wells and may reflect localized drawdown cones rather than regional declines. Also, these declines are small relative to the overall saturated thickness of the aquifer. Unfortunately, there are no long-term water-level data from the Navajo or Kayenta aquifer observation wells to show historical trends. Therefore, only steady-state models were developed for the main and Gunlock parts of the Navajo and Kayenta aquifers. The most recent year for which complete well discharge information was available was 1995. Water levels in wells were measured in 1996 and additional measurements were acquired in 1997 to fill in gaps. To evaluate the use of 1995 pumpage and 1996 to 1997 water levels for the steady-state model, February and March 1996 water levels were compared to measurements at 9 wells measured in February and March 1995 and 38 wells measured during June and July 1995. The average difference for the nine wells measured in February and March 1995 was a 1.6-ft decline in water levels, ranging from a rise of 2.5 ft to a decline of 12.8 ft. The average difference for the 38 wells measured in June and July 1996 was a 2.9-ft rise in water levels, ranging from a rise of 44.5 ft to a decline of 10.0 ft (Wilkowske and others, 1998, table 2). However, as stated earlier, most of the measured wells were production wells, so the larger changes (plus or minus more than 5 ft) were likely due to effects of seasonal pumping. Thus, while not ideal, the baseline simulation for the main Navajo-Kayenta model represents average conditions for the period 1995 to 1997. Although pumping did increase in 1996 and 1997, the 1995 withdrawals were an acceptable long-term average to try and represent in a steady-state simulation.

Main Part of the Navajo and Kayenta Aquifers

The ground-water flow model developed for the main part of the Navajo and Kayenta aquifers includes the area west of the Hurricane Fault and east of the Gunlock Fault where the Navajo Sandstone and Kayenta Formation are exposed, as well as an area extending up to 4 mi north of the Navajo Sandstone/Carmel Formation contact, where the formations are buried. The model was developed as a simplified representation of a complicated and extensive aquifer system. The approach was to create a baseline model with which to test various alternative conceptualizations of aquifer properties.

Model Characteristics and Discretization

The model is divided into 58 rows, 65 columns, and 2 layers with a total of 7,540 model cells (fig. 43). The model grid was designed to emphasize more detailed simulation of ground-water flow along the exposed outcrop part of the aquifers between the Hurricane Fault and Snow Canyon, where most hydrologic information is available. Therefore, the size of model cells ranges from about 2,000 ft by 2,000 ft along the center of the outcrop to about 2,000 ft by 5,000 ft along the northeast and the western parts of the simulation area. Layer 1 represents the Navajo aquifer and includes about 2,020 active cells simulating an area of about 330 mi^2. Layer 2 represents the Kayenta aquifer and includes about 2,340 active cells simulating an area of about 390 mi^2. The orientation of the grid was rotated clockwise about 10 degrees from true north so that the columns are parallel to the general orientation of predominant faulting and jointing.

The altitude of the base of layer 2 that represents the Kayenta aquifer is shown in figure 44. Generally this corresponds to altitudes 850 ft below the base of the Navajo Sandstone (Hurlow, 1998, pl. 5a), except where the base of the Kayenta aquifer is inferred to be lower than 1,850 ft below sea level in the northeast corner of the model. The saturated thickness of layer 1 ranges from 2,400 ft where the Navajo aquifer is confined by overlying formations towards the north, to less than 200 ft near its erosional extent. The saturated thickness of layer 2 ranges from 850 ft where the Kayenta aquifer is confined by overlying formations toward the north, to less than 200 ft near its erosional extent. A cross section of the model grid along column 20 shows the layer geometry used in the ground-water flow model (fig. 45).

Boundary Conditions

The hydrologic boundaries that represent the main part of the Navajo and Kayenta aquifers include no-flow boundaries, specified-flux boundaries, and head-dependent (general-head) boundaries. No-flow boundaries representing the erosional and fault-controlled extent of the aquifers are fairly well defined. However, other boundaries, such as those representing flow to and from underlying, adjacent, and overlying formations, are not well understood. In general, these underlying and overlying formations are represented by no-flow boundaries except where hydrologic or geochemical evidence indicates that ground water may be crossing these boundaries. Where the aquifers are

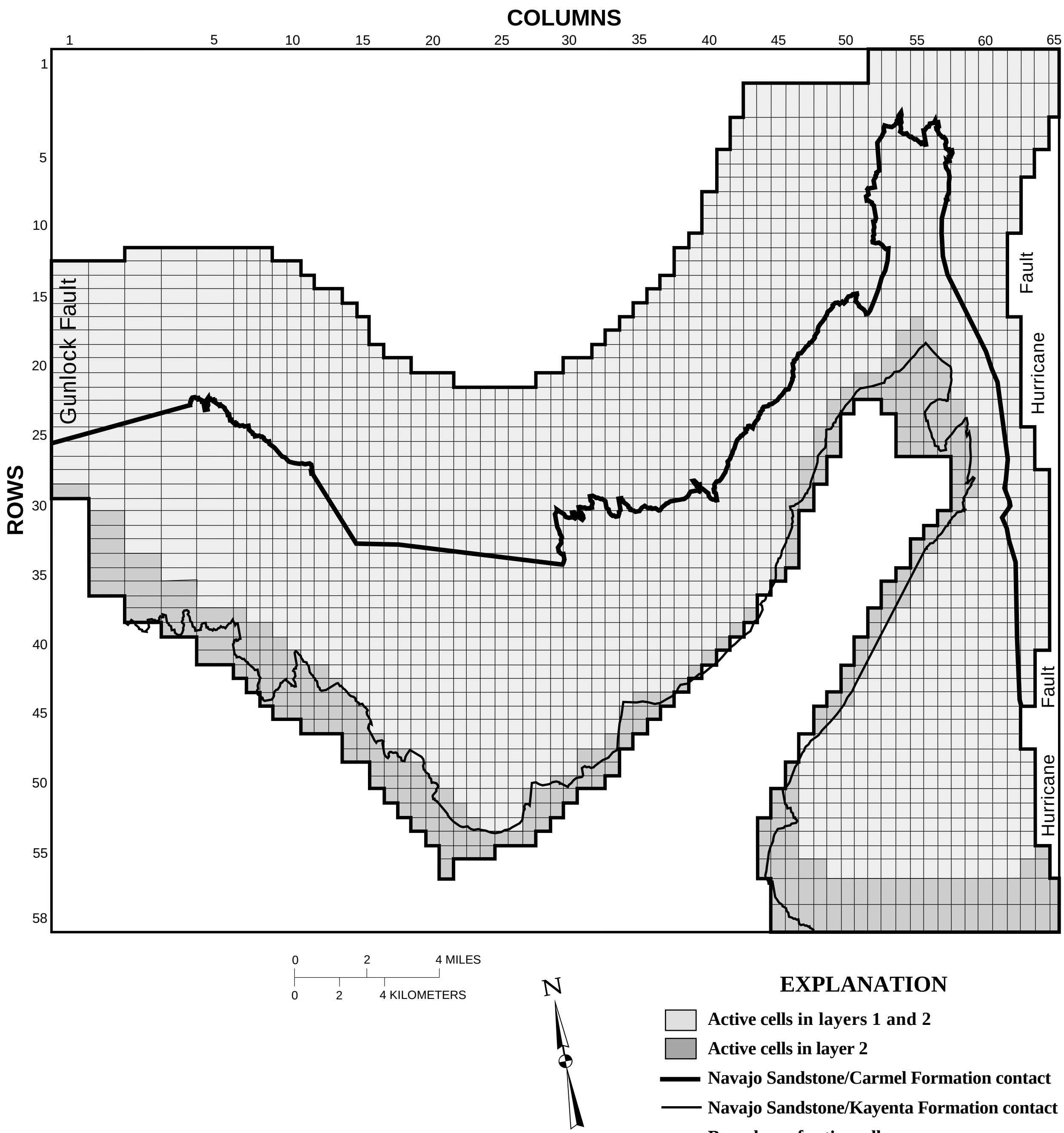

Figure 43. Model grid of the ground-water flow model of the main part of the Navajo and Kayenta aquifers within the central Virgin River basin study area, Utah.

