizontal dimensions vary from 300x300 feet at the boundaries to 100x100 feet in the central zone of the model grid (Fig. 7).

Consideration of the hydrogeological conceptual model and the desire to predict three-dimensional plume capture prompted using four discrete layers to simulate the Overburden and Bedrock Aquifers. All four layers were assigned a uniform thickness of 15, if possible, feet and were assumed to be under unconfined (water-table) conditions. The upper boundary of Layer 1 was configured to coincide with the June 1995 water-table surface. Because the Overburden Aquifer is not present throughout the entire modeled area due to shallow bedrock conditions, Layers 1, 2 and 3 simulate the Overburden Aquifer in some areas (e.g., bedrock valleys) and the Bedrock Aquifer in other locations (e.g., bedrock ridges). Inspection of Figure 5 reveals that Layer 3 includes all of the Overburden Aquifer in the southeastern part of the modeled area. Aquifer designation for Layers 1 through 3 was based on determination of the aquifer comprising more than one half (>7.5 ft) of the layer thickness. Because the maximum thickness of the Overburden Aquifer does not exceed 45 feet in the modeled area, Layer 4 represents the Bedrock Aquifer everywhere.

Three boundary conditions were applied in the model to simulate steady-state (time independent) flow. Constant-head boundary conditions were assigned to the upgradient (north) and downgradient (south) boundaries of the model. Constant-head boundaries can potentially allow an infinite inflow/outflow rate. They simulate overall ground-water flow from north to south, and cause water levels along these model boundaries to be unaffected by pumping. The east and west boundaries were modeled as no-flow boundaries, which assumes that ground-water streamlines parallel these boundaries and, consequently, no flow occurs in or through cells comprising these boundaries. In reality, some flow occurs across these boundaries; however, these model boundaries are sufficiently distant from the TCE plume to have no impact on the area of primary concern. A variable-head boundary condition was designated for the remaining cells in the modeled area, allowing heads to rise and fall in response to hydrologic stresses.

Union Creek south of the runway was simulated using the MODFLOW River Package. The River Package simulates both gaining and losing stream reaches.

The storm-sewer and sanitary sewer systems were simulated using both the Drain and River Packages. Which package was used for a specific location was dependent on the elevation of the static water level for June 1995 relative to the elevation of the sewer invert (bottom of pipe). If the invert elevation was lower than the static-water elevation, the Drain Package was utilized to simulate a line sink. The Drain Package simulates open and closed drains (line sinks), but discharge from the drain (sewer pipe) to the aquifer is not allowed. If the bottom-of-pipe elevation was higher than the June 1995 ground-water elevation, the sewer-line segment was simulated with the River Package. The River Package allows water to seep below the streambed (sewer pipe) when the water table falls below the sewer invert, a hydrologic condition known to occur at TAFB.

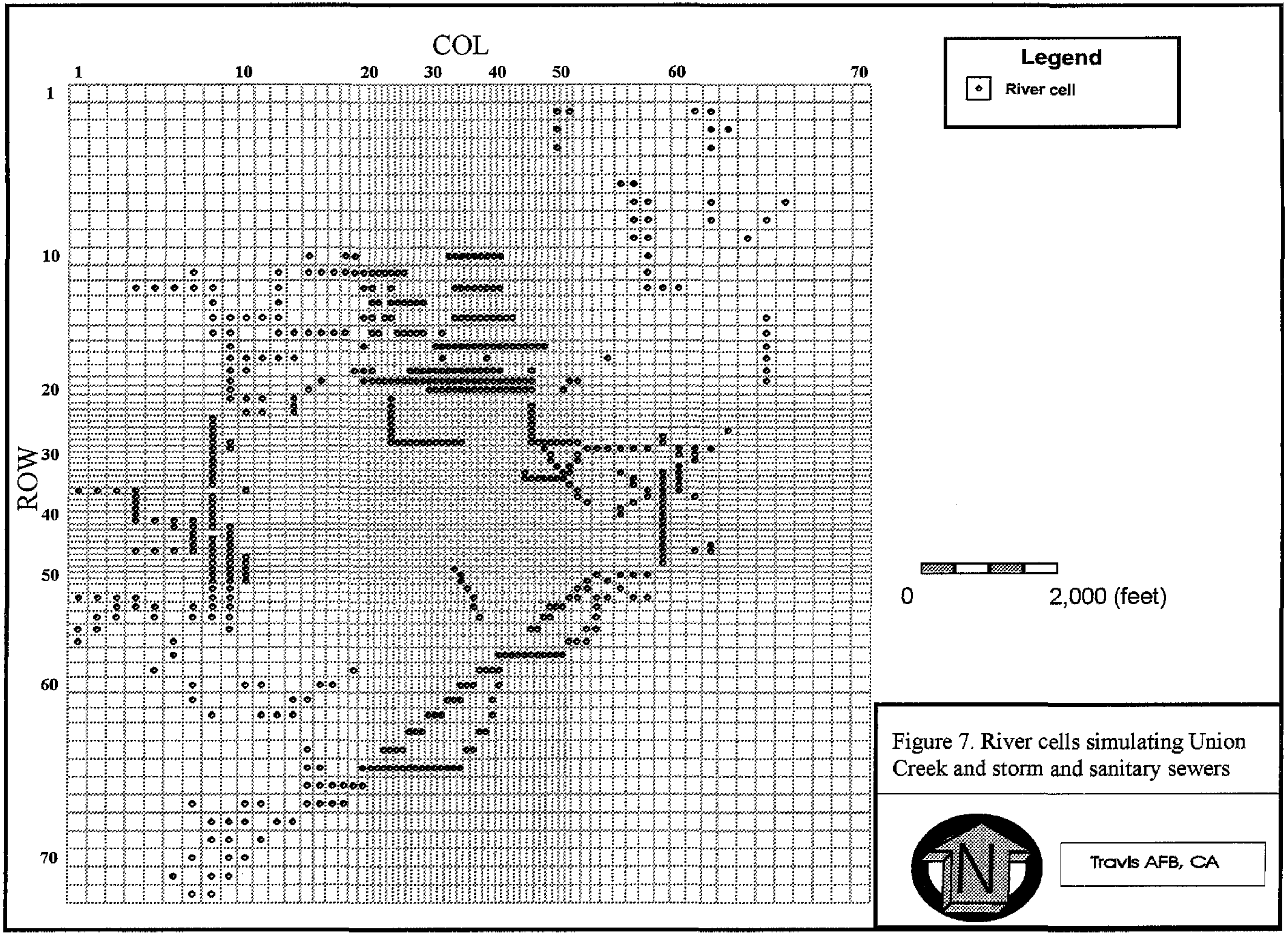

Figure 7. River cells simulating Union Creek and storm and sanitary sewers

DATA INPUT

Input data for model construction were obtained principally from contractor reports submitted for the Installation Restoration Program (IRP). Pertinent data for monitoring wells and boreholes (encompassing ground-surface elevations, water-table elevations, borehole lithology, depths to bedrock, and screened interval) were obtained from RADIAN and WESTON and were delivered to AFCEE/ERC on computer diskettes.

Most data file creation was accomplished through ModelCad, a preprocessor developed by Geraghty & Miller, Inc. ModelCad utilizes a graphics user interface (GUI) to allow visual design of the grid and simplified assignment of hydrologic property values for each grid cell.

Starting hydraulic heads were those measured by RADIAN in August 1994. Water-level elevations for approximately 130 monitoring wells were input into SURFER, a contour mapping software package (Golden Software, Inc., 1992). Kriging was the statistical method chosen for interpolation of head values to produce the SURFER grid file. Then this grid file was imported into ModelCad.

As noted above, well-pair data reveal a spatial and temporal mix of relatively small downward and upward vertical hydraulic gradients. Additionally, all well pairs located near the north and south model boundaries yielded negligible vertical gradients for August 1994. Consequently, starting heads for Layer 1 were also assigned to the three deeper layers.

