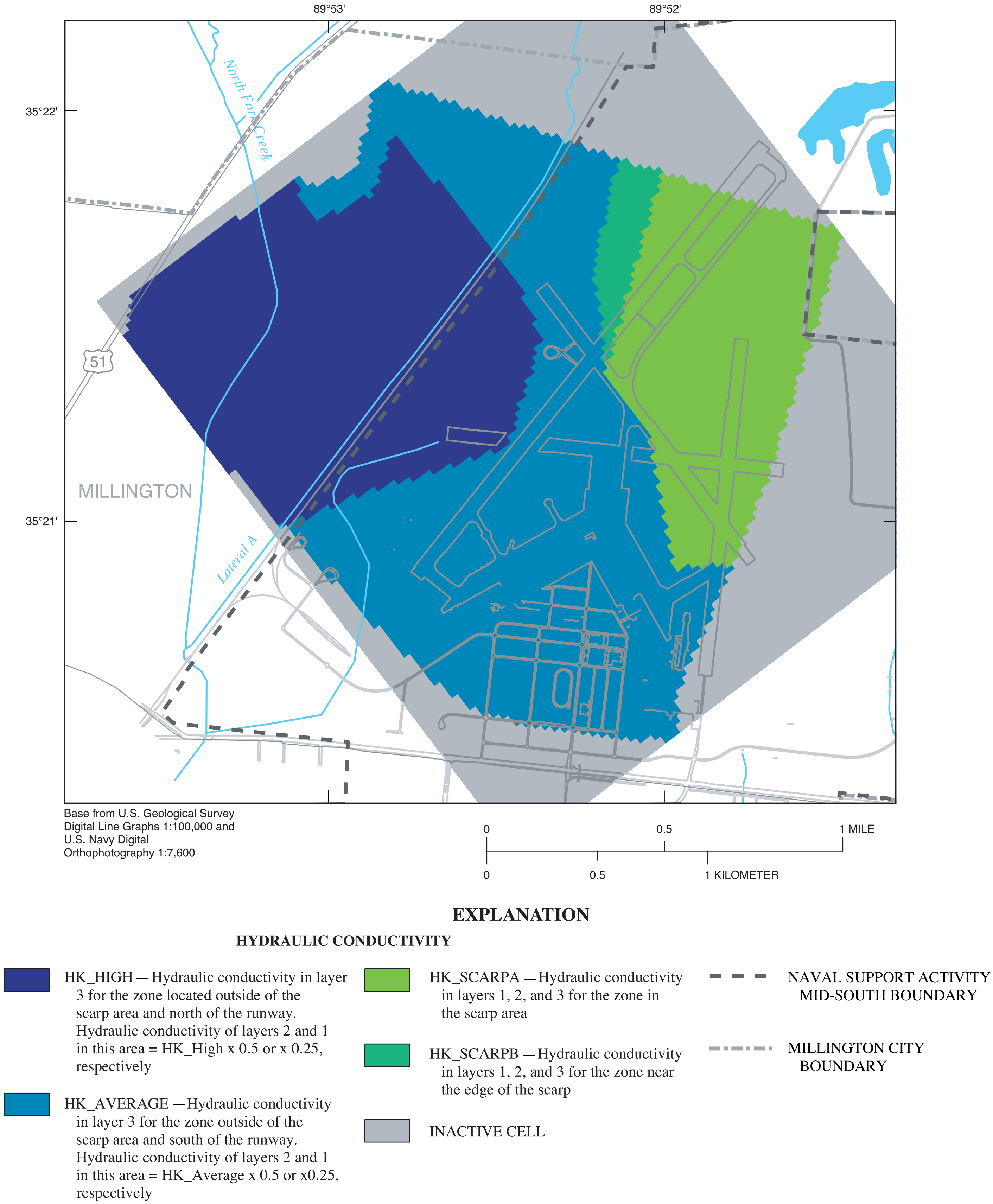

Figure 13. Hydraulic conductivity zones for the Area of Concern (AOC) A flow model, Naval Support Activity Mid-South, Millington, Tennessee.

Table 3. Relation between hydraulic conductivity parameters and hydraulic conductivity by layers for the Area of Concern A flow model, Naval Support Activity Mid-South

	Hydraulic conductivity zone			
	HK_Average	HK_High	HK_ScarpA	HK_ScarpB
Layer 1	0.25 * HK_Average	0.25 * HK_High	HK_ScarpA	HK_ScarpB
Layer 2	0.5 * HK_Average	0.5 * HK_High	HK_ScarpA	HK_ScarpB
Layer 3	HK_Average	HK_High	HK_ScarpA	HK_ScarpB

between simulated and measured water levels, and the simulated and estimated advective travel time. These observations were weighted, as described by Hill (1998), to account for the greater accuracy in the measured water levels and lesser accuracy in the estimated advective travel time. The four most sensitive parameters (HK_High, HK_Average, HK_ScarpA, and RECH) were estimated using the parameter-estimation process in MODFLOW-2000. The two least sensitive parameters, HK_ScarpB and the ratio of horizontal to vertical hydraulic conductivity (VANI), were calibrated manually during the calibration process.

Overall, simulated water levels (fig. 14) agree reasonably well with measured water levels (fig. 7). Water levels were available for comparison at 68 wells. The root mean square error (RMSE) was calculated to compare simulated and measured water levels. The RMSE, in feet, is calculated by

$$RMSE = \sqrt{\left(\sum_{i=1}^{N} \langle h_i^m - h_i^c \rangle^2\right) / N} \qquad (1)$$

where

- N is the number of observations;
- h_i^m is the measured water level, in feet; and
- h_i^c is the simulated water level, in feet.

The RMSE for water levels is 1.1 ft. The average difference between measured and simulated water levels for the calibration model simulation is 0.04 ft. Sixty-two percent of the simulated water levels are within 1 ft of the observed water levels and 96 percent are within 2 ft. The errors or residuals in simulated water levels show no significant spatial pattern; however, in a small area in the southeastern corner of the model, simulated water-levels tended to be consistently higher than observed water levels.