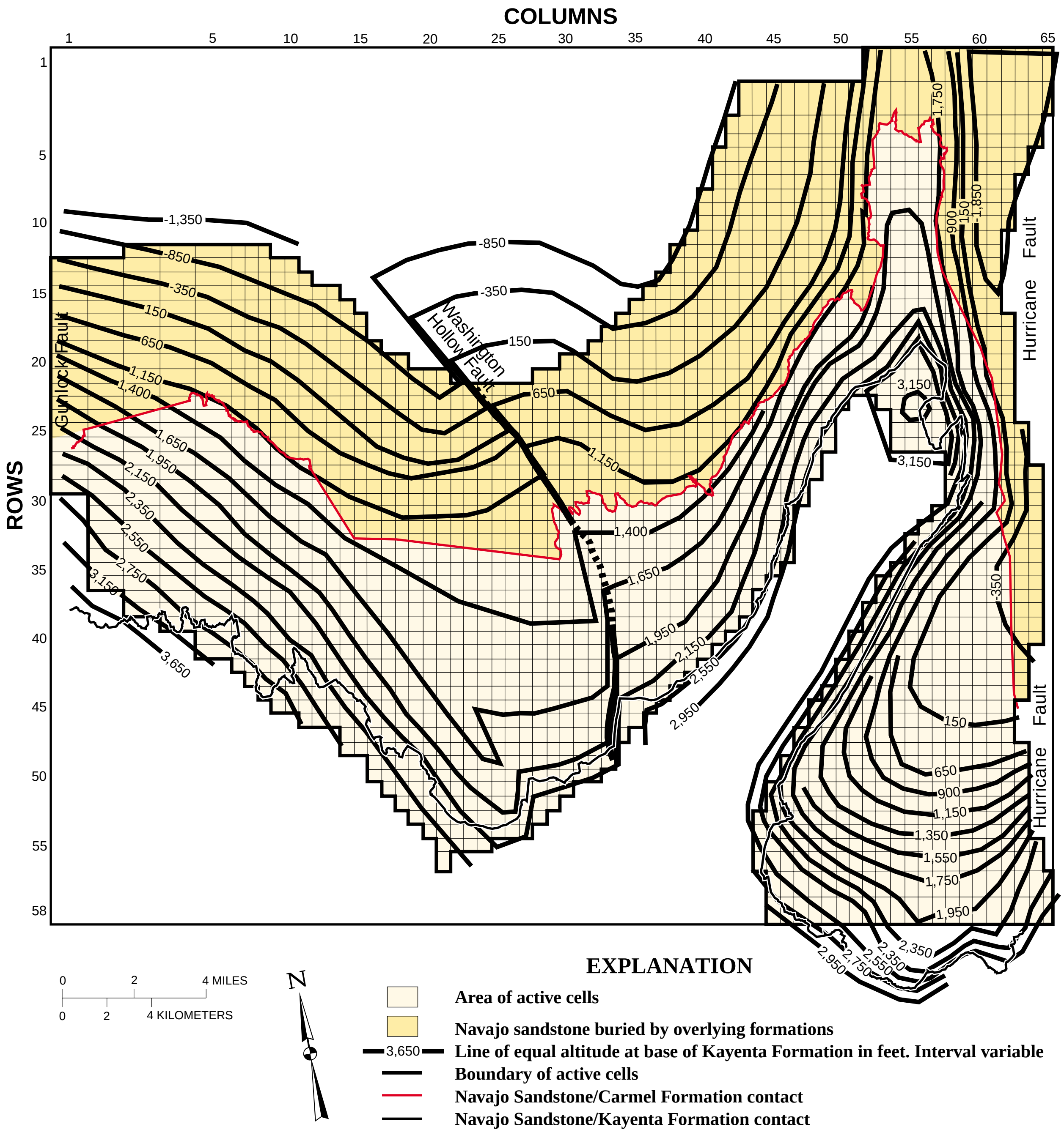

Figure 44. Altitude of the base level of layer 2, representing the base of the Kayenta Formation, in the ground-water flow model of the main part of the Navajo and Kayenta aquifers within the central Virgin River basin study area, Utah (Hurlow, 1998, pl. 5a).

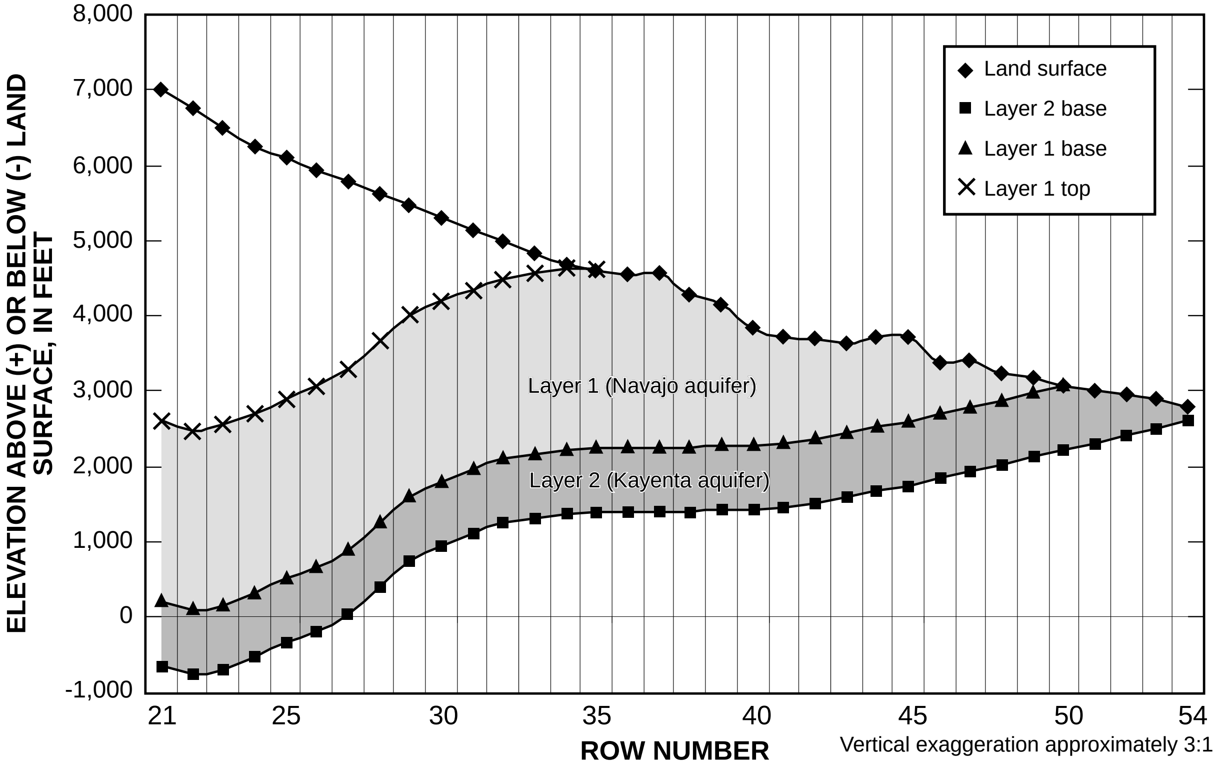

Figure 45. Generalized cross section along column 20 of the ground-water flow model of the main part of the Navajo and Kayenta aquifers within the central Virgin River basin study area, Utah.

unconfined along the Navajo Sandstone and Kayenta Formation outcrops, the water table generally is simulated as a recharge boundary to represent infiltration from precipitation, streams, and unconsumed irrigation water, but there are areas where the water table is simulated as a discharge boundary to represent spring discharge and seepage to the Virgin River.

Recharge Boundaries

The water table is simulated as a recharge boundary where the Navajo Sandstone and Kayenta Formation becomes fully saturated. The depth of this boundary could range from land surface to as much as 800 ft below land surface. Simulated sources of recharge along this boundary include infiltration from precipitation, perennial and ephemeral streams, and unconsumed flood-irrigation water. Recharge from underlying formations was simulated along parts of the base of layer 2 where higher dissolved-solids concentrations are contained within the Navajo and Kayenta aquifers.

Precipitation

Infiltration of precipitation was simulated with the recharge package at model cells that represent the outcrop of the Navajo Sandstone and the Kayenta Formation. The distribution of precipitation (fig. 3) was based on the average annual precipitation map (Utah Climate Center, 1996). Recharge from infiltration was initially specified as 10 percent of total annual precipitation. But as model refinement for the steady-state solution progressed, the percentage was increased along the part of the outcrop north of Anderson Junction where average annual precipitation exceeds 14 in/yr. A higher recharge rate was applied to this area because the Navajo Sandstone outcrop is more highly fractured and partially covered by more permeable alluvial material than elsewhere in the study area (Hurlow, 1998). The distribution of recharge from infiltration of precipitation simulated in the ground-water flow model is shown in figure 46.

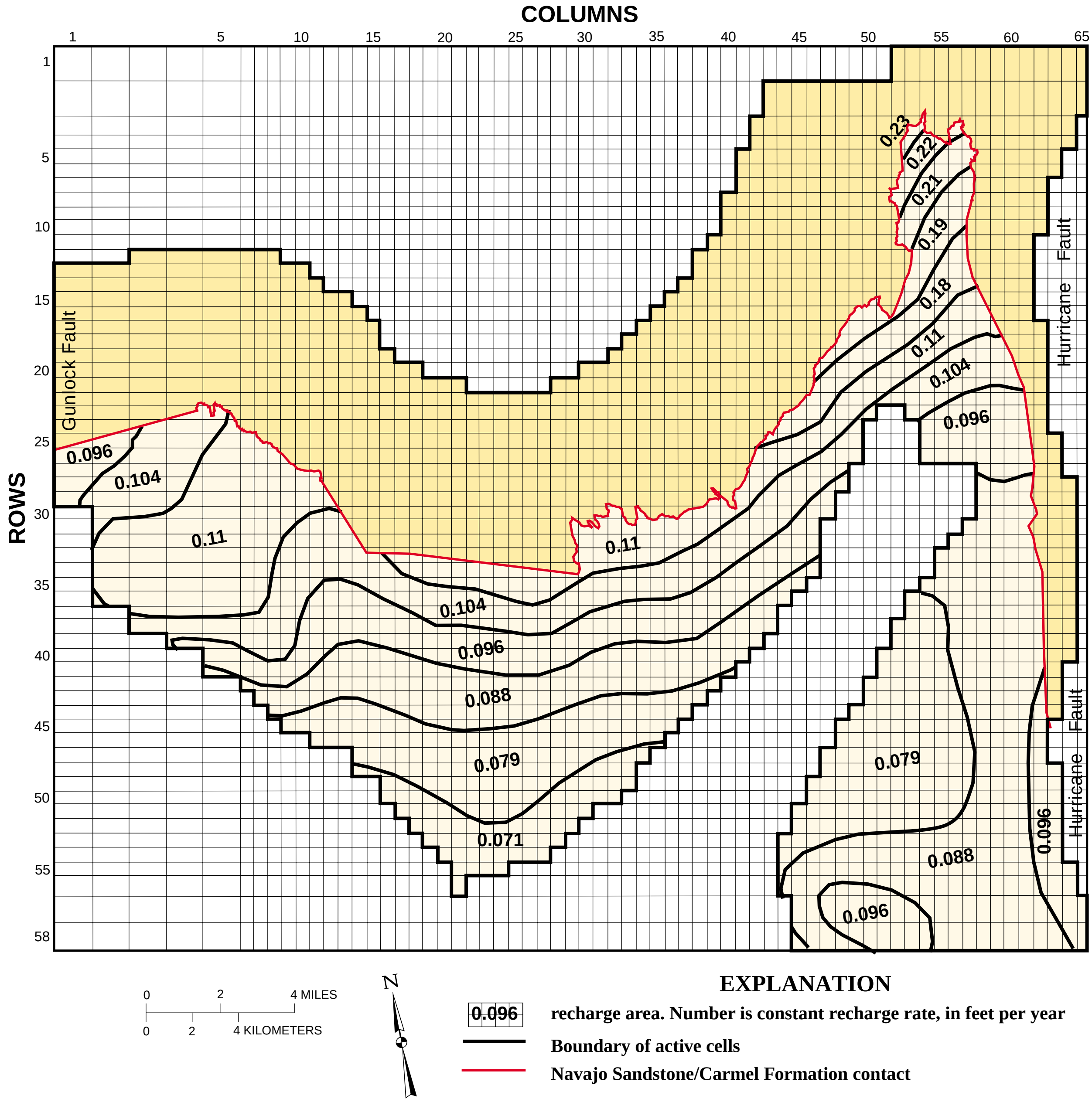

Figure 46. Distribution of recharge from infiltration of precipitation simulated in the ground-water flow model of the main part of the Navajo and Kayenta aquifers within the central Virgin River basin study area, Utah.