Starting hydraulic conductivity (K) values for the Overburden Aquifer were based on aquifer testing results for 19 monitoring wells. Five K values were obtained from pumping tests conducted between 1991 and 1994. The remaining 14 K values originated from slug testing performed by WESTON in 1991. A SURFER grid file of K values was produced using the kriging interpolation method and then was imported into ModelCad.

As noted in the Hydrogeology Section, the Bedrock Aquifer typically is less permeable than the Overburden Aquifer. Consequently, starting K values for the Bedrock Aquifer were assigned as follows: Layer 1, 10 ft/day; Layer 2, 8 ft/day; Layer 3, 6 ft/day; and Layer 4, 4 ft/day.

Vertical conductance, defined as vertical hydraulic conductivity divided by aquifer or layer thickness (K_Z/b), is an input parameter (Vcont) in MODFLOW. Based on communication with RADIAN, WESTON and CH2M Hill hydrogeologists, a horizontal to vertical K ratio of 100:1 was selected. Subsequently, this ratio was used to calculate Vcont input values for Layers 1 through 3.

Representation of the storm-sewer and sanitary-sewer systems as either river (Fig. 7) or drain (Fig. 8) segments required a lengthy process of data compilation and interpolation. First, the digitized maps of the storm-sewer and sanitary-sewer systems were obtained in electronic format from RADIAN. The digitized map of the storm sewers was then modified by the AFCEE Computer Systems Division (AFCEE/MSC) by adding manhole symbols and available invert elevations for these manholes. (Measured invert elevations were available for only a relatively small percentage of manholes, and data sources were the Base Tab G-3 maps (1964) and WESTON). The MSC-modified CAD map of the storm sewers and the sanitary-sewer digitized map were then imported into ModelCad, and ModelCad's digitizing capability was used to assign measured and interpolated invert elevations to appropriate cells of the modeled grid. These invert elevations then became input values for elevations of the bottom of the riverbed or of the drain for the River and Drain Packages, respectively. Where both storm-sewer and sanitary-sewer lines traversed the same grid cell, the storm-sewer invert was given priority because more evidence exists to document leaky storm-sewer lines than leaky sanitary-sewer lines.

MODFLOW's Recharge Package was used to simulate ground-water recharge originating from precipitation. Because apparently no organization has measured deep percolation of precipitation in the vicinity of TAFB, best-guess values for recharge were assigned. A large zone north of the runways and flight line was assigned a value of 2.5×10^{-4} ft/day (1.1 in/y). In a larger zone that encompasses the perimeter of TAFB and most of the modeled area south of the runways, where less paved surfaces and large buildings generally occur, a higher recharge rate of 5.0×10^{-4} ft/day (2.2 in/yr) was employed. In the "Triangle," a relatively small, largely unpaved zone near the center of the modeled area (encompassing MW 276), a recharge value of 2.5×10^{-3} ft/day (11 in/yr) was assigned due to ponded water frequently observed by Base personnel (M. Sandy, pers. comm., April 6, 1995). The Recharge Package was not invoked for most areas underlying runways, taxiways, ramps and other areally extensive concrete and asphalt surfaces.

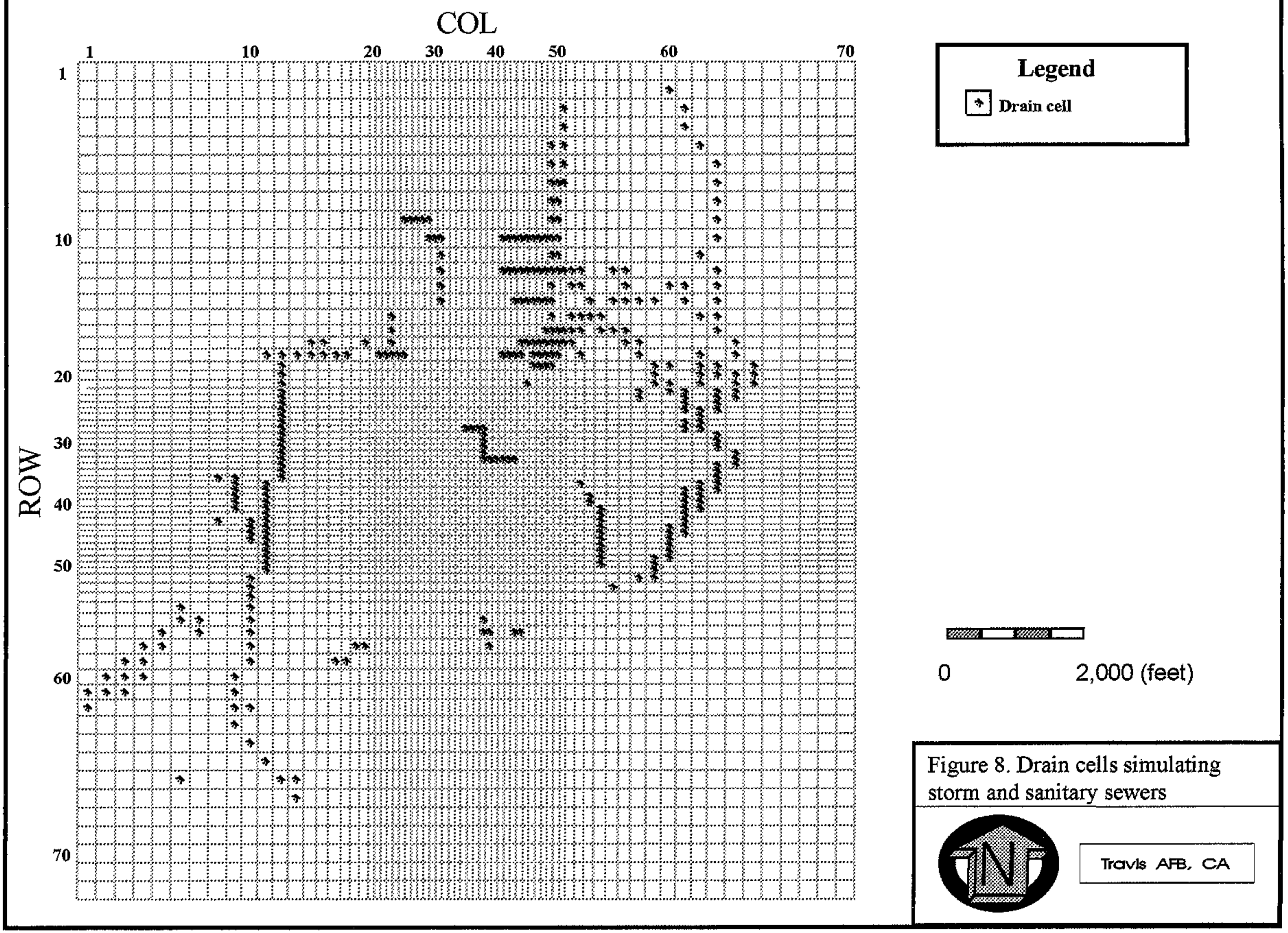

Figure 8. Drain cells simulating storm and sanitary sewers

MODEL CALIBRATION AND RESULTS

Trial-and-error calibration of the model consisted of varying hydraulic conductivity values, areal recharge, and river and drain cell conductances in an intuitive and logical fashion until acceptable heads, drain and river cell flow rates, and water balance errors were obtained. The range in K values was limited to the range encompassed by available pumping-test data and recent slug-test data (approximately 1-100 ft/day).

When the model was executed using the initial input parameter values, the resulting heads for Layer 1 diverged noticeably from the observed heads for August 1994. The divergence was greatest where three dominant bedrock highs occur in the northern half of the modeled area. Additionally, four Layer 1 cells comprising the bedrock high in the northeastern corner of the model grid (High #1) went dry. Consequently, K values in these high bedrock and water-table areas were adjusted downward to a range of 1 to 4 ft/day. Additionally, for ground-water "troughs," such as the buried bedrock valley situated between bedrock Highs #2 ("Hospital Hill") and #3 (southeast- to northwest-trending ground-water/bedrock high lying immediately west of the TCE plume), K values for some cells in Layers 1, 2 and 3 were increased (however, no K values were increased beyond 90 ft/day). Rationale for this K upper-boundary value is: Pumping-test data and predominant lithology of the Overburden Aquifer do not justify using higher values.