Calibrated horizontal hydraulic conductivities for the AOC A flow model range from 1.2 to 65 ft/d (table 4). These values are comparable to measured values from well hydraulic tests (Robinson and others, 1997, table 3; Ensafe, Inc., written commun., 2000). Calibrated transmissivities for layer 1 vary from 7.9 to 430 ft^2/d (fig. 15) with an average of 110 ft^2/d and a median of 61 ft^2/d. The highest transmissivities in layer 1 are in the northwestern part of the model area where a thick section of the alluvial-fluvial deposits aquifer coincides with higher than average hydraulic-conductivity values. Calibrated transmissivities for layer 2 vary from 7.9 to 870 ft^2/d (fig. 16) with an average of 220 ft^2/d and a median of 120 ft^2/d. Calibrated transmissivities for layer 3 vary from 7.9 to 1,700 ft^2/d (fig. 17) with an average of 430 ft^2/d and a median of 240 ft^2/d. The calibrated hydraulic conductivities used in this model are greater than the conductivities used by Robinson and others (1997) for the basewide flow model. The higher calibrated values for the AOC A model are the result of data collected from additional wells and the EnSafe, Inc., aquifer test that indicates hydraulic conductivities of the alluvial-fluvial deposits aquifer at AOC A are higher than the value of about 5 ft/d assumed to be representative of this aquifer by Robinson and others (1997). Additionally, the areal and vertical distribution of hydraulic conductivities at AOC A are now better understood on the basis of additional data collected since 1997.

The ratio of horizontal to vertical hydraulic conductivity (VANI) for the calibrated AOC A flow model is 100. This ratio is supported by horizontal and vertical hydraulic-conductivity data presented in Robinson and others (1997, tables 2 and 3).

The AOC A flow model calibrated recharge rate is 1.82 in/yr. This recharge rate is higher than the natural recharge rate of 0.32 in/yr used in the basewide ground-water model by Robinson and others (1997). The basewide model also included anthropogenic recharge in some areas at rates between 0.67 and 1.8 in/yr. The AOC A area, however, had no anthropogenic recharge applied in the basewide model. Differences in these recharge rates are discussed in the section “Model Limitations.” This recharge rate of 1.82 in/yr results in a ground-water flux of 0.31 ft^3/s through the model. This is the total flux through the model because recharge is the only source of water for the model. All water leaves the model through the constant-head boundary near the northwestern edge of the model area.

Many of the estimated parameters for the calibrated AOC A flow model show high correlation coefficients (table 5).

Table 4. Calibrated hydraulic conductivities of the Area of Concern A flow model, Naval Support Activity Mid-South

	Calibrated hydraulic conductivity, in feet per day			
	HK_Average	HK_High	HK_ScarpA	HK_ScarpB
Layer 1	3.6	16	1.2	8.0
Layer 2	7.3	32	1.2	8.0
Layer 3	15	65	1.2	8.0

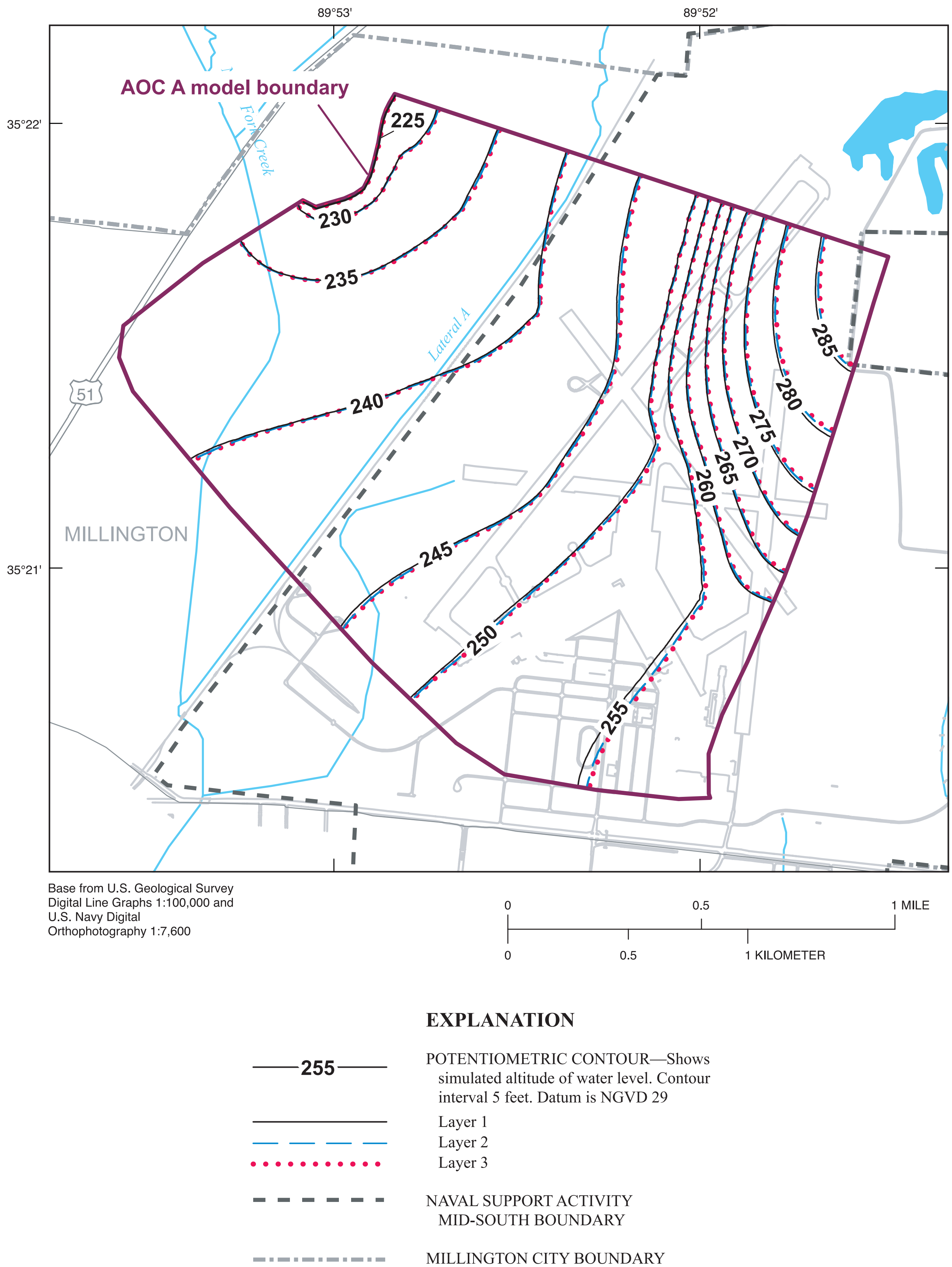

Figure 14. Simulated steady-state water levels for layers 1, 2, and 3 of the Area of Concern (AOC) A flow model, Naval Support Activity Mid-South, Millington, Tennessee.