Streams

Recharge from perennial and ephemeral streams flowing along the Navajo Sandstone outcrop was simulated with the river package (fig. 47). When the water level in the aquifer is below the bottom of the stream, a constant amount of water is simulated to recharge the aquifer and is determined by the difference between the stream stage and the altitude of stream bottom multiplied by the vertical hydraulic conductivity of the streambed deposits. When the water level in the aquifer is between the stream-bottom altitude and the stream stage, simulated recharge to the aquifer is variable and depends on this head difference. When the water level in the aquifer is above the stream stage, the aquifer discharges water to the stream, depending on the difference between the stream stage and the aquifer water level. Therefore, the river package can either simulate recharge to or discharge from the aquifer.

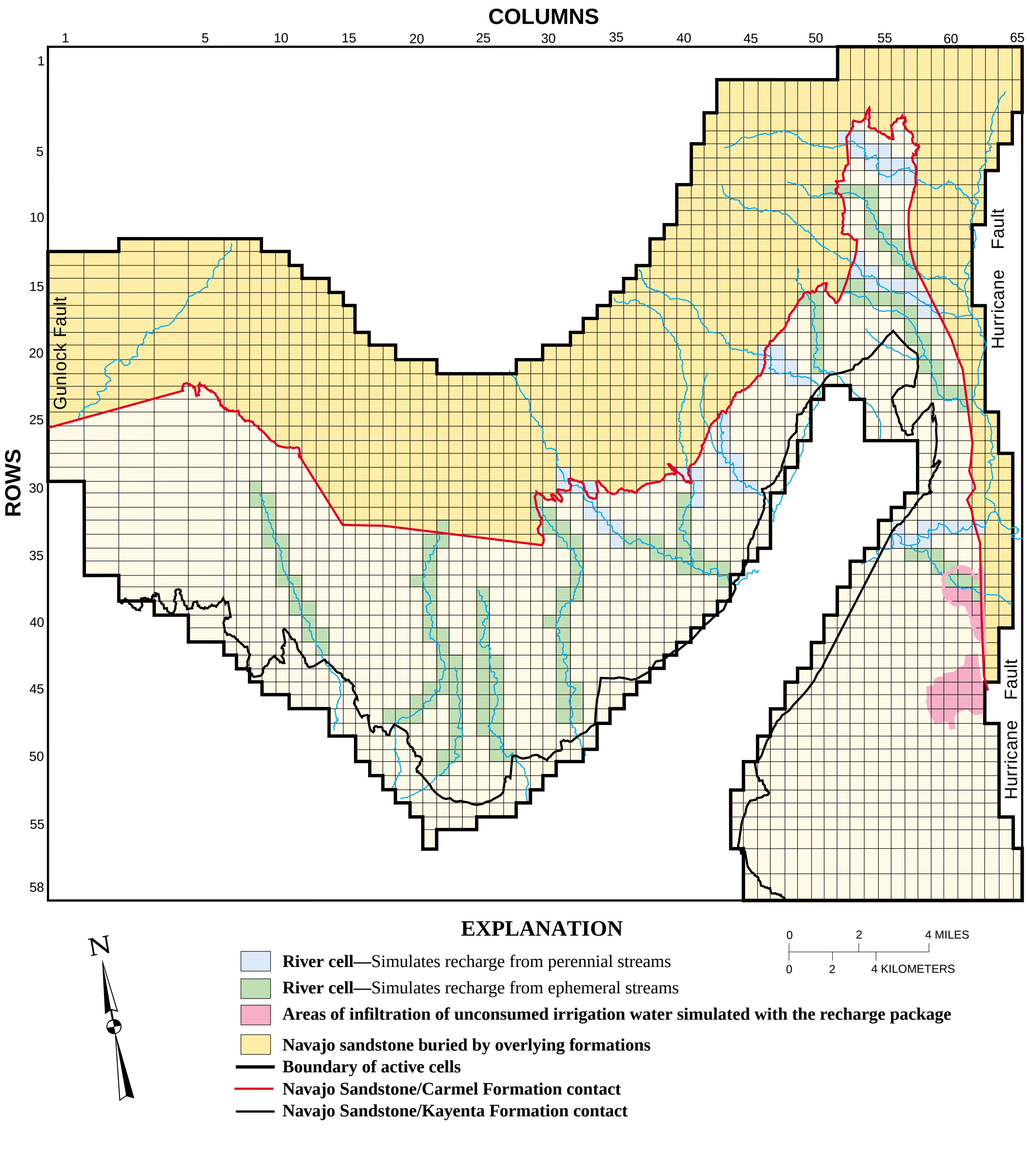

Figure 47. Distribution of recharge from streams and infiltration of unconsumed irrigation water simulated for layer 1 of the ground-water flow model of the main part of the Navajo and Kayenta aquifers within the central Virgin River basin study area, Utah.

The perennial streams that cross the Navajo Sandstone and Kayenta Formation outcrops within the study area are assumed to be in hydraulic connection with the water table. A test of the model's accuracy in representing the Navajo and Kayenta aquifers is its ability to simulate this surface-water/ground-water interaction. Therefore, it was important to evaluate whether stream reaches that are known to recharge water to the aquifer also simulate recharge in the model; conversely, streams reaches that are known to gain water from aquifer discharge are expected to simulate this flow. The model does simulate recharge along the same five stream reaches where seepage studies indicate recharge (South Ash Creek, Wet Sandy Creek, Leeds Creek, Quail Creek, and Cottonwood Creek) (table 11). Conversely, simulated discharge to the Virgin River is consistent with the seepage study done in November 1994 that indicated discharge from the Navajo and Kayenta aquifers (Herbert, 1995).

The simulated amount of recharge or discharge depends on the streambed conductance, the elevation of the streambed, the stream stage, and the head at the node in the cell underlying the stream. Streambed conductance is the product of the vertical hydraulic conductivity and the cross sectional area of the streambed divided by the thickness of the streambed. Field data on actual streambed conductance were not available. Therefore, for the five perennial creeks draining southeastward from the Pine Valley Mountains, an initial stream-bed conductance value of about 0.01 ft^2/d was assumed. This value represents a vertical hydraulic conductivity that is 1 to 2 orders of magnitude less than the estimated 2 ft/d horizontal hydraulic conductivity of the Navajo aquifer. The altitude of the stream assigned for each river cell was estimated from topographic maps with 40-ft contour intervals. On the basis of measurements made during seepage studies, the width of all five streams is estimated to be about 10 ft. The stream stage was originally estimated to be 2 ft above the bottom altitude of each stream reach. However, with these conductance values, simulated recharge was much less than measured recharge for all five streams. To more closely approximate measured recharge, stage was uniformly increased to 20 ft above the streambed elevation for all five streams. This was a simplistic way of increasing stream seepage to the aquifer and might not be appropriate for any other conditions or stresses on this system. A model intended for use as a predictive tool should be structured to more realistically depict this interaction between stream and aquifer. After these changes, simulated recharge rates along Leeds, Quail, and Cottonwood Creeks more closely approximated measured values. To closely approximate measured recharge along Wet Sandy and South Ash Creeks, the streambed conductance was increased five-fold and ten-fold, respectively, to 0.05 and 0.1 ft/d. This is consistent with surficial geologic studies, which indicate that the unconsolidated deposits along the streambeds north of Anderson Junction are coarser and more permeable (Hurlow, 1998).

Ephemeral streams that cross the Navajo Sandstone and Kayenta Formation outcrops within the study area are not assumed to be in hydraulic connection with the water table because of their sporadic nature. However, to allow prospective users of the model to keep line recharge mechanisms separate from aerial recharge mechanisms such as precipitation, the river package was chosen to simulate recharge from ephemeral streams. In this initial simulation, a constant flow was assumed for each ephemeral stream reach. To do this, the stream bottom and stage were assigned a higher altitude than the potentiometric surface of the aquifer and the stream stage was assigned a value 1 ft higher than the stream bottom. This allowed a constant flow to be specified on the basis of the streambed conductance and length of the reach. The total specified amount of ephemeral stream recharge for layer 1 was initially 4.1 ft^3/s (3,000 acre-ft/yr). This corresponds to the median values (assuming 10 percent infiltration) determined above from estimated annual stream discharge (method 1, table 13). However, to be consistent with the increased infiltration rates for precipitation north of Anderson Junction, the infiltration rate for Dry Sandy (the only ephemeral stream north of Anderson Junction) was increased to 15 percent, so that the total simulated recharge from ephemeral streams in layer 1 is 4.4 ft^3/s (3,200 acre-ft/yr).