The final K values for Layer 1 ranged from 1.0 to 90 ft/day. Final K values for Layer 2 ranged from 1.0 to 70 ft/day. Final K values for Layer 3 ranged from 4 to 20 ft/day. Final K values for Layer 4 ranged from 4 to 10 ft/day. Spatial distribution for K values in all model layers is shown in Figure 9.

A plausible explanation for the apparently high recharge occurring at bedrock High #1 is as follows. Landfill activity has caused topographic depressions that collect and hold precipitation. Precipitation slowly percolates downward from the resulting vernal pools to the shallow water table (D. Stanley, pers. comm., 10 Aug 95). Consequently, areal recharge in this area was increased to one zone of 2.5×10^{-3} ft/day (11 in/yr) and a second zone of 5.0×10^{-3} ft/day (22 in/yr) (Fig. 10).

Potential sources of recharge to "Hospital Hill" (High #2) and High #3, include: (1) leaking storm-sewer lines not simulated in the model due to lack of invert-elevation data; and (2) leaking potable water-supply lines. Consequently, areal recharge was added to these ground-water highs up to a rate of 1.0×10^{-3} ft/day (4.4 in/yr) (Fig. 10). Anderson and Woessner (1992, p. 153) assert that defining recharge zones and assigning reasonable recharge rates to each zone "... is usually justified on the basis of a successful calibration." This assertion is based on the typically significant spatial and temporal variations in ground-water recharge rates and the paucity of field-measured recharge data.

In an attempt to reduce the negative residual (observed - calculated) head values in Layer 1 in the southeastern corner of the modeled area, the horizontal to vertical K ratio for Layer 1 in this rectangular area encompassing 21,270,000 ft^2 was reduced from 1:100 to 1:50. This 50 percent increase in K_z and Vcond values resulted in only a 0.05 foot decrease in head at one Layer 1 calibration target (monitoring well) within this area. No other changes to the starting K_z and Vcont values were made during calibration.

A primary criterion for determining that a steady-state model is properly calibrated (i.e., it accurately simulates hydrogeological conditions existing in the modeled area) is small residuals between observed and calculated static heads at each calibration point. Currently, no standard protocol exists for evaluating, qualitatively or quantitatively, the calibration process (Anderson and Woessner, 1992). ASTM Standard Guide D 5490 (ASTM, 1994) contains techniques for comparing model output data to measured field data as part of the calibration process. However, this ASTM guide does not establish criteria or standards for successful calibration. For a recent ground-water-flow and pathline analysis modeling study conducted by the US Geological Survey (Barlow, 1994), mean errors between calculated and observed heads averaged four to five percent of the total relief of the water table over the modeled area. Applying this calibration standard to the Travis AFB model, where total relief of the water-table surface is approximately 50 feet, a maximum acceptable mean head residual would be 2.5 feet.

Figure 6 depicts contours of calibrated and observed ground-water elevations for Layer 1 of the modeled ground-water flow system. This figure also shows residual head values for 34 monitoring wells that served as calibration targets. Residual heads ranged from a maximum negative value of -3.17 feet (west-central section, MW 1205) to the maximum positive value of 5.51 feet for a calibration point in High #2 (MW 276). The absolute residual mean is 1.60 feet. The scattergram for Layer 1 calibration targets (Fig. 11) depicts the trend of positive residuals associated with bedrock/water-table highs. The absolute residual mean was 1.18 ft. for the twelve Layer 2 calibration wells. The spatial distribution of these residuals is shown on Figure 12. For 10 Layer 3 calibration well targets, the absolute residual mean was 1.84 ft. Figure 13 depicts the areal distribution of these calibration target residuals. Three Layer 4 calibration wells yielded a mean absolute residual of 1.01 ft. Mean absolute residuals and simulated flow directions for all four model layers are acceptable. Complete final "run" calibration statistics, including listings of calibration target residuals, are tabulated in Appendix A.

The percent discrepancy in the water budget for the modeled ground-water system is -- -0.88. Inflows include areal recharge at the rate of 73,960 ft^3/day (385 gpm), river (stream, storm-sewer and sanitary-sewer line) leakage of 9,985 ft^3/day (52.0 gpm), and ground-water inflow (constant-head contribution) at 9,540 ft^3/day (49.7 gpm). Total inflow is 93,480 ft^3/day (510 gpm). Total outflow of 94,300 ft^3/day (491 gpm) includes: ground-water outflow (constant-head contribution), 34,160 ft^3/day (178 gpm); flow from drains (storm and sanitary sewers), 20,690 ft^3/day (108 gpm); and river (stream and storm-sewer line) leakage, 25,200 ft^3/day (131 gpm); and well discharge, 14,250 ft^3/day (74.2 gpm).