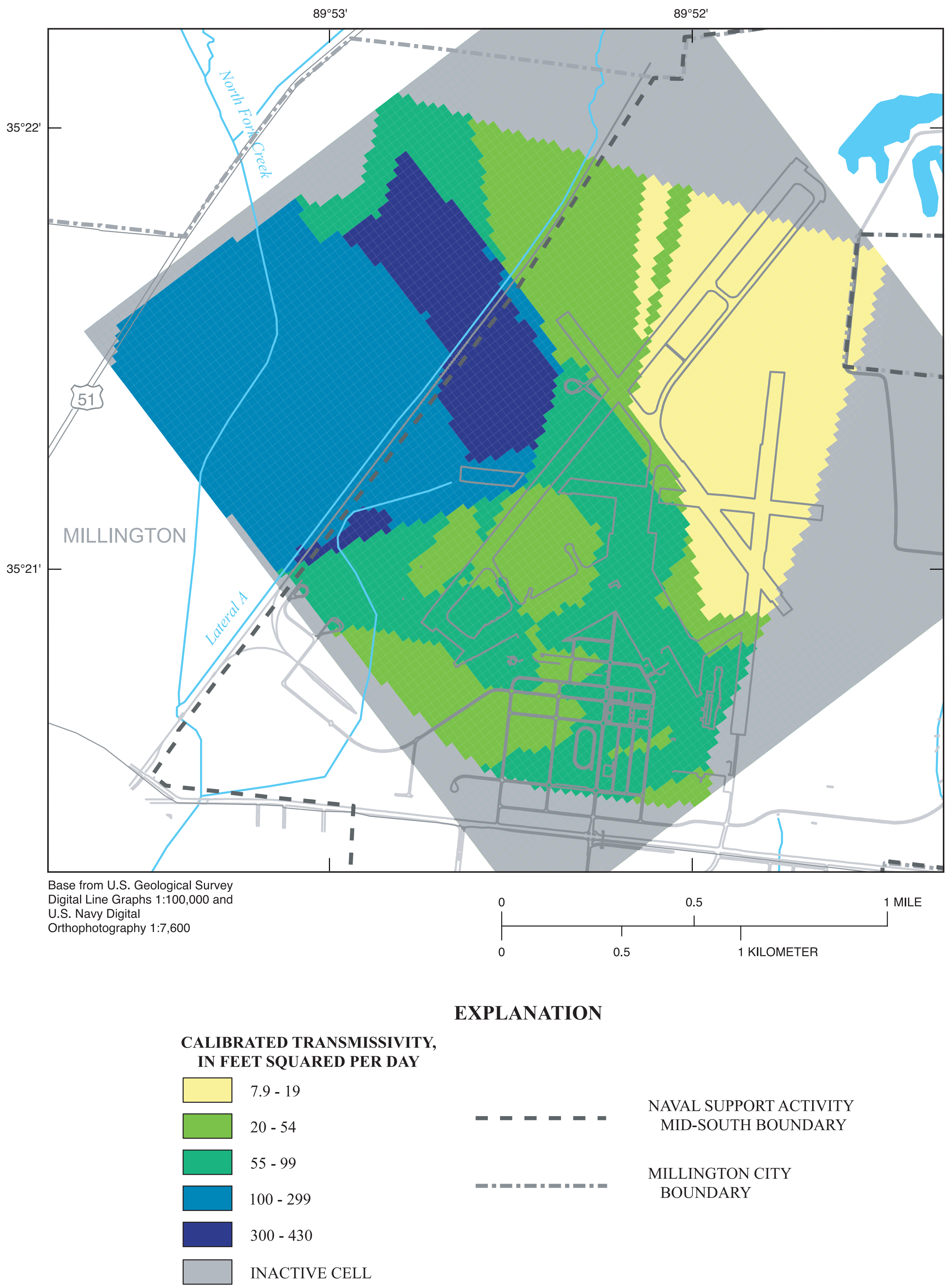

Figure 15. Calibrated transmissivities for layer 1 of the Area of Concern (AOC) A flow model, Naval Support Activity Mid-South, Millington, Tennessee.