Some recharge is assumed along the ephemeral streams north of where Leeds Creek crosses the Kayenta Formation outcrop. Assuming the same infiltration rates specified for the reaches that cross the Navajo Sandstone outcrop, an estimated 0.6 ft^3/s recharges the Kayenta aquifer along Anderson Junction and Grapevine Wash (fig. 48). Because the Kayenta aquifer to the south between Snow Canyon and Mill Creek is a major area of discharge, it is assumed that ephemeral streams along the Kayenta Formation outcrop in this southern area do not recharge the aquifer.

Underlying Formations

Recharge as seepage from underlying formations was simulated with the general-head package. This represents inflow of water with a higher dissolved-solids concentration assumed to come from the area north of St. George and southwest of Hurricane (fig. 22). The cells in layer 2 that simulate this recharge are shown in figure 48. The amount of simulated recharge is a function of (1) the head difference between the cell and a fixed head that represents the water level in the underlying formation and (2) the conductance of the material between the cell and the fixed-head location. Both of these parameters are very speculative for the two areas of higher dissolved-solids concentration because the potentiometric surface and the vertical hydraulic conductivity of the underlying formations in these areas are unknown. A conductance value of 2.5×10^{-5} (ft/d)/ft was assigned to both general-head boundary areas. This value was determined during model refinement and assumes that the hydraulic conductivity of the material between the Kayenta aquifer and the underlying formations was 2.5×10^{-3} ft/d, or about three orders of magnitude less than the estimated vertical hydraulic conductivity of layer 2. For both areas the fixed general head was assumed to be about 200 ft higher than the average head in the aquifer, which is about 3,250 ft for the area north of St. George and 3,130 ft for the area southwest of Hurricane. A vertical distance of 1,000 ft between layer 2 and the location of the fixed general head was assumed for both areas.

Irrigation

Recharge from unconsumed irrigation water beneath the flood-irrigated fields southwest of Hurricane is simulated as a specified flux with the recharge package (fig. 47). A recharge rate of about 0.5 ft/yr over the flood-irrigated area of 2,100 acres (1,050 acre-ft/yr) was applied at this location. This amount is within the estimated range of 0 to 5 ft^3/s (3,600 acre-ft/yr) of recharge.

Discharge Boundaries

Discharge is simulated as both constant-flow and head-dependent boundaries in the ground-water flow model. Sources of discharge include well discharge, spring discharge, seepage to the Virgin River, and seepage to adjacent and underlying formations.

Wells

Simulated pumpage was based on well discharge records from various city, county, and state water agencies. A total of about 14 ft^3/s (10,100 acre-ft/yr) of well discharge is simulated with the well package. About 80 percent, or 11 ft^3/s (8,000 acre-ft/yr) of the well discharge is simulated from layer 1 (fig. 49), whereas about 20 percent, or 3 ft^3/s (2,200 acre-ft/yr) is simulated from layer 2 (fig. 50). Originally, an estimated discharge of 12.7 ft^3/s (9,200 acre-ft/yr) was specified for 1995. However, simulated water levels were much higher than measured water levels in the Mill Creek area. Although 1991 and 1993 well discharge at Washington City's Mill Creek wells was not reported to the Utah Division of Water Rights, 1992 and 1994 well discharge in the Mill Creek area was about 40 percent higher than reported 1995 pumpage. Because the Navajo and Kayenta aquifers may buffer short-term variations in pumping, measured water levels do not likely reflect the anomalously small amount of 1995 Mill Creek well discharge. Therefore, specified well discharge was increased by 40 percent, or about 1.3 ft^3/s (900 acre-ft/yr), at the Mill Creek area to reflect longer-term average pumping rates.

Springs

Spring discharge was simulated with the drain package. Because of coarse vertical discretization, spring discharge from the Navajo aquifer could not be accurately simulated in layer 1 because numerical oscillation would cause drying of these cells. Therefore, all of the spring discharge was simulated in layer 2. This is a reasonable approximation because most of the spring discharge from the Navajo aquifer occurs just above the contact with the Kayenta Formation. The location of drain cells that represent spring discharge is shown in figure 50. The discharge from drain cells is head-dependent and is determined by the difference in head (the simulated water level at the cell compared with the specified altitude of the spring) multiplied by the spring conductance. Altitude of each spring was determined from 1:24,000 USGS topographic maps. Because of the 40-ft contour interval on these maps, specified spring altitudes may have as much as plus or minus 20 ft in error. As with the river package, the conductance represents the permeability of material at the spring location. Because of the strong influence of fracturing, this conductance is highly variable and could not be measured. Therefore, conductance values were adjusted during model refinement to approximate the

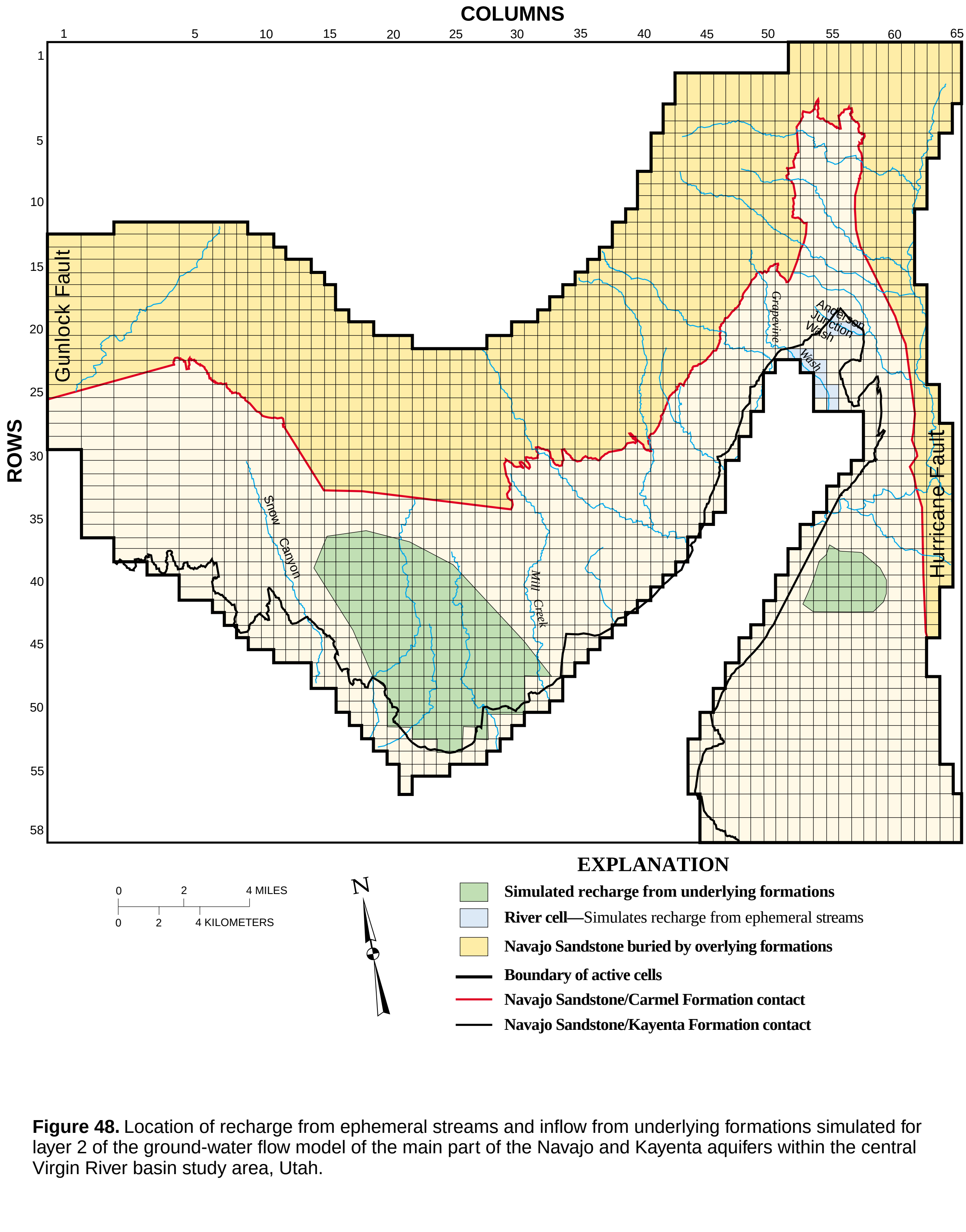

Figure 48. Location of recharge from ephemeral streams and inflow from underlying formations simulated for layer 2 of the ground-water flow model of the main part of the Navajo and Kayenta aquifers within the central Virgin River basin study area, Utah.