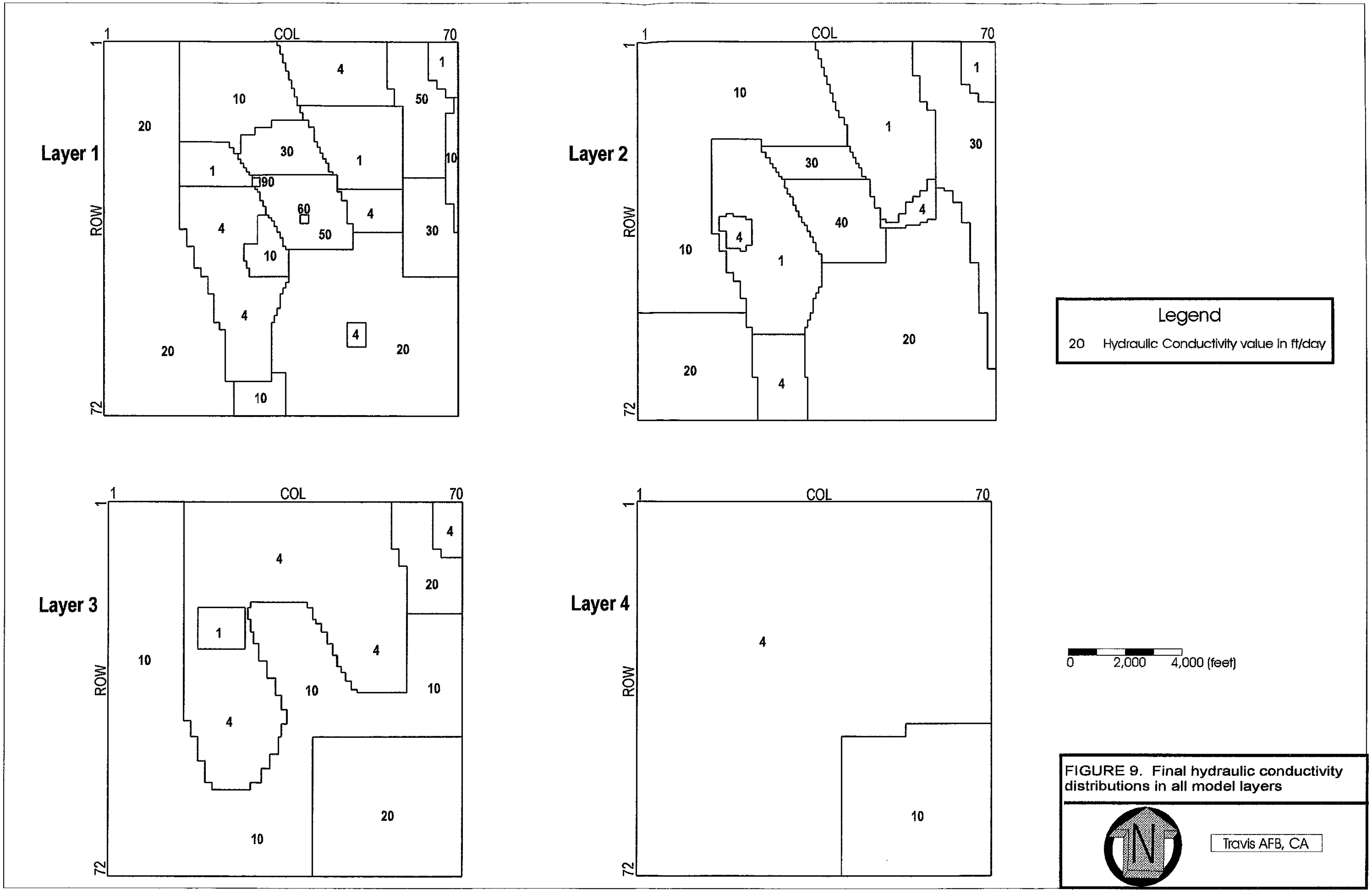

FIGURE 9. Final hydraulic conductivity distributions in all model layers

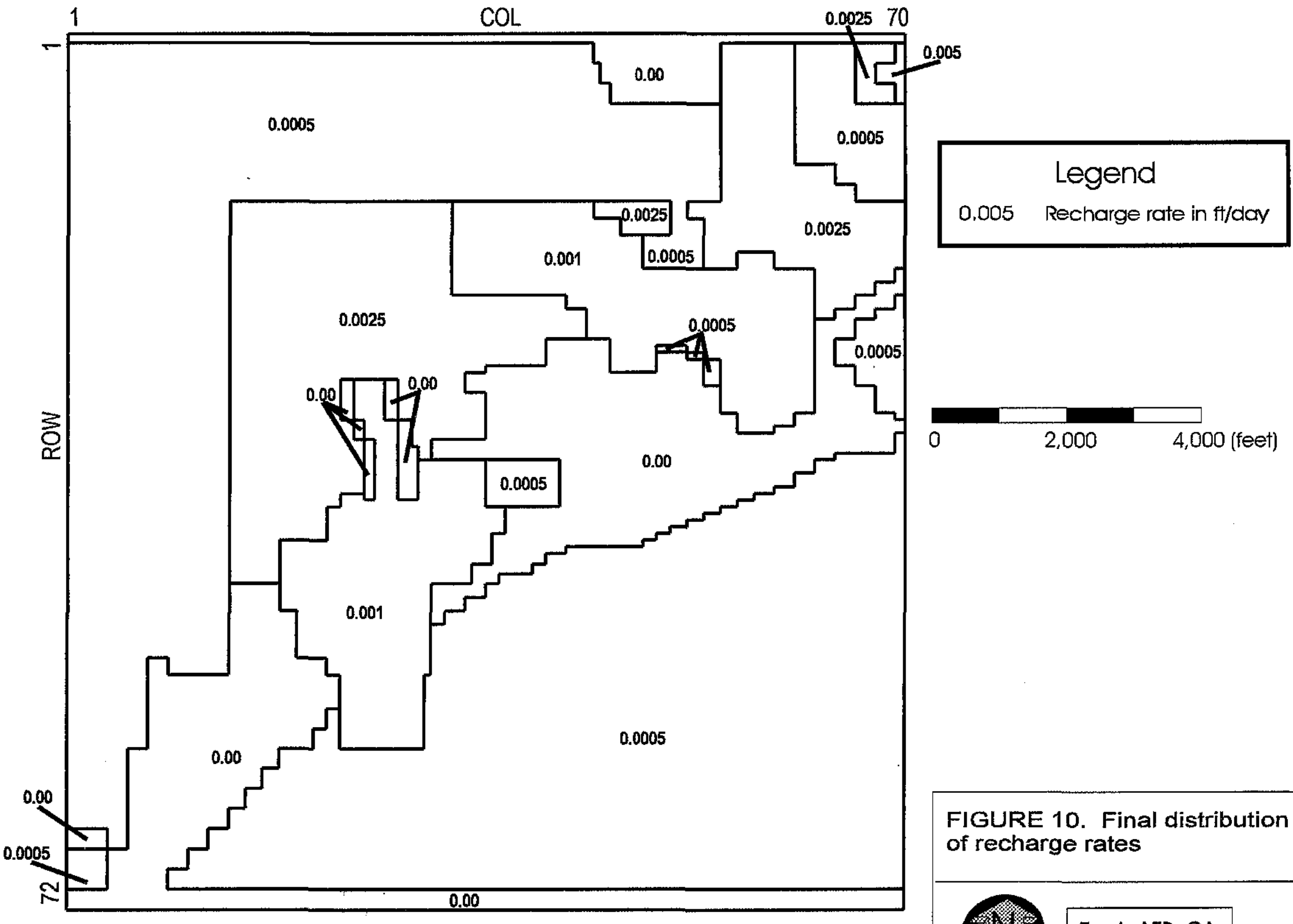

FIGURE 10. Final distribution of recharge rates

Travis AFB, CA

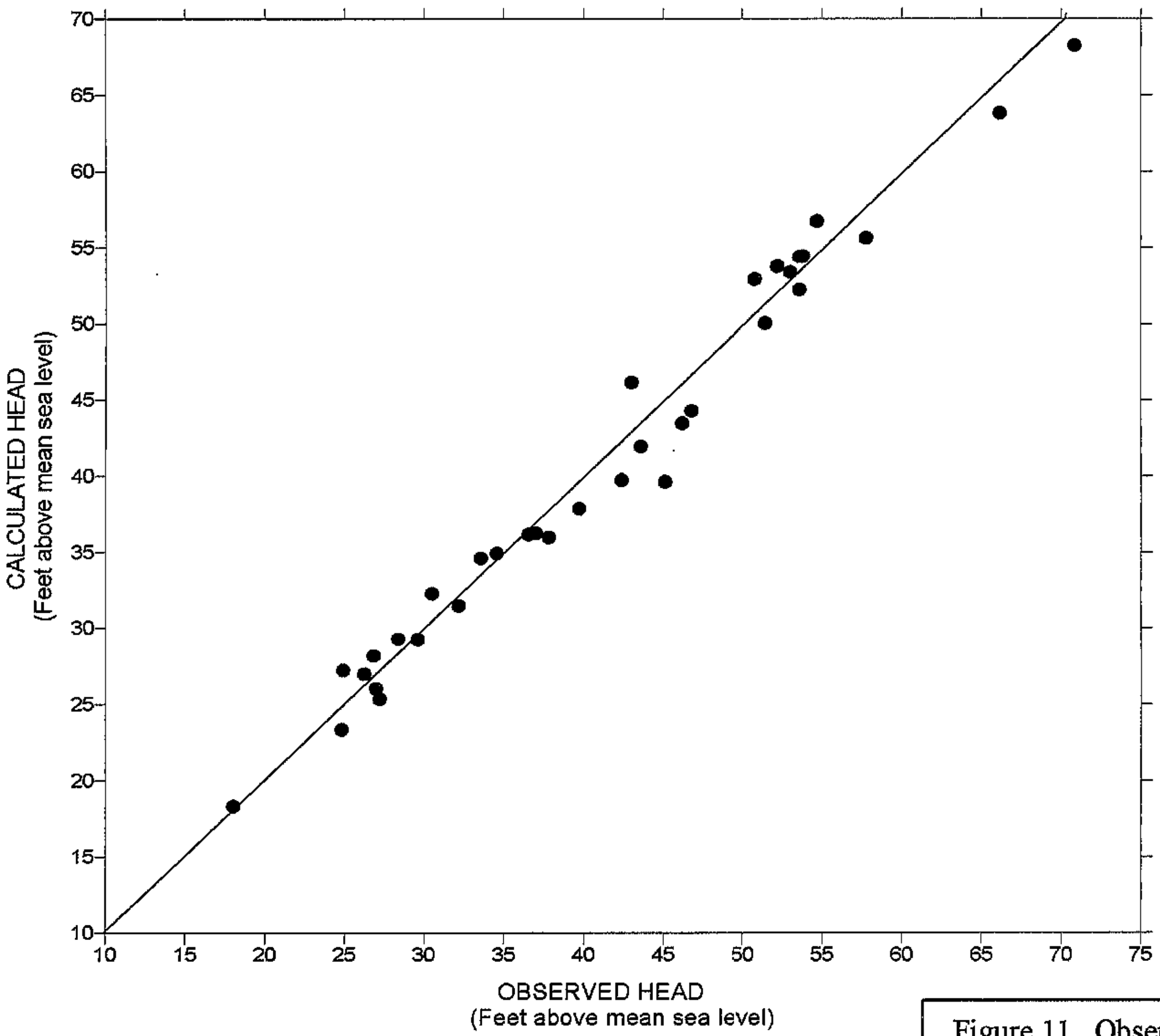

Figure 11. Observed versus calculated heads in model Layer 1

Travis AFB, CA

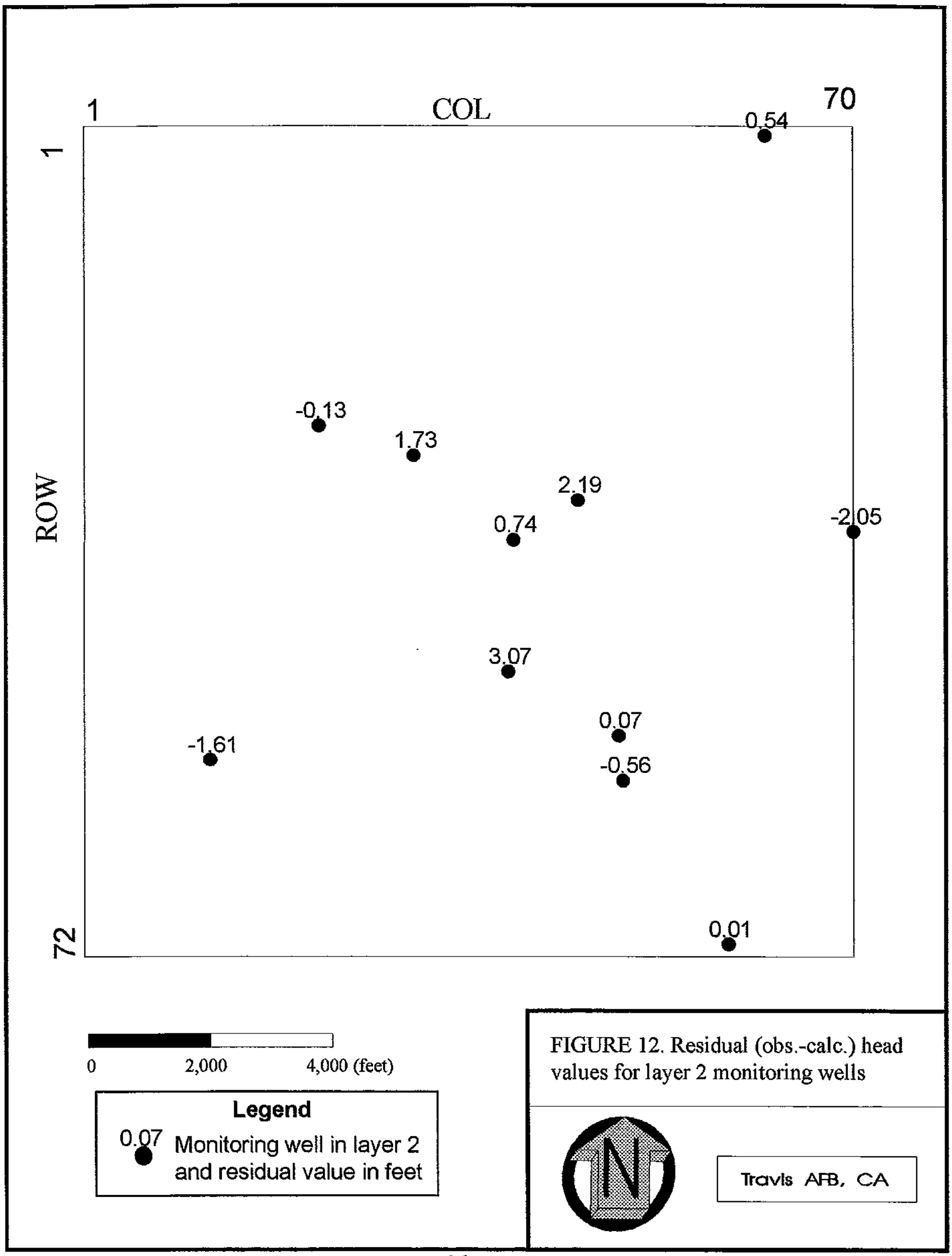

FIGURE 12. Residual (obs.-calc.) head values for layer 2 monitoring wells

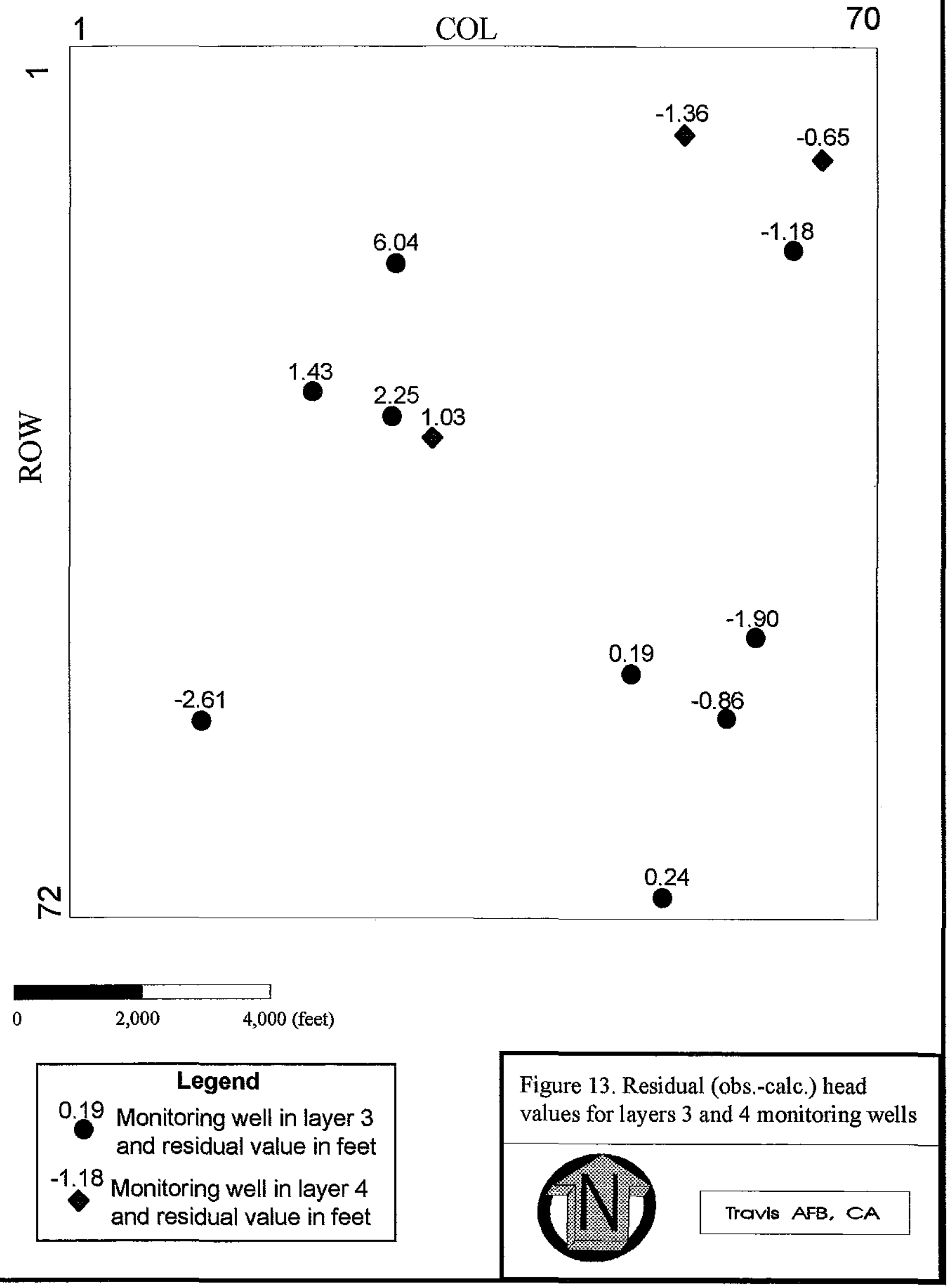

Figure 13. Residual (obs.-calc.) head values for layers 3 and 4 monitoring wells

CONCLUSIONS

Considering the complex configuration of the observed head distribution, agreement of the calculated water-table configuration with that of the observed configuration is excellent. Mean absolute head residual for Layer 1 based on 35 calibration well targets is 0.89 foot. Relatively high residuals for several calibration wells result from data uncertainty and lack of pertinent data pertaining to potential inflow sources (e.g., lack of invert elevations for many storm-sewer manholes, inflow/outflow data for sanitary sewers, lack of a digitized water-supply system map). Alternately, these anomalously high water levels may reflect discontinuous or perched water tables.