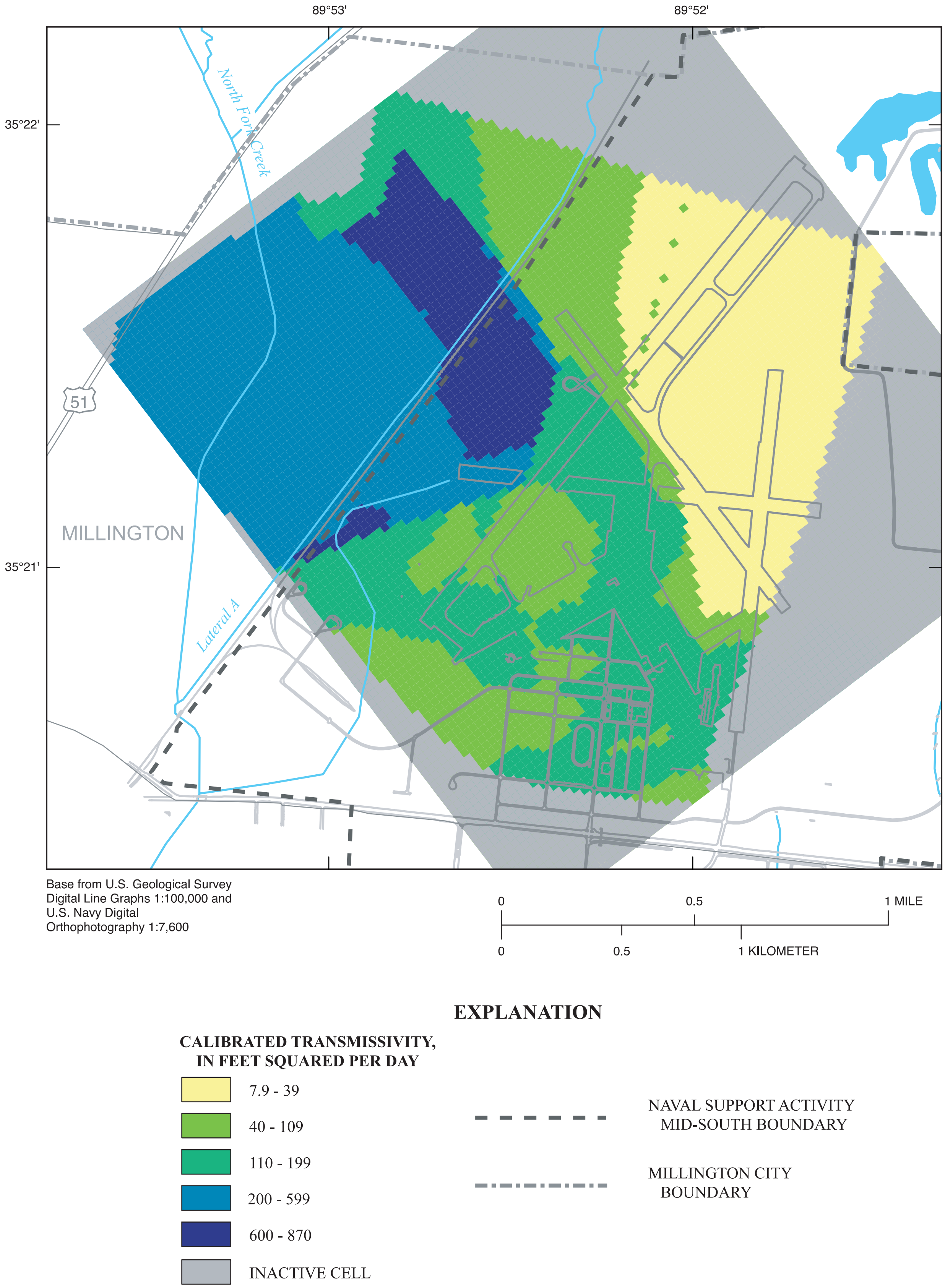

Figure 16. Calibrated transmissivities for layer 2 of the Area of Concern (AOC) A flow model, Naval Support Activity Mid-South, Millington, Tennessee.