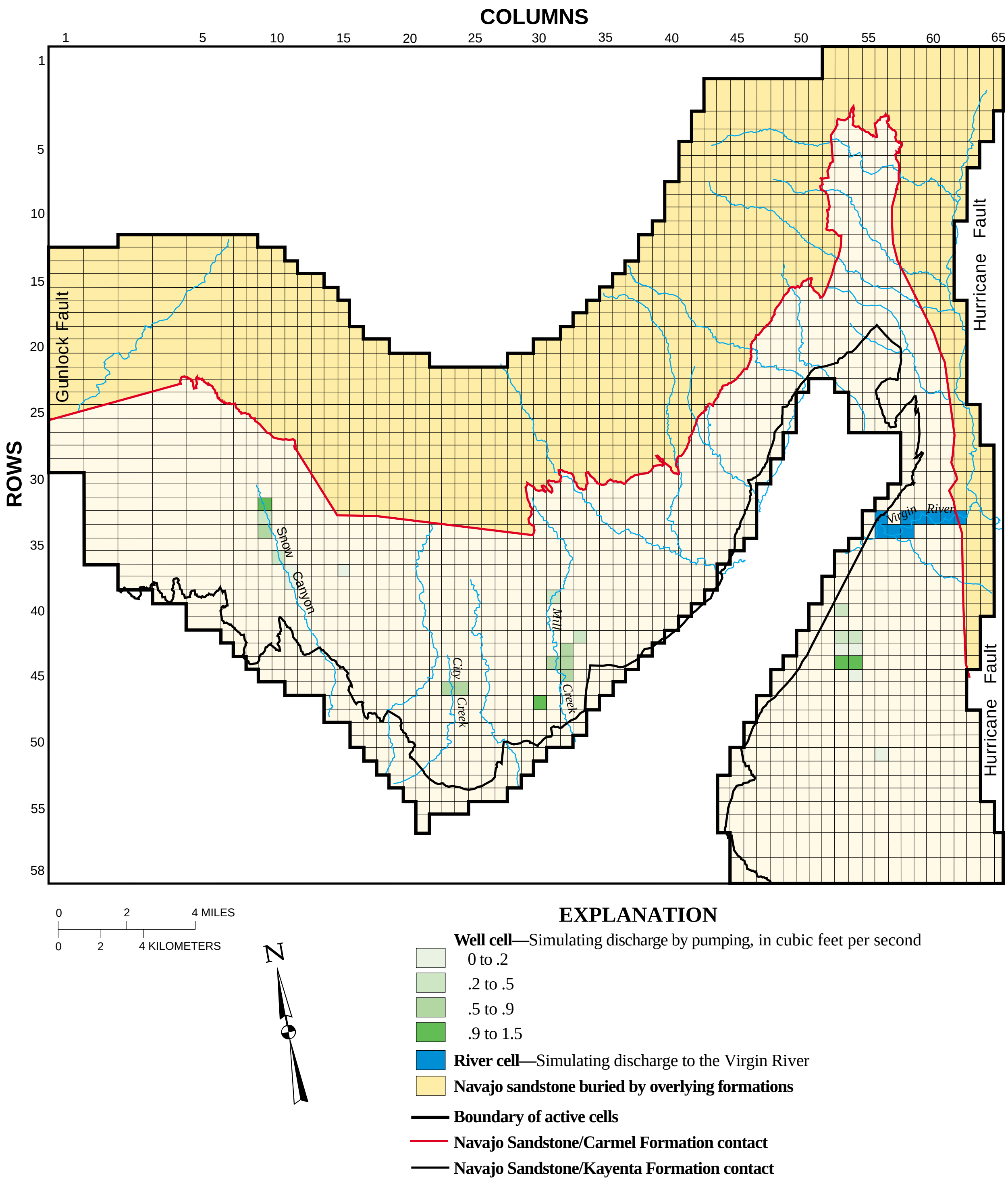

Figure 49. Discharge to wells and to the Virgin River from layer 1 of the ground-water flow model of the main part of the Navajo and Kayenta aquifers within the central Virgin River basin study area, Utah.

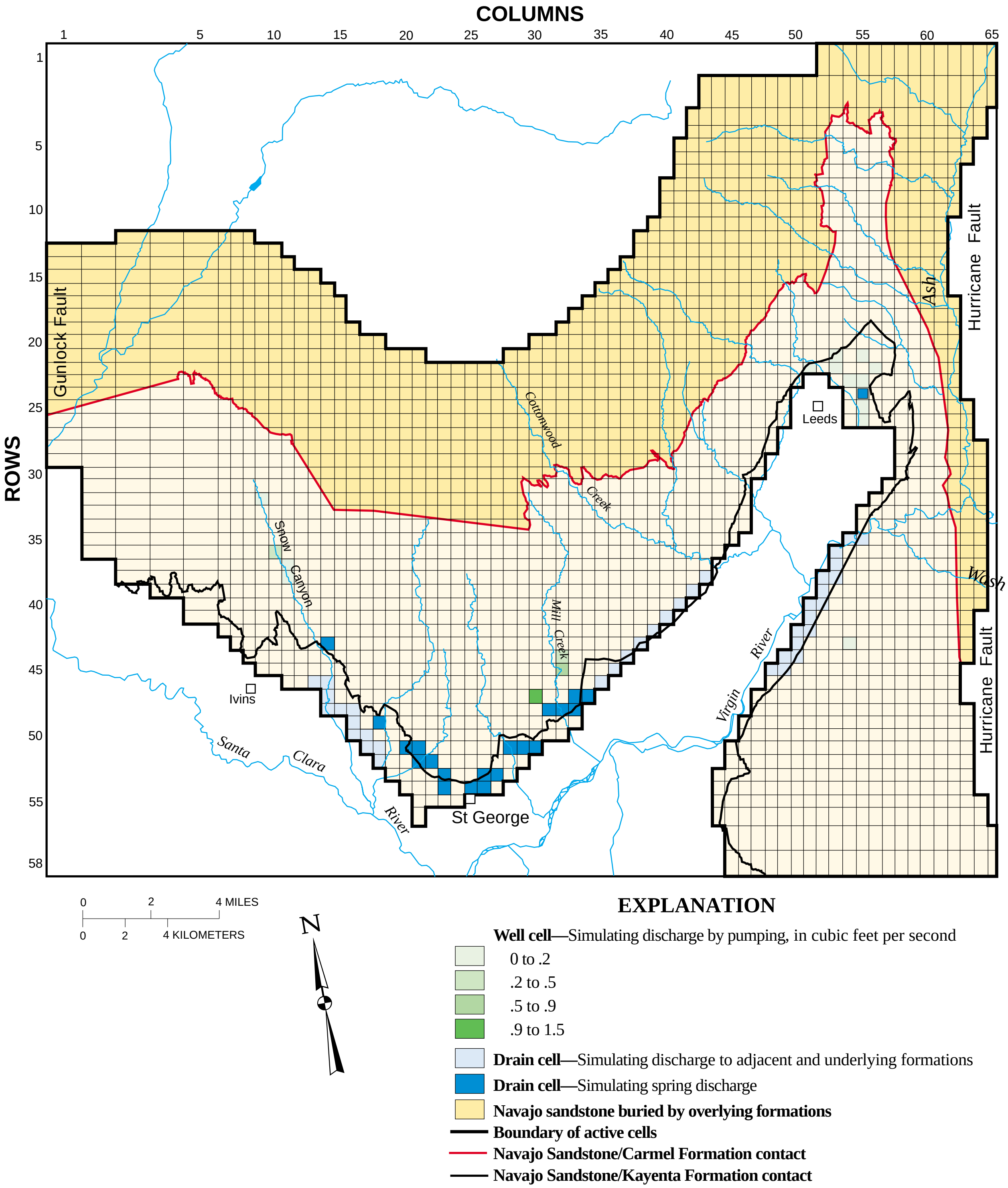

Figure 50. Discharge to wells, springs, and subsurface outflow to adjacent and underlying formations from layer 2 of the ground-water flow model of the main part of the Navajo and Kayenta aquifers in the central Virgin River basin study area, Utah.

discharge measured at each spring area. The final specified conductance ranges from about 0.02 to 0.8 ft^2/s (1,700 to 70,000 ft^2/d).

Virgin River

The river package is used to simulate seepage to the Virgin River from layer 1 (fig. 49). Riverbed conductance was estimated at about 0.1 ft^2/d. The vertical hydraulic conductivity used in this conductance term is more than one order of magnitude less than the estimated 2 ft^2/d horizontal hydraulic conductivity of the Navajo aquifer. On the basis of measurements made during seepage studies, the width of the river is estimated to be about 100 ft and the stage altitude is estimated to be about 3 ft above the bottom altitude of each stream reach. The altitude assigned for each river cell was based on 1:24,000 USGS topographic maps with 40-ft contour intervals.

Adjacent and Underlying Formations

Seepage to adjacent and underlying formations is simulated as a head-dependent flux boundary with the drain package. The drain cells simulating discharge to adjacent and underlying formations shown in figure 50 represent (1) discharge to the Virgin River downstream of the Navajo Sandstone outcrop, (2) discharge to the Santa Clara River on the reach between Ivins and St. George, and (3) discharge to numerous seeps and springs along the Moenave and Chinle Formation outcrop between St. George and Leeds. The altitude assigned for each drain cell was based on topographic maps with 40-ft contour intervals. For simplicity, a uniform conductance of about 0.1 ft^2/d was assigned for all three areas.

No-Flow Boundaries

In general, no ground-water movement is simulated to enter or exit the Navajo and Kayenta aquifers at the erosional extents of the formations toward the south, where the aquifers are deeply buried toward the north, across the Hurricane and Gunlock Faults, or at the base of the Kayenta aquifer (layer 2). However, exceptions to this include two areas of general-head boundary cells at the base of layer 2 that simulate inflow of water with higher dissolved-solid concentrations from underlying formations and drains along part of the erosional extent of the Kayenta aquifer that represent subsurface outflow to adjacent or underlying formations.

Because little recharge is thought to enter the Navajo and Kayenta aquifers where they are deeply buried by younger formations to the north, little ground-water flow is assumed in this region. Therefore, an arbitrary no-flow boundary was assigned at the northern edge of the ground-water flow model about 4 mi north of the contact with the Carmel Formation (fig. 43). This was considered sufficiently far from any potential ground-water development so that additional well discharge would not cause drawdown effects along these boundaries.

Distribution of Aquifer Characteristics

Although horizontal hydraulic-conductivity values for the Navajo aquifer, determined from aquifer tests, varied by more than two orders of magnitude because of fracturing and other heterogeneities, not enough information was available to accurately simulate this variation throughout the model area. Therefore, uniform hydraulic-conductivity values were simulated for each layer of the baseline model. The simulated hydrologic properties were within the range of measured values for the Navajo and Kayenta aquifers (see sections on Navajo and Kayenta aquifer properties). While keeping within this range, horizontal hydraulic-conductivity values for layers 1 and 2 were varied more than one order of magnitude to yield the best matches to measured or estimated water levels and fluxes. The final specified horizontal hydraulic-conductivity values are 2 ft/d for layer 1 (the Navajo aquifer) and 0.5 ft/d for layer 2 (the Kayenta aquifer) (table 21).