RECOMMENDATIONS

To more fully understand the complex hydrogeology of TAFB and to obtain hydrologic information (encompassing ground-water recharge sources) necessary to accurately simulate ground-water flow and contaminant transport, the following recommendations are provided:

(1) Investigate, in greater detail, hydrogeologic conditions at the three primary bedrock/ground-water highs described in this report (e.g., conduct pumping tests to better define the lateral and vertical distribution of hydraulic conductivity, assess vertical hydraulic gradients, confirm that monitoring wells are in good hydraulic connection with screened aquifer)

(2) Identify the major sources of ground-water recharge in the three primary bedrock/ground-water highs and measure, to the extent feasible, recharge rates from these sources (e.g., storm-water and sanitary sewers, water-supply system) and

(3) Conduct a water-budget study for the Base, to encompass flow measurements in Union Creek and the storm sewers, rainfall measurements, measurement of water levels in Duck Pond, analysis of Base water use, and inflow/outflow studies of the storm-water and sanitary-sewer systems.

OPTIMIZATION FORMULATION FOR OSA PUMP AND TREAT SYSTEM

GENERAL FORMULATION

The goal is to optimize the pump and treat (P&T) operation at the OSA needed to capture the TCE plume in the top model layer. To do this, a groundwater simulation/optimization (S/O) model is used. The model objective is to determine the least pumping needed to prevent the TCE plume from further migration to the southeast. The following criteria are used:

1. Only steady-state hydraulic optimization is performed. No transport model has been calibrated to predict plume concentrations over time.
2. Extraction rates from extraction wells are not permitted to result in less than 3 feet of saturated thickness at the well casing. We assume the pumping strategy is sustainable if at least 3 feet of saturated thickness exists at the well casing at all times during simulated pumping. Thus a lower bound on head at the well was used within the S/O model when computing optimal pumping rates.
3. The developed pumping strategies will capture the TCE-contaminated groundwater plume as provided by TAFB. For lack of better data, a 2-D plume is assumed (i.e., uniform concentrations with depth in the top model layer). Only TCE concentrations above MCL are captured (MCL value for TCE is 5 ppb).
4. Capture is demonstrated in the computer model using particle tracking. Because of the always-present model uncertainty, we tried to assure plume capture in the field by using a safety factor in the model. The safety factor is implemented by capturing contaminated pathlines for a range of aquifer hydraulic conductivity values. Tracked particles are placed at the center (x,y,z) of cells around the 5 ppb contour.
5. USU considered 20 potential locations for the extraction wells downstream from the plume (Figure 14). The S/O model determined that only 5 wells should pump to optimally capture the plume.
6. While computing the first optimal capture strategy, USU assumed the same boundary conditions and background pumping rates used for the calibration. USU had no data to make other assumptions. Based on post-optimization sensitivity analysis, USU then developed a more robust capture strategy.

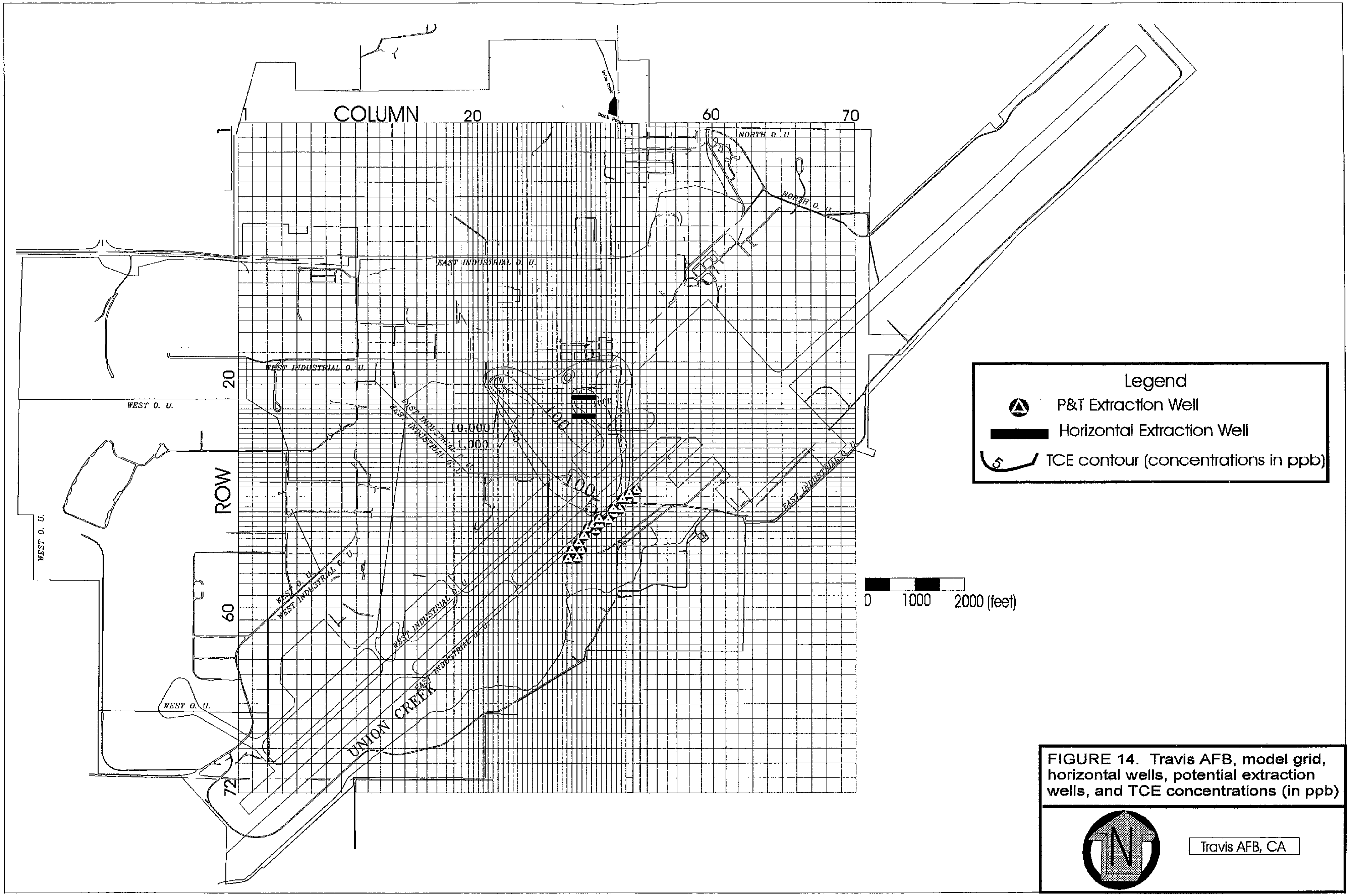

FIGURE 14. Travis AFB, model grid, horizontal wells, potential extraction wells, and TCE concentrations (in ppb)

DEVELOPED PUMPING STRATEGIES

A steady pumping strategy consists of a spatially distributed set of pumping rates. The first optimal pumping strategy (strategy A) assures capture by requiring hydraulic gradients downstream from the extraction wells to be toward the northwest. Table 1 contains optimal pumping rates for strategy A. Figure 15 shows groundwater pathlines that will result from implementing strategy A.