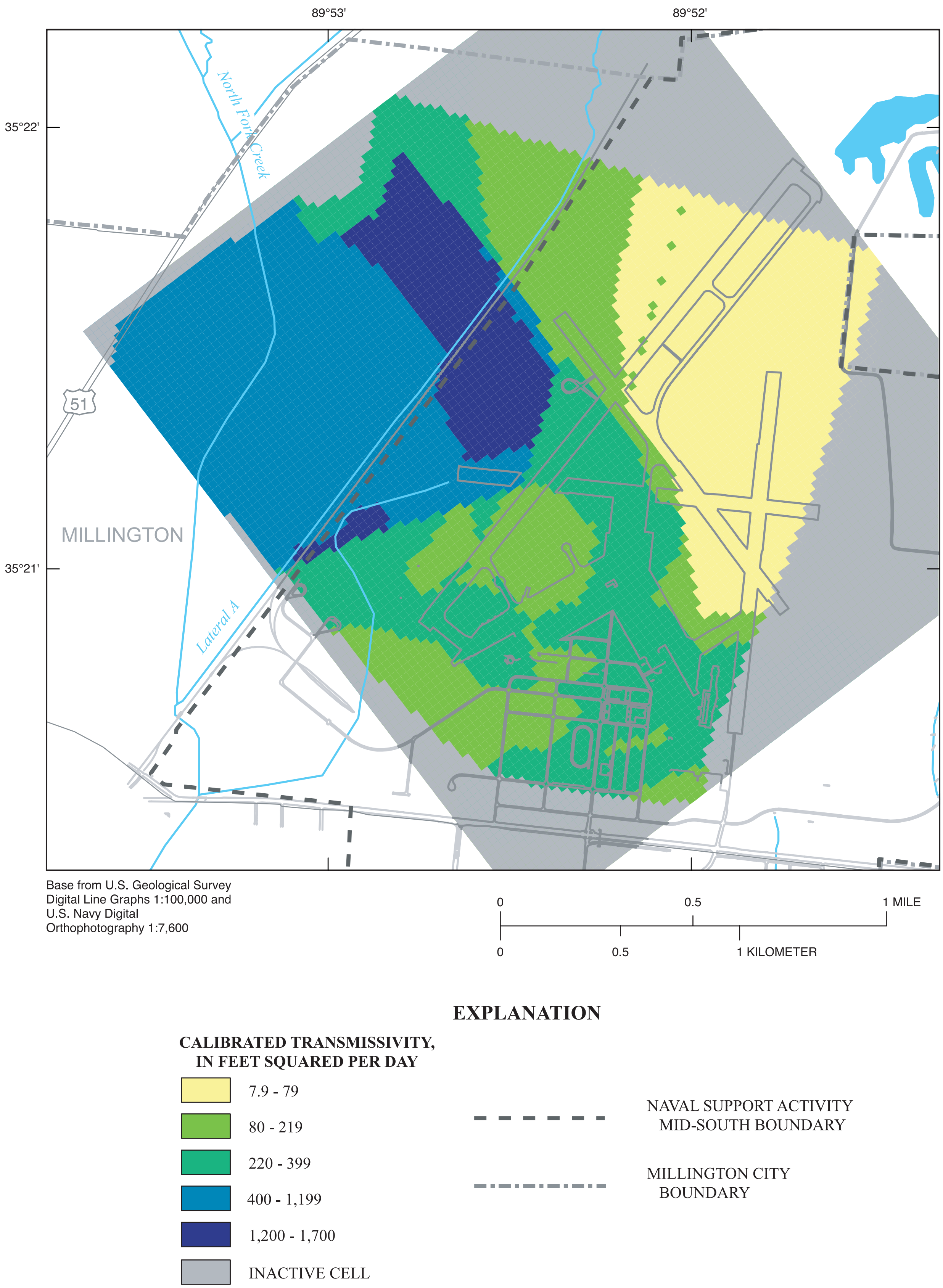

Figure 17. Calibrated transmissivities for layer 3 of the Area of Concern (AOC) A flow model, Naval Support Activity Mid-South, Millington, Tennessee.

Table 5. Correlation coefficients between estimated parameters of the Area of Concern A flow model, Naval Support Activity Mid-South

Estimated parameters	Correlation coefficients			
	RECH	HK_High	HK_Average	HK_ScarpA
RECH	1.00			
HK_High	0.97	1.00		
HK_Average	0.98	0.91	1.00	
HK_ScarpA	0.98	0.95	0.96	1.00

When parameters are correlated, the parameter-estimation process may not have enough information to estimate parameters individually and may estimate only the ratio or sums of parameters. To determine if the parameters were uniquely estimated, the parameter estimation was run from several different sets of starting parameter values. In each case, the regression converged to the same final values. This result indicates that the final values probably were estimated individually. Testing during model calibration indicates that without the advective-flow observation, parameters could not have been estimated individually.

Sensitivity Analysis

Composite scaled sensitivities were calculated for the calibrated AOC A flow model by using the sensitivity process in MODFLOW-2000 for all the hydraulic-conductivity and recharge parameters (fig. 18). Hill and others (2000) describe how sensitivities can be calculated for any of the model parameters discussed by Harbaugh and others (2000). Composite scaled sensitivities can be used to compare the importance of different parameters to the calculation of model simulated water levels and flows (Hill, 1998). Parameters with greater composite sensitivities have greater importance and influence on the model solution. The most sensitive parameter in the AOC A flow model is the recharge rate (RECH). The next most sensitive parameter is the hydraulic conductivity for the average zone (HK_Average), followed by the hydraulic conductivity for the high zone (HK_High). The model is least sensitive to the hydraulic conductivity in the scarp area (HK_ScarpA and HK_ScarpB) and the ratio of horizontal to vertical hydraulic conductivity (VANI).

Model Limitations

The AOC A flow model is calibrated as a steady-state model to water levels measured in the study area in February and March 2000. These measurements are assumed to be representative of long-term average conditions; however, not enough long-term water-level data exist for the study area to define the actual long-term average conditions. The flow paths investigated in the study area are estimated to be about 40 years old, but continuous water-level data are available for only about 9 years at well Sh:U-101 screened in the fluvial deposits at AOC A (fig. 8). If conditions in the aquifer have changed significantly over the past 40 years, the model flow field may not be representative of long-term conditions in the aquifer. The hydrograph shows no obvious trends, increasing or decreasing, in water levels for the period of record. Overall, water levels for the February and March 2000 map are about 3 ft lower than the average of the water levels for April and October 1996 that were used by Robinson and others (1997) to calibrate the basewide model, but the horizontal gradients across the study area are similar. Therefore, the assumption that the aquifer is at steady state is considered adequate to investigate flow paths within the study area.

The AOC A model is consistent with the current conceptual model of ground-water flow and assumed boundary conditions. However, the model, by necessity, is a simplified approximation of the actual ground-water system at AOC A. For example, the model simulates known variations in hydraulic conductivity, both areally and with depth, by using four hydraulic-conductivity zones and three layers, but this representation of the aquifer still is a simplification of the actual spatial variations and patterns of aquifer properties. Similarly, the model uses a uniform recharge rate to simulate water leakage through the loess. The actual recharge rate probably varies spatially, but the processes that control water movement through the loess are poorly understood; therefore, the spatial pattern of recharge was assumed to be uniform. Additionally, the model cannot provide simulations on a scale finer than the grid resolution.

The model provides a reasonable match to measured water levels and gradients (figs. 7 and 14), but no independent check on the model flux (recharge or discharge) is available. This lack of an independent check on model flux is the most important limitation of the flow model. Robinson and others (1997,

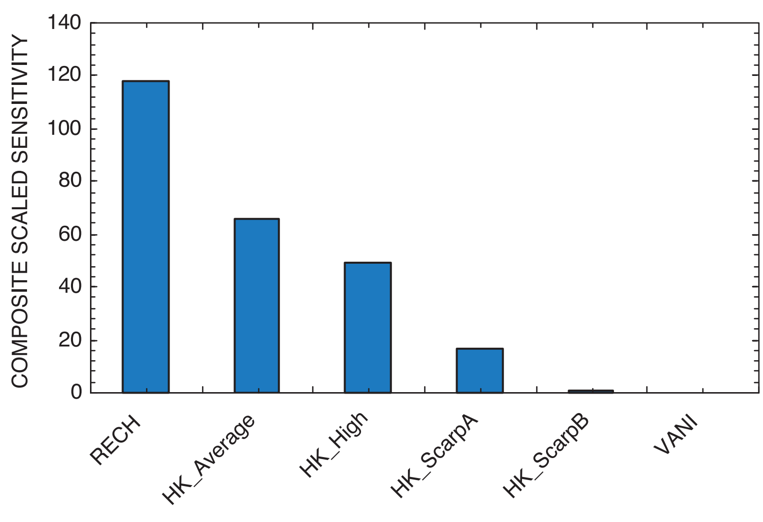

Figure 18. Composite scaled sensitivities for Area of Concern (AOC) A flow model parameters, Naval Support Activity Mid-South, Millington, Tennessee.