There are no nearby pairs of wells perforated in the Navajo and Kayenta aquifers. Therefore, vertical gradients between the two aquifers can only be inferred. If potentiometric gradients are extended from Kayenta aquifer wells to the closest Navajo aquifer wells, water-level differences are estimated to be generally less than 100 ft and indicate a slight downward vertical gradient. This is consistent with the conceptualization that most recharge to the Kayenta aquifer is from downward vertical migration of water from the Navajo aquifer. At certain locations, such as the two areas of higher dissolved-solids concentration, there may be an upward vertical gradient between the Kayenta and Navajo aquifers. The vertical hydraulic-conductivity value for each layer was varied by up to one order of magnitude to determine the best match to water levels and ground-water budget components. The final specified values for vertical hydraulic conductivity are 1.5

Table 21. Measured, estimated, and simulated hydraulic-conductivity values for the main part of the Navajo and Kayenta aquifers, central Virgin River basin, Utah

	Measured or estimated, in feet per day	Baseline simulation, in feet per day
Layer 1 (Navajo aquifer) horizontal hydraulic conductivity	[1]0.2 to 32	2
Layer 1 (Navajo aquifer) vertical hydraulic conductivity	[2].08 to 22	1.5
Layer 2 (Kayenta aquifer) horizontal hydraulic conductivity	[3]8.2×10^{-4} to 6	.5
Layer 2 (Kayenta aquifer) vertical hydraulic conductivity	[3]8.2×10^{-4} to 0.5	.25

[1] From table 10.
[2] Determined by assuming a vertical-to-horizontal hydraulic conductivity ratio of 0.4 to 0.7.
[3] Discussed earlier in the "Aquifer properties—Kayenta aquifer" section.

ft/d for layer 1 (the Navajo aquifer) and 0.25 ft/d for layer 2 (the Kayenta aquifer) (table 21).

Conceptual Model and Numerical Simulation

Comparison between the conceptual and numerical ground-water budgets shows that simulated flows are within the estimated ranges (table 22a). The two head-dependent recharge flows, seepage from perennial streams and seepage from underlying formations, are near or at the maximum of the estimated ranges. Of the three head-dependent discharge flows, spring discharge and seepage to underlying formations are at or near the maximum of the estimated ranges. Simulated discharge to the Virgin River is the same as measured during the seepage investigation.

Water-level comparisons, however, are not as close (table 22b). In general, simulated water levels are higher in the central area and lower in the Anderson Junction area than measured water levels at selected observation wells (fig. 51). The simulated water levels in the Hurricane Bench area are similar to measured values. It was not considered important to match measured water levels exactly because of several factors: (1) most measured water levels were from production wells and may have been influenced by residual drawdown cones (depending on the time interval since pumping ceased); (2) simulated water levels are the calculated average water levels for each cell, which may not be the same as the water level at a point within the area (at least 2,000 ft by 2,000 ft) of each model cell, especially at pumping wells. However, the relatively large water-level differences in the central and Anderson Junction areas indicate that the baseline simulation only offers a general approximation to the actual hydrologic system. Various factors, such as heterogeneity of aquifer properties and inaccurate estimates for some of the ground-water budget components may be the reason for these differences.

The potentiometric surface for the baseline simulation shows a pattern of ground-water movement (fig. 52) similar to that conceptualized from sparse water-level measurements (pl. 2).

Model Applicability

The baseline simulation was developed to better understand ground-water flow in the main part of the Navajo and Kayenta aquifers. It is the first computer model developed to represent these aquifers and represents a very simplified conceptualization of a complicated ground-water flow system. Certain boundaries and boundary conditions are well understood, but others have not been well defined. Therefore, rather than being considered a "calibrated" model, it should be considered as a tool for testing alternative conceptualizations of the flow system. Although the baseline simulation is a viable representation of the ground-water system, there likely are other combinations of aquifer properties that may yield a similar or improved representation of measured or estimated hydrologic properties.

Alternative Conceptualizations

The baseline numerical simulation concentrated on testing the effects of simulating various combinations of fluxes and uniform hydraulic properties; however, heterogeneous aquifer properties were not tested. Because of sparse spatial information about aquifer properties and the large model area, localized heterogeneity in aquifer properties was not simulated. However, generalized, non-uniform alterations of hydraulic con-

Table 22. (a) Conceptual and simulated ground-water budgets and (b) simulated versus measured water-level differences for the main part of the Navajo and Kayenta aquifers, central Virgin River basin, Utah

(a) Ground-water budget

Flow component	Conceptual model	Baseline numerical simulation[1] (rounded)
Recharge, in acre-feet per year		
Infiltration of precipitation	7,200 to 21,700	14,500
Seepage from perennial streams	1,300 to 4,000	4,000
Seepage from ephemeral streams	200 to 4,500	3,600
Seepage from underlying formations	0 to 3,000	2,400
Infiltration of unconsumed irrigation water	0 to 4,400	1,100
Total	8,700 to 37,600	[2]25,600
Discharge, in acre-feet per year		
Well discharge	7,200 to 10,900	10,200
Spring discharge	5,000 to 6,200	5,900
Seepage to the Virgin River	4,700 to 5,700	5,200
Seepage to underlying formations	0 to 5,400	4,500
Total	16,900 to 28,200	[2]25,800

[1]Budget amounts listed in italics were specified fluxes. All others are head -dependent fluxes determined by the model.
[2]Numbers do not match due to slight rounding error.

(b) Difference between simulated and measured water levels

Water level	Central area	Anderson Junction area	Hurricane Bench area
Number of water levels compared	18	7	17
Maximum computed above measured, in feet	160	61	197
Maximum computed below measured, in feet	-158	-305	-58
Mean of differences, in feet	62	-158	12
Root mean square, in feet	91	196	58

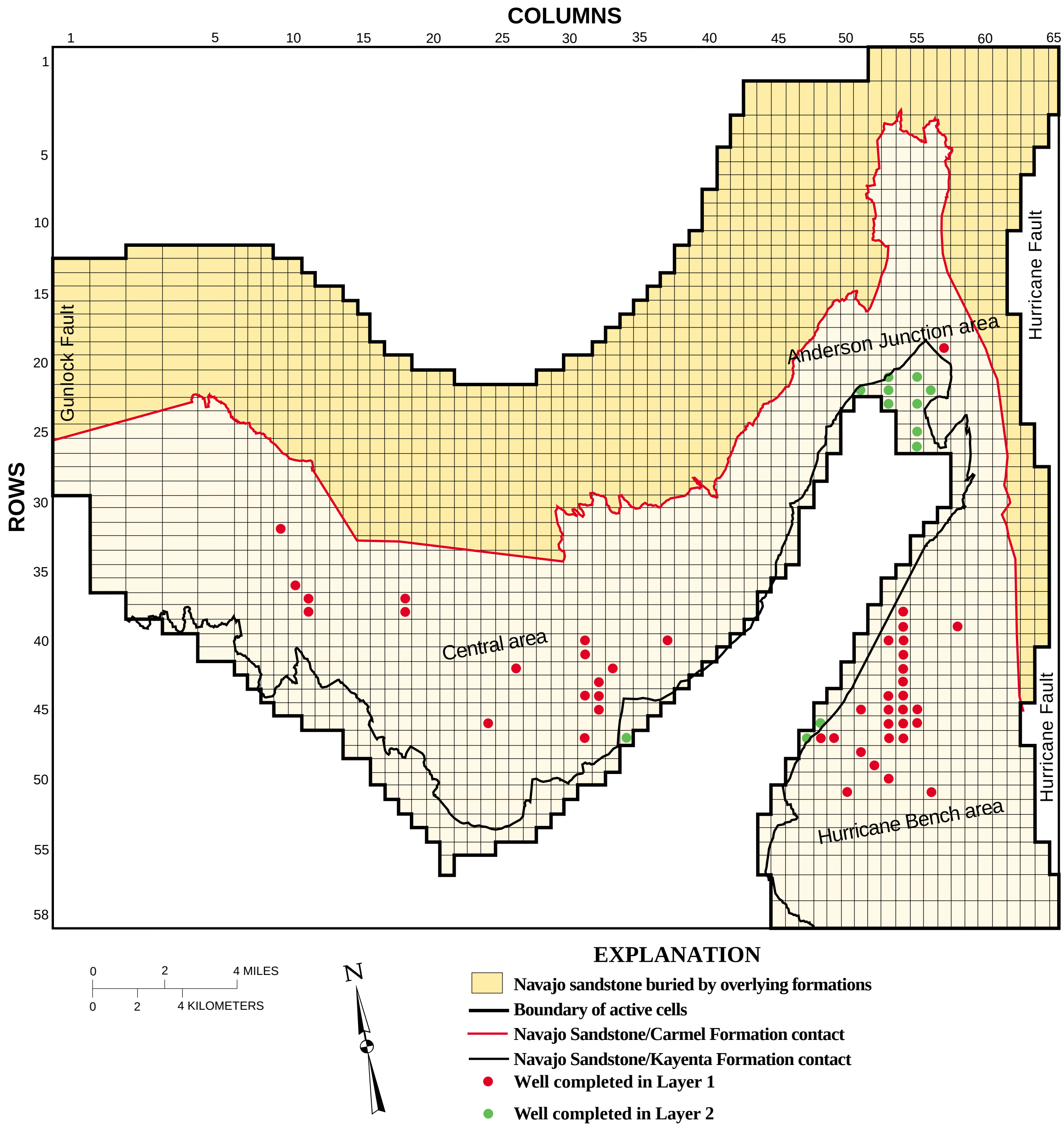

Figure 51. Location of observation wells used for comparison of computed and measured water levels for the ground-water flow model of the main part of the Navajo and Kayenta aquifers within the central Virgin River basin study area, Utah.