To test the robustness of plume capture resulting from pumping strategy A, a sensitivity analysis was conducted. In this analysis, pumping strategy A was input into a simulation model for several sets of hydraulic conductivity values. Each set consisted of the calibrated hydraulic conductivity values multiplied by a different factor. The resulting set of conductivities ranged between 50% and 150% of calibrated hydraulic conductivity. This analysis showed that capture was most sensitive to using larger values for the hydraulic conductivity. When hydraulic conductivity was increased by 25%, TCE-contaminated groundwater near the plume's outer edge was not captured (Figure 16).

To provide protection in case field conductivity values are different from the calibrated values, another pumping strategy was developed (strategy B). Optimal pumping strategy B was developed for a set of conductivity values that are 25% greater than calibrated values. Figure 17 shows the pathlines predicted (using the calibrated conductivity values) when strategy B is implemented. Table 1 contains strategy B extraction well locations and pumping. Table 1 also lists information useful for well screen design.

RECOMMENDATIONS

We recommend strategy B for use by Travis Air Force Base. Strategy B requires about 26% more pumping than strategy A. However, strategy B is a robust pumping strategy that will capture the plume under a range of hydraulic conductivity values. If extra horizontal wells are installed inside the TCE plume, we can reduce the pumping rates required in strategy B. If strategy B is not modified, installing extra horizontal wells inside the plume can only make the plume capture more robust.

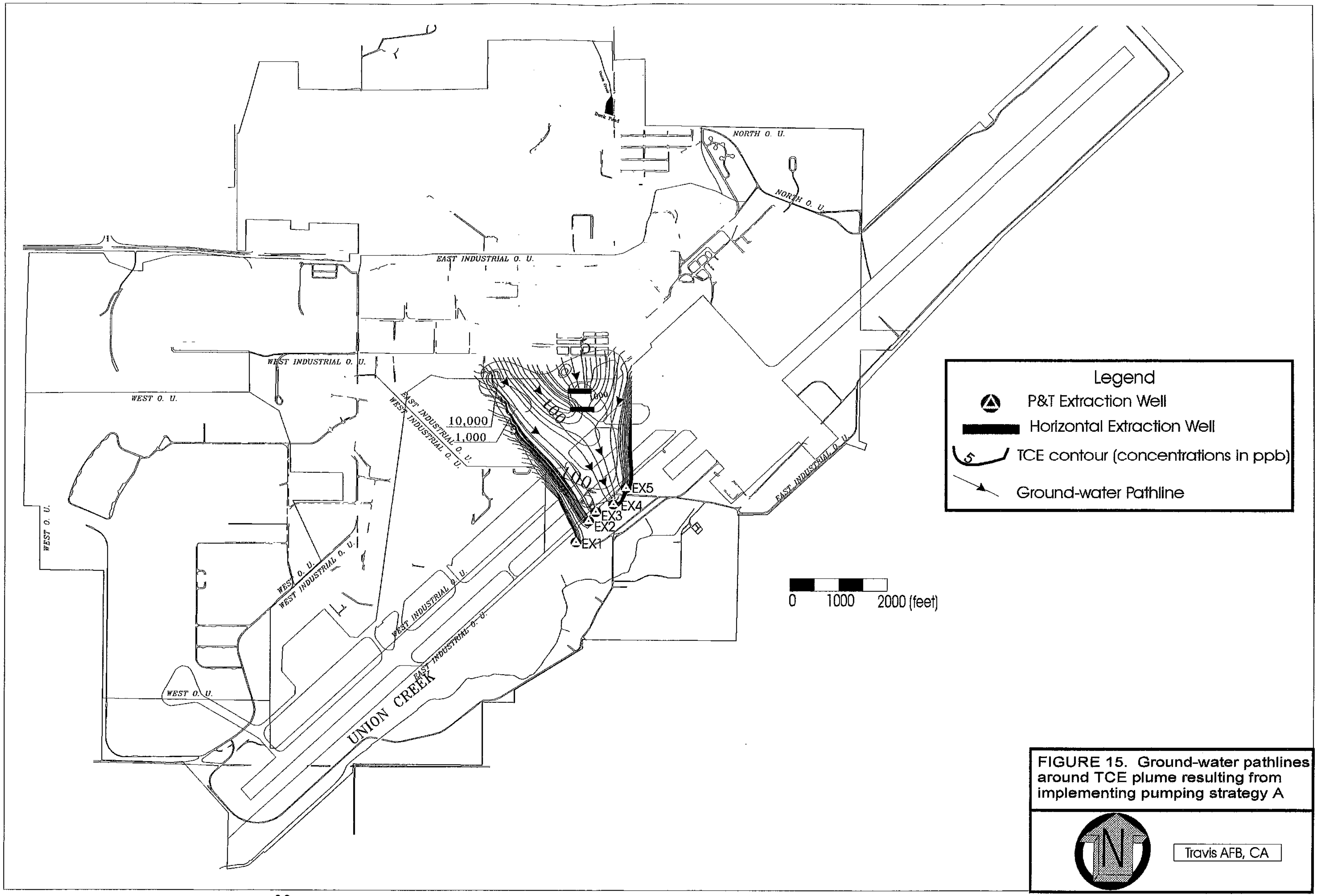

FIGURE 15. Ground-water pathlines around TCE plume resulting from implementing pumping strategy A