p. 45-46) clearly explain this limitation with the basewide model. With no independent measurement of the recharge flux, any constant ratio of recharge flux and hydraulic conductivity will produce the same simulated potentiometric surface. Therefore, in both of these models, the calibrated value of recharge is directly dependent on the values and distribution of hydraulic conductivity. This explains why the AOC A model presented in this report has a higher value of recharge (1.82 in/yr) than that used for the AOC A area of the basewide model (0.32 in/yr) of Robinson and others (1997). The basewide model assumed a constant hydraulic conductivity of about 5 ft/d for the alluvial-fluvial deposits aquifer based on the aquifer test conducted south of the western end of the airfield apron. Additional data and well tests indicated that the hydraulic conductivity in parts of the alluvial-fluvial deposits aquifer at AOC A is higher than 5 ft/d. The basewide model underestimated the hydraulic conductivity at AOC A and therefore underestimated the recharge rate. Given that the hydraulic-conductivity values and distribution have been better defined at AOC A since 1997, the calibrated recharge rate of 1.82 in/yr should be a more realistic estimate of recharge for the area, but this estimate still is limited by the confidence in the hydraulic-conductivity data.

The advective-flow observation helps overcome the lack of ground-water flux data and allows the conductivity and recharge parameters to be estimated individually. Although the mapped contaminant plume clearly defines the advective flow path, the estimate of the advective travel time is uncertain. The exact time when the contaminants were released to the aquifer is unknown. Other factors such as dispersion, retardation, and degradation affect travel times, causing the contaminants to move faster or slower than the ground water. An advective travel time of 40 years used to calibrate the AOC A model is consistent with all known data and results in estimates of parameters that are within expected ranges. If the advective travel time is actually 30 years, then the model would converge to higher parameter values for hydraulic conductivity and recharge, but the ratio of conductivity to recharge remains constant. Similarly, if the advective travel time is actually 50 years, then the model would converge to lower parameter values for hydraulic conductivity and recharge (table 6).

Advective Flow Particle Tracking

Ground-water-flow paths were simulated from two sites at AOC A suspected as being contaminant-plume source areas. The sites simulated as source areas are the “grassy area” and the “north edge of apron” (fig. 19). MODPATH, a particle-tracking program (Pollock, 1994), was used to simulate ground-water-flow directions and times-of-travel from these areas. The particle-tracking analysis does not account for physical and chemical processes such as dispersion, sorption, or degradation that would cause dissolved contaminants to move at velocities different from the average ground-water velocity. A contaminant plume, as the result of dispersion, also would spread out more than the advective flow paths indicated. A uniform effective porosity of 25 percent was assumed for the particle-tracking analysis conducted for this study (Robinson and others, 1997). The flow paths indicated by the particle tracking (fig. 19) agree reasonably well with the interpreted maps of TCE plumes (fig. 3). The time-of-travel plots show that travel times from the north edge of the apron area source to the model boundary are faster than travel times from the grassy area source to the same boundary. Particles originating at the north edge of the apron area source enter the high hydraulic conductivity zone of the A1 aquifer sooner than particles originating from the grassy area source, which decreases their travel time to the boundary. This simulation illustrates how the distribution of hydraulic conductivities can affect travel times.

Table 6. Estimated parameter values using alternate advective travel times, Area of Concern A flow model, Naval Support Activity Mid-South

Parameter	Advective travel times		
	30 years	40 years	50 years
RECH (inches)	2.47	1.86	1.49
HK_High (feet/day)	86.3	65.0	52.0
HK_Average (feet/day)	19.3	14.6	11.6
HK_ScarpA (feet/day)	1.57	1.17	0.929