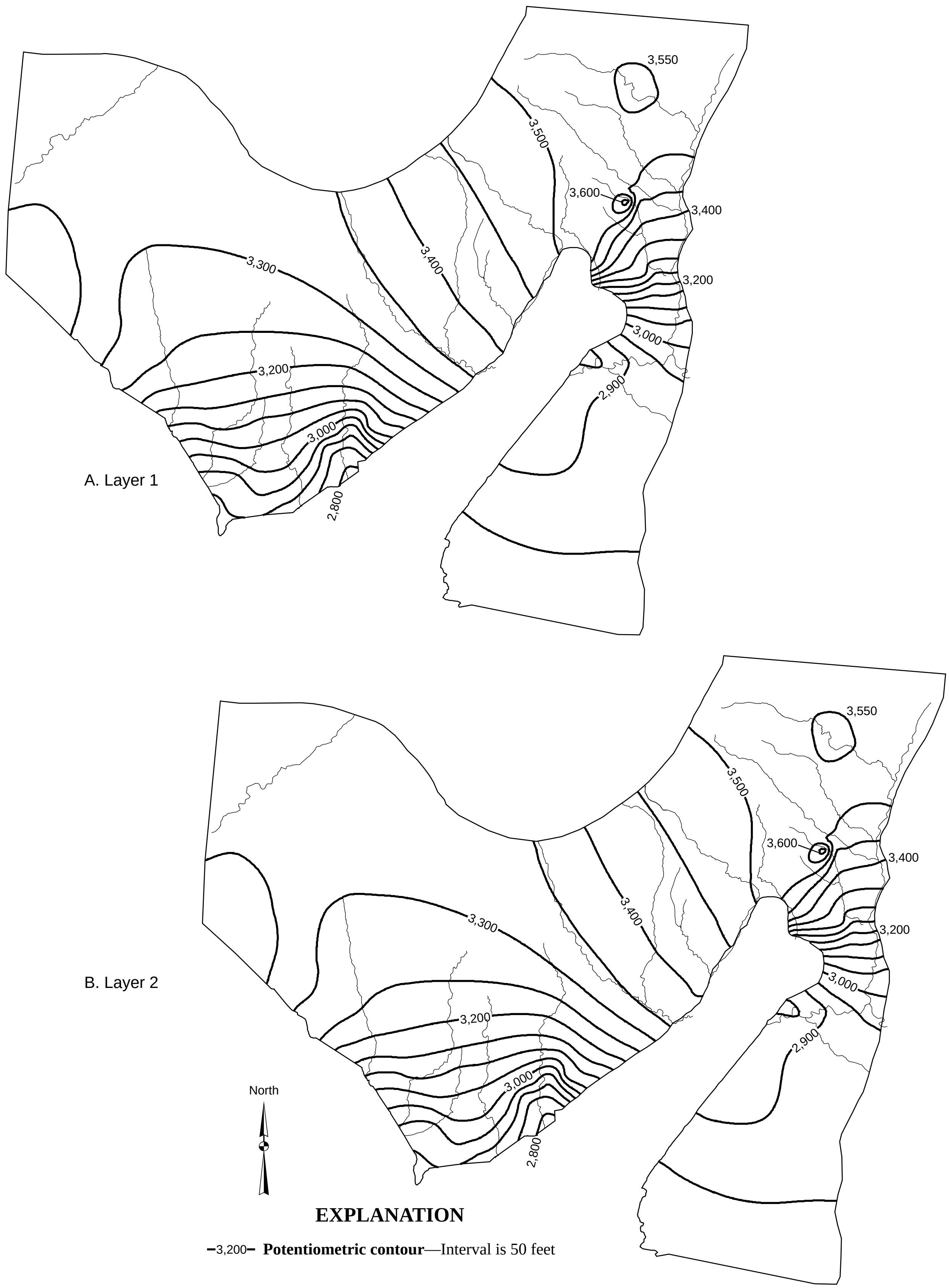

Figure 52. Simulated potentiometric contours for (a) layer 1 and (b) layer 2 of the baseline main Navajo aquifer ground-water flow model.

ductivity, related to fracturing, were examined. Two types of alternative simulations were tested that explored the effects of decreased ground-water flow perpendicular to large faults and increased ground-water flow parallel to predominant fracture orientations.

Alternative 1—Effects of Faulting

Several faults have been mapped in the Navajo Sandstone and the Kayenta Formation between the Gunlock Fault and the Hurricane Fault. Actual offset along most of these faults is difficult to determine and may be minor; however, the Washington Hollow Fault and an unnamed fault near Anderson Junction are assumed to have substantial offset (Hurlow, 1998). Ground-water flow is assumed to be impeded across formations substantially offset by faults as a result of shearing within the fault zone, which likely creates fine-grained fault gouge and increased remineralization. To explore the possibility of decreased flow across these faults, the horizontal hydraulic-conductivity value of both model layers was reduced by one order of magnitude for a line of cells along the two fault traces (fig. 53). Horizontal hydraulic conductivity was decreased from 2.0 ft/d to 0.2 ft/d for these "fault" cells in layer 1 (the Navajo aquifer). Likewise, horizontal hydraulic conductivity was decreased from 0.5 ft/d to 0.05 ft/d for "fault" cells in layer 2 (Kayenta aquifer).

The most important effect of this simulation is a rise in water levels in the Anderson Junction area between the two faults (fig. 54). The mean of the difference between simulated and measured water levels in this area was reduced from -158 ft in the baseline simulation to -2 ft in alternative simulation 1 (table 23). Simulated water levels in alternative 1 were somewhat higher in the Snow Canyon part of the central area and somewhat lower in the Mill Creek and City Creek parts. Simulated water levels in the Hurricane Bench area were essentially unchanged. The primary ground-water budget effects were decreased spring discharge in the central area and decreased seepage to the Virgin River, offset by increased seepage to underlying formations (table 23). These simulated ground-water budget components were generally within the ranges estimated in the conceptual model. Because of the improved match between simulated and measured water levels in the Anderson Junction area, the simulation of decreased horizontal hydraulic conductivity along the two faults is an improvement over the baseline simulation.

Alternative 2—Combined Effects of Faulting and Anisotropy

Extensive fracturing within the Navajo and Kayenta aquifers likely causes anisotropic conditions with increased ground-water flow along predominant fracture orientations. Outcrop-scale scan-line surveys and areal-photograph analyses (Hurlow, 1998, pl. 6) indicate that the predominant fracture orientation changes across the study area. On the basis of surface fracturing and multiple-well aquifer testing (appendix 1), the general fracture orientation is interpreted to be in a north-south direction in the central area and in an east-west direction in the Anderson Junction area. Although a multiple-well aquifer test at the Winding Rivers property did not indicate anisotropic conditions within the Navajo aquifer at that site, surface-fracture data indicate a predominant northeast-southwest fracture orientation for the Hurricane Bench area.

To investigate the possibility of anisotropic conditions, two simulations testing anisotropy ratios of 1.5 to 1 along the column direction (roughly north-south; alternative 2a) and 1.5 to 1 along the row direction (roughly east-west; alternative 2b) for both layers were tested, while maintaining the decreased flow across major faults simulated with alternative 1. Because of limitations with the finite-difference numerical method, anisotropy could not be evaluated at oblique angles to the model-grid orientation. For the north-south anisotropy simulation, horizontal hydraulic-conductivity values were increased in the north-south direction from 2 ft/d to 3 ft/d in layer 1 and from 0.5 ft/d to 0.75 ft/d in layer 2. For the east-west anisotropy simulation, horizontal hydraulic-conductivity values were increased in the east-west direction by the same amount.

Results from these simulations (table 23) indicate that increased horizontal hydraulic conductivity in the north-south direction (alternative 2a) substantially improves the match of simulated to measured water levels in the central area (generally higher water levels (fig. 55) and generally stays within the ground-water budget constraints estimated in the conceptual model. However, simulated water levels in the Anderson Junction area, although closer to measured values than the baseline simulation, showed a poorer match than in the homogeneous alternative with faulting only (alternative 1). The water-level match in the Hurricane Bench area was better than in both the baseline and alternative 1 simulations.

The anisotropic simulation with increased hydraulic conductivity in the east-west direction (alternative 2b) did not produce close matches to measured