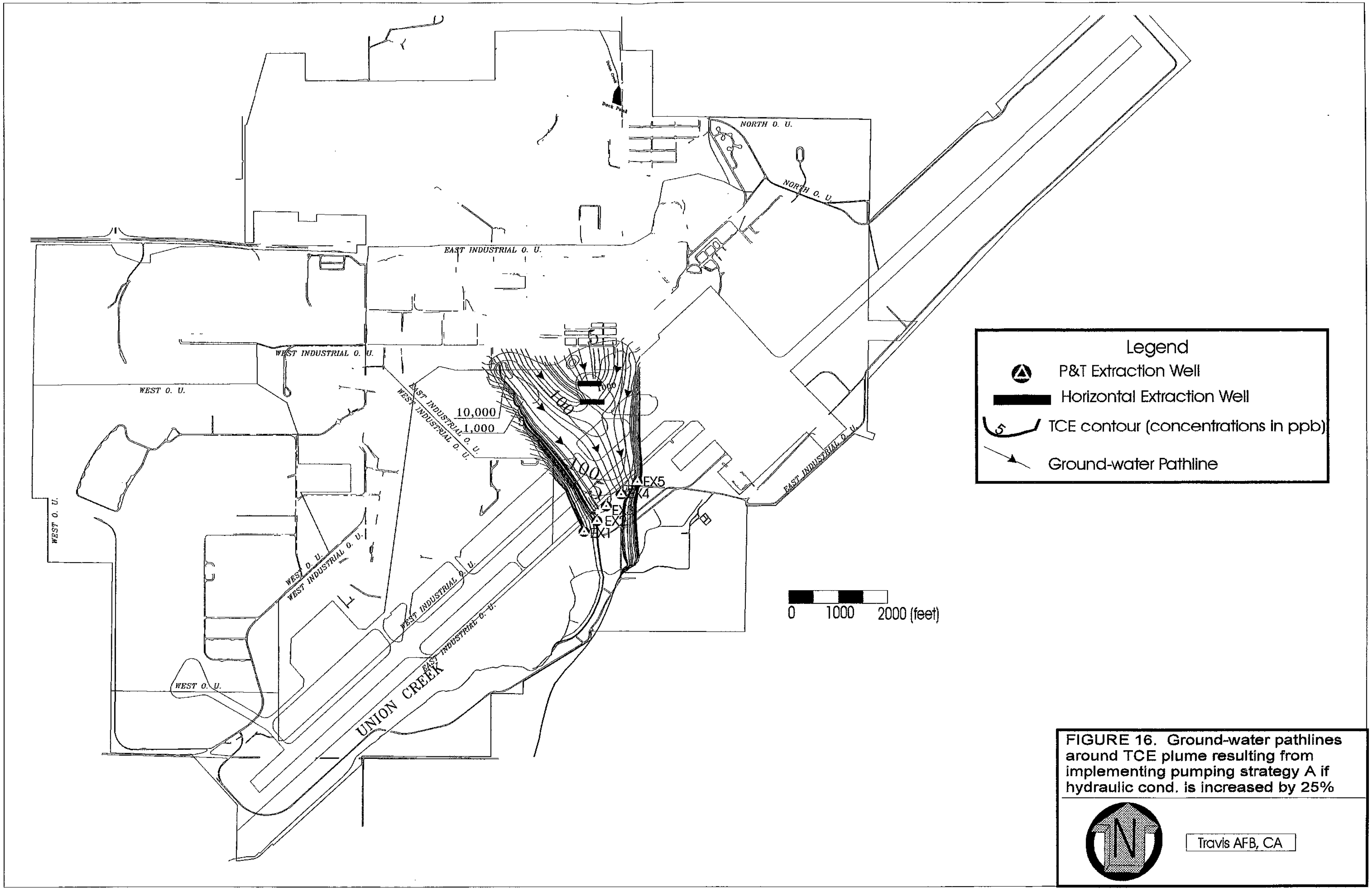

FIGURE 16. Ground-water pathlines around TCE plume resulting from implementing pumping strategy A if hydraulic cond. is increased by 25%

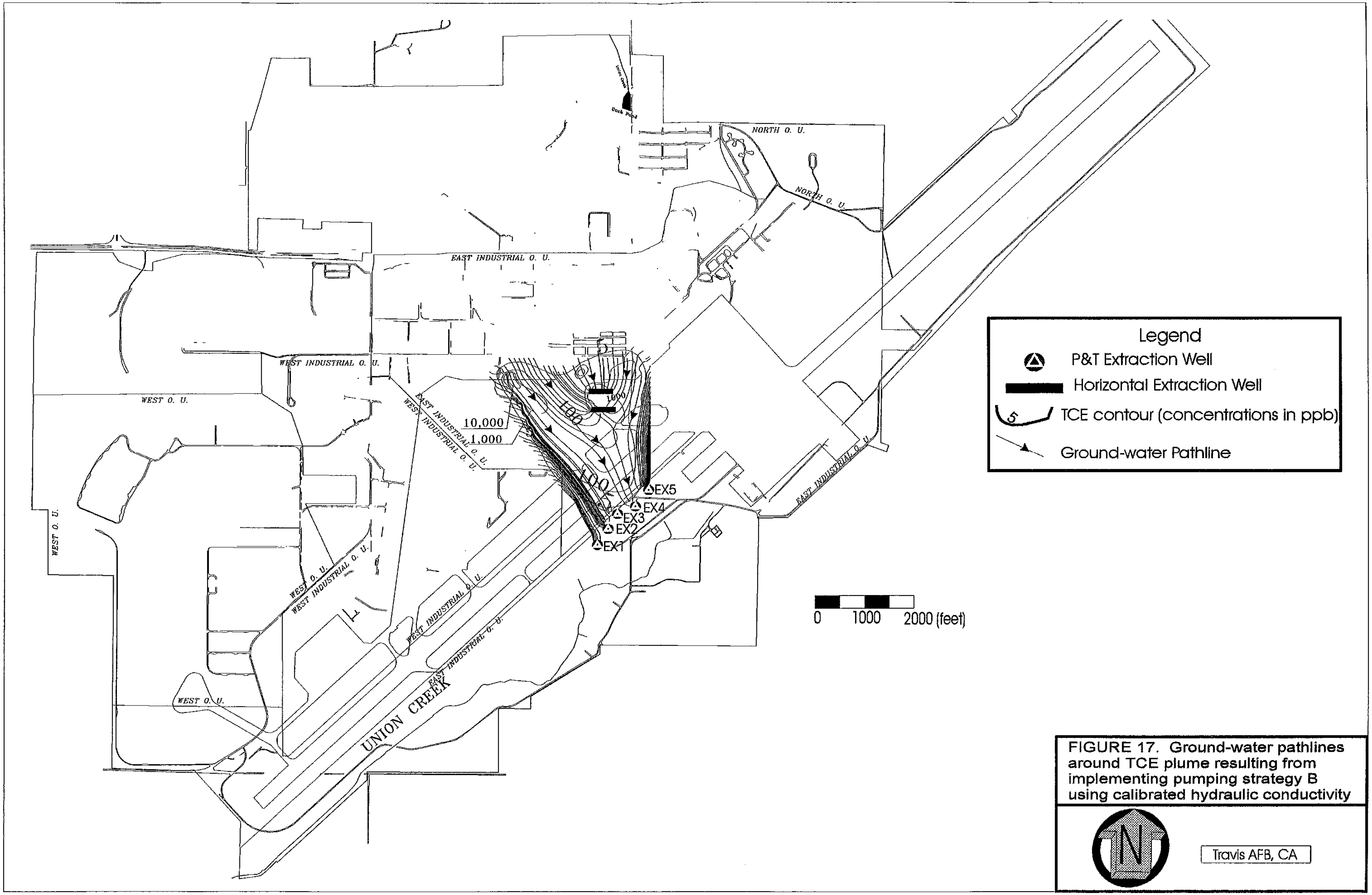

FIGURE 17. Ground-water pathlines around TCE plume resulting from implementing pumping strategy B using calibrated hydraulic conductivity

Table 4. Well locations and pumping rates

Name	Row	Col	Easting (ft)	Northing (ft)	Strategy A Pumping Rate (gpm)	Strategy B Pumping Rate (gpm)	Pumping Layer Bottom Elev (ft)	Steady State Water Table Elev. (ft) (no P&T)	Steady State Water Table Elev. (ft) (Strategy A)	Steady State Water Table Elev. (ft) (Strategy B)
EX1	54	42	6,578,139	1,852,286	6	9	16.1	31.5	25.2	20.0
EX2	51	45	6,578,499	1,852,646	8	10	16.8	32.9	23.9	19.8
EX3	49	46	6,578,619	1,852,886	6	6	17.1	33.5	26.9	26.1
EX4	47	50	6,579,099	1,853,126	9	11	16.9	33.6	25.0	21.0
EX5	44	52	6,579,339	1,853,486	5	8	17.2	34.0	31.3	30.0
Total					35	44				

Notes:

1. All elevations are in feet above MSL.
2. Steady state water table elevation without pump and treat is computed by simulating steady state groundwater under current (existing) conditions.
3. Steady state water table elevations for strategies A and B are computed just outside 6-inch well casings. These elevations are computed using the wellhead correction described in the REMAX manual.

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APPENDIX A. Final "Run" Calibration Statistics

```
Residual Summary for all layers
===================================

Maximum Residual =        6.04
Average Residual =        0.28
Minimum Residual =       -3.17
Sum of Squared Res. =          218.0788
Sum of Absolute Res. =          92.0443
Number of Positive Residuals =          32
Number of Negative Residuals =          28

Residual Summary for layer 1
===================================
Maximum Residual =        5.51
Average Residual =        0.46
Minimum Residual =       -3.17
Sum of Squared Res. =          124.2749
Sum of Absolute Res. =          54.4462
Number of Positive Residuals =          19
Number of Negative Residuals =          15

Residual Summary for layer 2
===================================
Maximum Residual =        3.07
Average Residual =        0.21
Minimum Residual =       -2.05
Sum of Squared Res. =           27.2630
Sum of Absolute Res. =          14.1415
Number of Positive Residuals =           7
Number of Negative Residuals =           5

Residual Summary for layer 3
===================================
Maximum Residual =        6.04
Average Residual =        0.19
Minimum Residual =       -2.61
Sum of Squared Res. =           59.0796
Sum of Absolute Res. =          18.3886
Number of Positive Residuals =           5
Number of Negative Residuals =           5

Residual Summary for layer 4
===================================
Maximum Residual =        1.03
Average Residual =       -0.33
Minimum Residual =       -1.36
Sum of Squared Res. =            3.3276
Sum of Absolute Res. =           3.0349
Number of Positive Residuals =           1
Number of Negative Residuals =           2
```