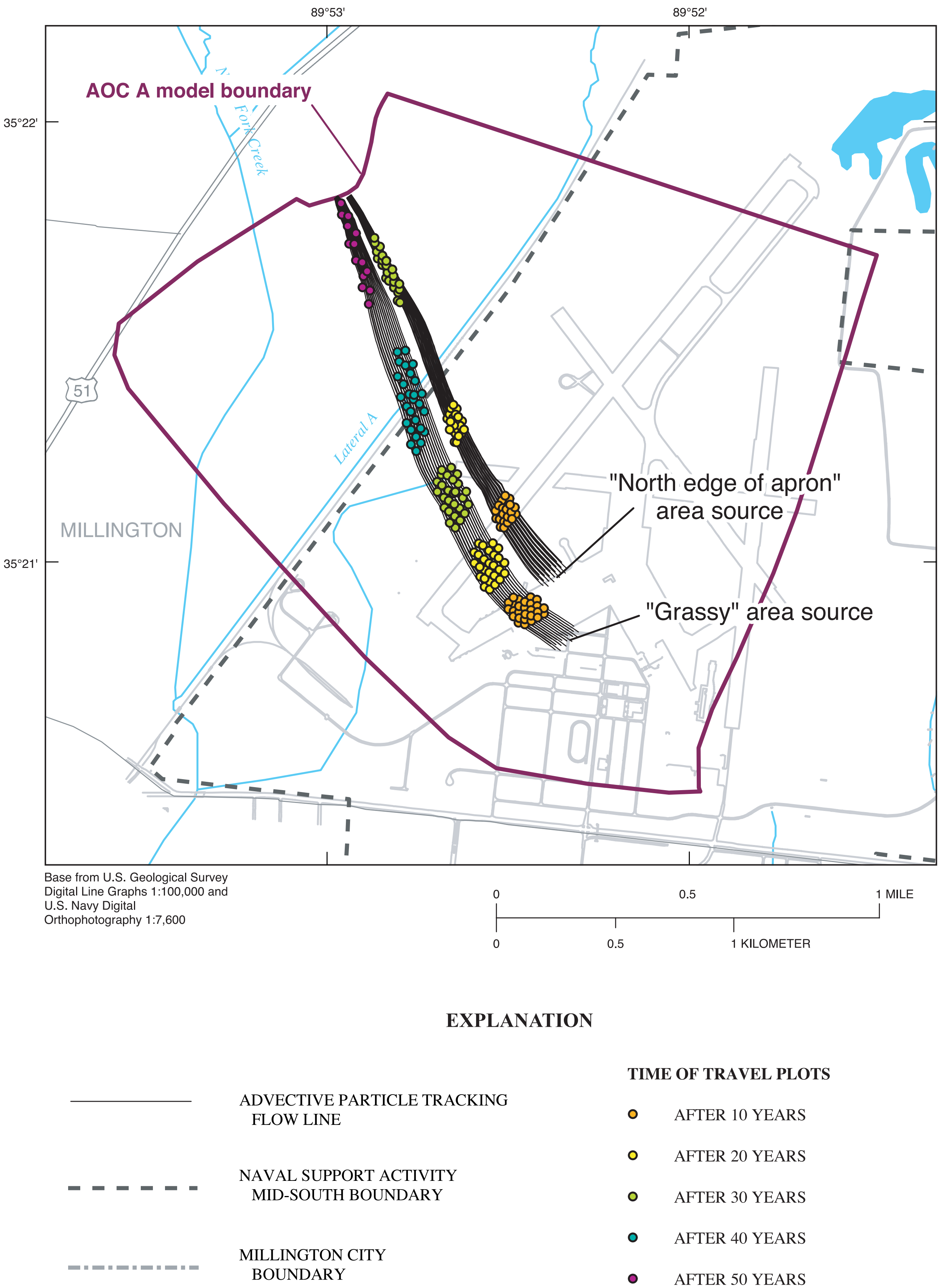

Figure 19. Advective flow path lines from the "grassy" area and "north edge of apron" area at Area of Concern (AOC) A, Naval Support Activity Mid-South, Millington, Tennessee.

Summary and Conclusions

Naval Support Activity (NSA) Mid-South is a Department of the Navy base located in Millington, Tennessee. During environmental investigations at the base, plumes of dissolved chlorinated solvents resulting from past aircraft maintenance and training operations were identified in shallow ground water beneath the airfield area. The area containing the plumes has been designated as Area of Concern (AOC) A. Chlorinated solvents, primarily trichloroethene, are the principal contaminants in the ground water at AOC A. The nature and extent of the primary plumes at AOC A were addressed during a Resource Conservation and Recovery Act (RCRA) Facility Investigation (RFI), and selected options for remediation currently (2004) are being implemented under a corrective action program.

Geologic units of primary importance to hydrogeologic investigations conducted under the RFI at AOC A include the alluvium, loess, fluvial deposits, and Cockfield Formation. Saturated and hydraulically connected sections of the lower, coarse-grained part of the alluvium and the fluvial deposits constitute the alluvial-fluvial deposits aquifer, the primary part of the shallow aquifer at NSA Mid-South. Within the AOC A study area, the alluvial-fluvial deposits aquifer is interpreted as comprising only the fluvial deposits because the coarse-grained lower part of the alluvium is absent beneath the middle and upper reaches of the alluvial valleys of North Fork Creek and its tributary Lateral A located in the western part of the area. The upper, fine-grained sections of the alluvium and loess generally retard recharge to and serve as the upper confining unit for the alluvial-fluvial deposits aquifer, and clay in the Cockfield Formation and underlying Cook Mountain Formation serve as the lower confining unit for the aquifer and the upper confining unit for the Memphis aquifer. Discontinuous saturated sand lenses are present locally in the Cockfield Formation and constitute the Cockfield aquifer. Within the AOC A study area, the alluvial-fluvial deposits and Cockfield aquifers are interpreted as hydraulically connected across an erosional scarp in the Cockfield Formation located in the northern part of the area.

Recent investigations at and near the facility have produced new data prompting updates to two USGS reports published in 1997. The updates consist primarily of (1) refinements to geologic structure maps presented in the 1997 reports that show the altitude of the base of the loess or silt and clay in the upper alluvium, and the altitude of the base of sand and gravel in the lower alluvium or fluvial deposits at AOC A on the basis of data collected from new wells at on- and off-base locations; (2) additional hydraulic-conductivity data for the alluvial-fluvial deposits aquifer at AOC A from a multiple-well, 24-hour constant-rate-withdrawal aquifer test conducted by EnSafe, Inc., in 1999; and (3) construction of a potentiometric-surface map of the A1 aquifer for the northern part of the NSA Mid-South area for February and March 2000 water-level conditions. As part of the study, the USGS also developed and calibrated a numerical ground-water-flow model of AOC A.

A steady-state model of the shallow aquifer at AOC A was constructed and calibrated to conditions of February and March 2000. Following model calibration, a particle-tracking simulation was used to analyze ground-water-flow paths and time-of-travel from selected locations suspected as being contaminant source areas within AOC A. The modeled aquifer, designated as the A1 aquifer for a previous modeling study at NSA Mid-South, consists of the alluvial-fluvial deposits aquifer within most of the modeled area and the upper part of the Cockfield aquifer in the scarp area and to the northeast. The A1 aquifer in this study was divided into three layers to simulate vertical variations in lithology and hydraulic conductivity in the fluvial deposits. Horizontal hydraulic conductivity of the alluvial-fluvial deposits aquifer at AOC A increases with depth; therefore, in areas where the A1 aquifer consists of the alluvial-fluvial deposits aquifer, layer 1 has the lowest hydraulic conductivity and layer 3 has the highest hydraulic conductivity. In the scarp area and to the northeast, where the alluvial-fluvial deposits are unsaturated and the A1 aquifer consists of the upper part of the Cockfield aquifer, hydraulic conductivity is assumed to be constant with depth. Recharge to the modeled aquifer occurs as leakage from the overlying loess. Ground water does not discharge to streams or springs anywhere in the model area. Ground water leaves the modeled area through a constant head boundary at the 225-ft potentiometric contour that defines a depression in the potentiometric surface in the alluvial-fluvial deposits aquifer. This constant-head boundary is near an area where the alluvial-fluvial deposits aquifer thickens and the Cockfield Formation thins. Downward leakage of water locally occurs from the alluvial-fluvial deposits aquifer through the Cockfield and Cook Mountain confining units and is indicated by observed water levels in the alluvial-fluvial deposits aquifer in this depression that are approximately equal in altitude to water levels in the Memphis aquifer in this area.

The model developed for this study was calibrated to steady-state conditions as defined by the potentiometric-surface map for February and March 2000. The model was calibrated to observed water levels and measured hydraulic-conductivity values. To provide additional information to help calibrate the model, an advective-flow observation was added. Overall, simulated water levels agree reasonably well with measured water levels. Water levels were available for comparison at 68 wells. The RMSE for water levels is 1.1 ft. The average difference between measured and simulated heads for the calibrated model is 0.04 ft.

Calibrated horizontal hydraulic conductivities for the AOC A flow model range from 1.2 to 65 ft/d. The calibrated hydraulic conductivities used in the AOC A model are greater than the value of 5.3 ft/d used for the "basewide" model of NSA Mid-South calibrated in 1996. The higher calibrated values for the AOC A model are the result of data from the 1999 aquifer test that indicate hydraulic conductivities in parts of the alluvial-fluvial deposits aquifer at AOC A are higher than previously determined.

The AOC A flow model calibrated recharge rate is 1.82 in/yr. This recharge rate is higher than the natural recharge rate of 0.32 in/yr used in the basewide ground-water model. The higher recharge rate also is the result of hydraulic conductivity values being higher in the AOC A study area than previously determined.

The model provides a reasonable match to measured water levels and gradients, but no independent check on the model flux (recharge or discharge) is available. This lack of an independent check on model flux is the most important limitation of the flow model. With no independent measurement of the recharge flux, any constant ratio of recharge flux and hydraulic conductivity will produce the same simulated potentiometric surface. Given that the hydraulic conductivity values and distribution have been better defined within AOC A, the calibrated recharge rate of 1.82 in/yr should be a more realistic estimate of recharge for the area, but this estimate still is limited by the confidence in the hydraulic-conductivity data.

Many of the estimated parameters for the calibrated AOC A flow model show high correlation coefficients. Testing during model calibration indicates that without the advective-flow observation, parameters could not have been estimated individually. The advective-flow observation helps overcome the lack of ground-water flux data and allows the hydraulic conductivity and recharge parameters to be estimated individually. The most sensitive parameter in the AOC A flow model is the recharge rate (RECH). The next most sensitive parameter is the hydraulic conductivity for the average zone (HK_Average), followed by the hydraulic conductivity for the high zone (HK_High).

Ground-water-flow paths were simulated from two suspected contaminant-plume source areas at AOC A. The sites simulated as source areas are the “grassy area” and the “north edge of apron” area. The flow paths indicated by the particle tracking agree reasonably well with the interpreted maps of TCE plumes. The time-of-travel plots show that travel times from the north edge of the apron source to the model boundary are faster than travel times from the grassy area source to the same boundary.

Selected References

Anderman, E.R., and Hill, M.C., 1997, Advective-transport observation (ADV) package, a computer program for adding advective-transport observations of steady-state flow fields to the three-dimensional ground-water flow parameter-estimation model MODFLOWP: U.S. Geological Survey Open-File Report 97-14, 67 p.

Carmichael, J.K., Parks, W.S., Kingsbury, J.A., and Ladd, D.E., 1997, Hydrogeology and ground-water quality at Naval Support Activity Memphis, Millington, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 97-4158, 64 p.

Frederiksen, N.O., Bybell, L.M., Christopher, R.A., Crone, A.J., Edwards, L.E., Gibson, T.G., Hazel, J.E., Repetski, J.E., Russ, D.P., Smith, C.C., and Ward, L.W., 1982, Biostratigraphy and paleoecology of lower Paleozoic, upper Cretaceous, and lower Tertiary rocks in U.S. Geological Survey New Madrid test wells, southeastern Missouri: Tulane Studies in Geology and Paleontology, v. 17, no. 2, p. 23-45.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, The U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Hill, M.C., 1998, Methods and guidelines for effective model calibration: With application to UCODE, a computer code for universal inverse modeling, and MODFLOWP, a computer code for inverse modeling with MODFLOW: U.S. Geological Survey Water-Resources Investigations Report 98-4005, 90 p.

Hill, M.C., Banta, E.R., Harbaugh, A.W., and Anderman, E.R., 2000, MODFLOW-2000, The U.S. Geological Survey modular ground-water model—User guide to the observation, sensitivity, and parameter-estimation processes and three post-processing programs: U.S. Geological Survey Open-File Report 00-184, 209 p.

Kingsbury, J.A., and Carmichael, J.K., 1995, Hydrogeology of post-Wilcox Group stratigraphic units in the area of Naval Air Station Memphis, near Millington, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 95-4011, 1 sheet.

Kingsbury, J.A., and Parks, W.S., 1993, Hydrogeology of the principal aquifers and relation of faults to interaquifer leakage in the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 93-4075, 18 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: Techniques of Water-Resources Investigations of the United States Geological Survey, book 6, chap. A1, 576 p.

Moore, G.K., and Brown, D.L., 1969, Stratigraphy of the Fort Pillow test well, Lauderdale County, Tennessee: Tennessee Division of Geology Report of Investigations 26, 1 sheet.

Parks, W.S., 1990, Hydrogeology and preliminary assessment of the potential for contamination of the Memphis aquifer in the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 90-4092, 39 p.

Parks, W.S., and Carmichael, J.K., 1989, Geology and ground-water resources of the Fort Pillow Sand in western Tennessee: U.S. Geological Survey Water-Resources Investigations Report 89-4120, 20 p.

Parks, W.S., and Carmichael, J.K., 1990, Geology and ground-water resources of the Cockfield Formation in western Tennessee: U.S. Geological Survey Water-Resources Investigations Report 88-4181, 17 p.

Pollock, D.W., 1994, User’s guide for MODPATH/MODPATH-PLOT, version 3: A particle tracking post-processing package for MODFLOW, the U.S.Geological Survey finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94-464, variously paginated.

Robinson, J.L., Carmichael, J.K., Halford, K.J., and Ladd, D.E., 1997, Hydrogeologic framework and simulation of ground-water flow and travel time in the shallow aquifer system in the area of Naval Support Activity Memphis, Millington, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 97-4228, 56 p.