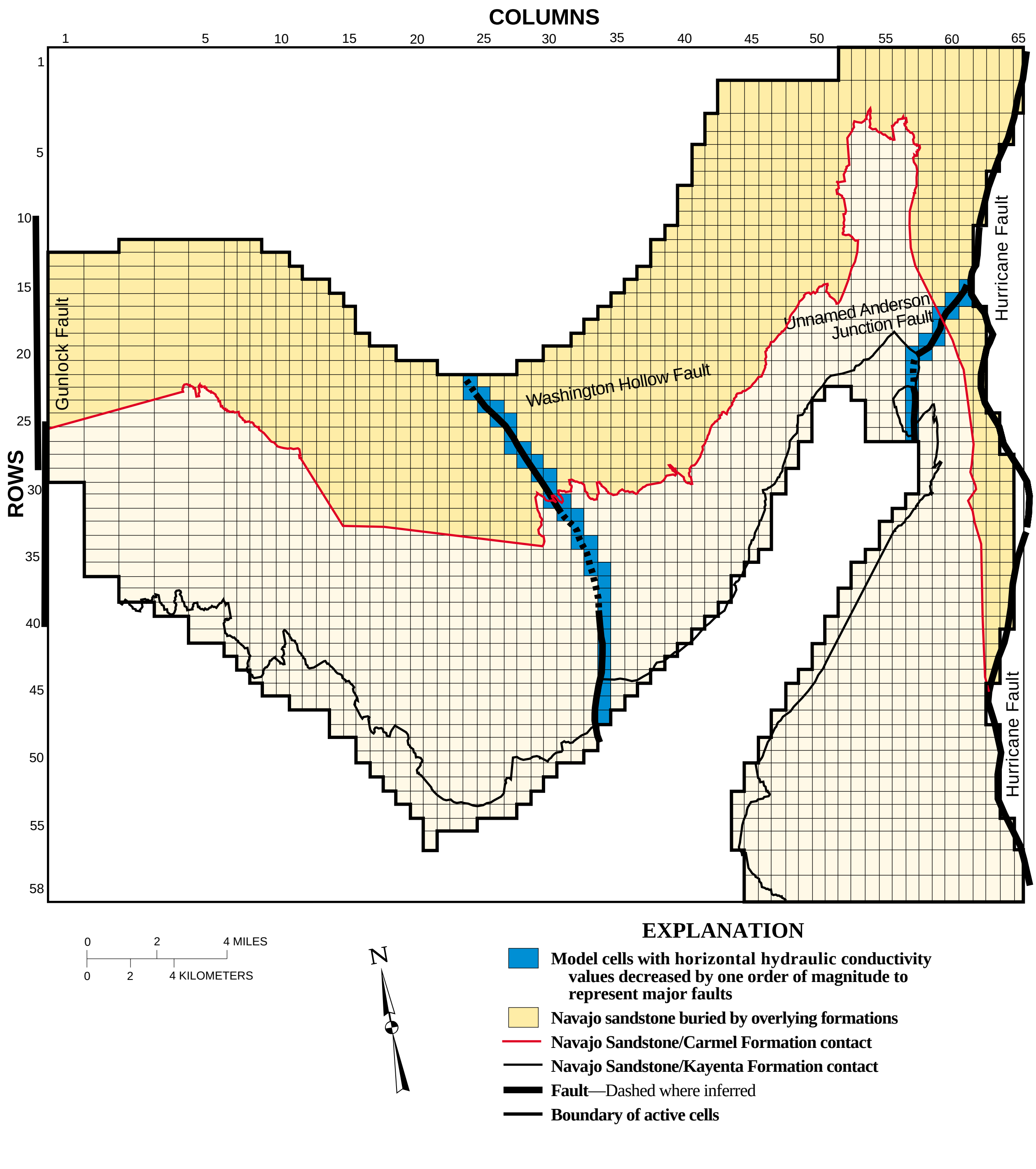

Figure 53. Location of model cells that simulate effects of faulting in the ground-water flow model of the main part of the Navajo and Kayenta aquifers within the central Virgin River basin study area, Utah.

Figure 54. Simulated potentiometric contours for (a) layer 1, and (b) layer 2 of the alternative depicting effects of faulting, main Navajo aquifer ground-water flow model.

Table 23. (a) Conceptual and simulated ground-water budgets and (b) simulated versus measured water-level differences for the baseline simulation and simulations testing faulting and anistropy in the main part of the Navajo and Kayenta aquifers, central Virgin River basin, Utah

(a) Ground-water budget

Flow component	Conceptual	Baseline simulation	Alternative 1: decreased fault-flow simulation	Alternative 2a: increased north-south anisotropy simulation (1.5:1)	Alternative 2b: increased east-west anisotropy simulation (1.5:1)
Recharge, in acre-feet per year					
Infiltration of precipitation	7,200 to 21,700	*14,500*	*14,500*	*14,500*	*14,500*
Seepage from perennial streams	1,300 to 4,000	4,000	4,000	4,000	4,000
Seepage from ephemeral streams	200 to 4,500	*3,600*	*3,600*	*3,600*	*3,600*
Seepage from underlying formations	0 to 3,000	2,400	2,300	2,800	2,400
Infiltration of unconsumed irrigation water	0 to 4,400	*1,100*	*1,100*	*1,100*	*1,100*
Total (rounded)	8,700 to 37,600	[2]25,600	[2]25,500	[2]26,000	[2]25,600
Discharge, in acre-feet per year					
Well discharge	7,200 to 10,900	*10,200*	*10,200*	*10,200*	*10,200*
Spring discharge	5,000 - 6,200	5,900	5,600	6,200	5,900
Seepage to the Virgin River	4,700 to 5,700	5,200	4,600	4,800	4,200
Seepage to underlying formations	0 to 5,400	4,500	5,300	5,200	5,500
Total (rounded)	17,000 to 28,000	[2]25,800	[2]25,700	[2]26,400	[2]25,800

[1]Budget amounts listed in italics are specified fluxes. All others are head-dependent fluxes determined by the model.
[2]Numbers do not match due to slight rounding error.

(b) Difference between simulated and measured water levels

Water-level comparison	Central area				Anderson Junction area				Hurricane Bench area			
	Baseline simulation	Decreased fault-flow simulation	Decreased fault flow and increased north-south anisotropy simulation (1.5:1)	Decreased fault flow and increased east-west anisotropy simulation (1.5:1)	Baseline simulation	Decreased fault-flow simulation	Decreased fault flow and increased north-south anisotropy simulation (1.5:1)	Decreased fault flow and increased east-west anisotropy simulation (1.5:1)	Baseline simulation	Decreased fault-flow simulation	Decreased fault flow and increased north-south anisotropy simulation (1.5:1)	Decreased fault flow and increased east-west anisotropy simulation (1.5:1)
Number of water levels compared	18				7				17			
Maximum computed above measured, feet	160	183	132	187	61	253	164	234	197	196	182	194
Maximum computed below measured, feet	-158	-160	-160	-161	-305	-197	-295	-210	-58	-60	-64	-63
Mean of differences, feet	62	67	16	73	-158	-2	-101	-22	12	11	2	13
Root mean square, feet	91	97	69	104	196	137	174	138	58	58	57	58

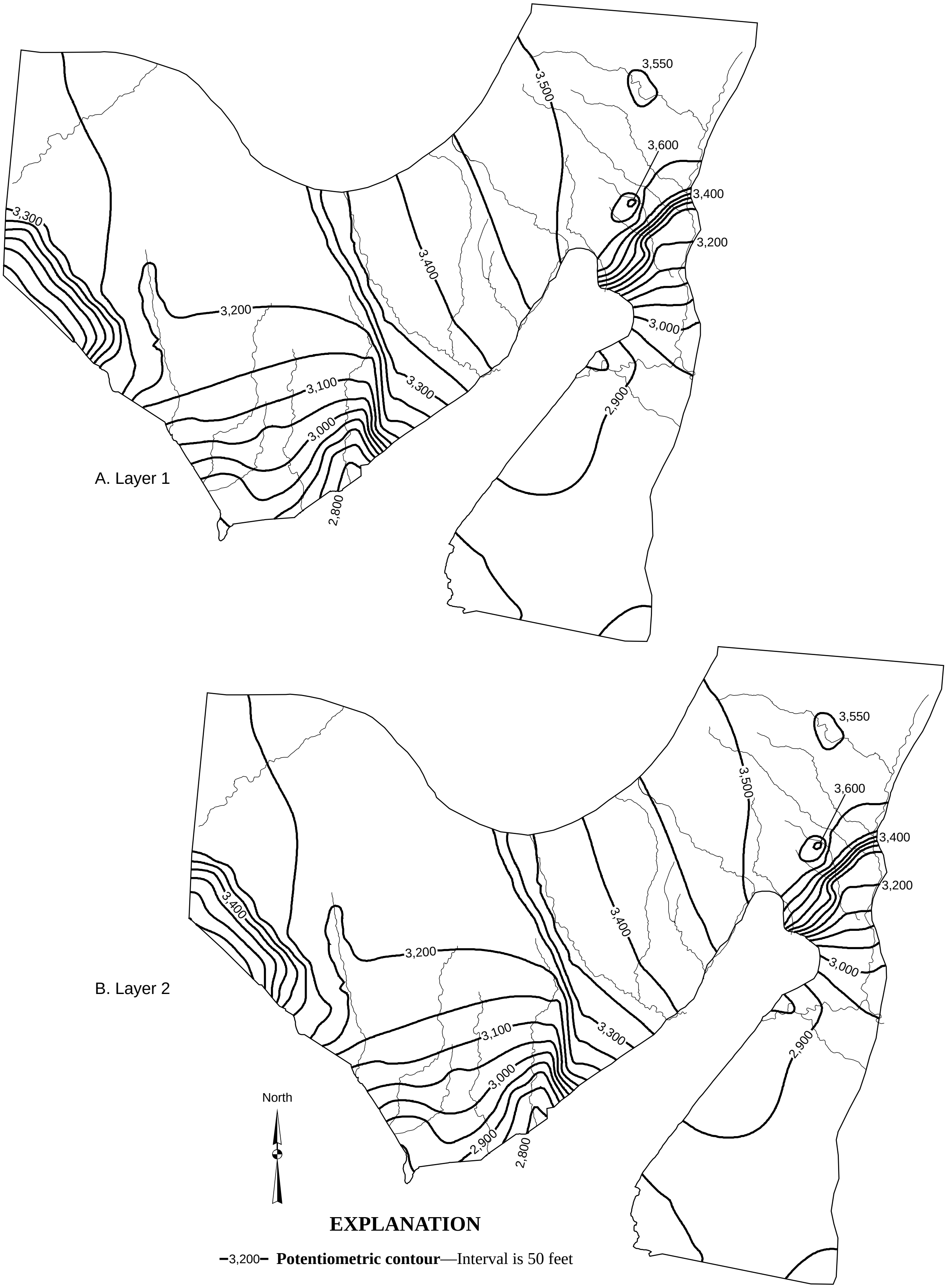

Figure 55. Simulated potentiometric contours for (a) layer 1, and (b) layer 2 of the alternative depicting effects of faulting and north-south anisotropy of the main Navajo aquifer ground-water flow model.

water levels, except for the Anderson Junction area where water levels are higher than in the baseline model (figs. 52, 56). The improvement at Anderson Junction is consistent with the directional anistropy determined from the aquifer test. Also, the seepage to the Virgin River with this simulation was about 20 percent less than measured. Therefore, the east-west anisotropy simulation is not viewed as an improvement to the overall model. However, if future versions of the MODFLOW software package permit directional changes in anistropy at different parts of the model, both the east-west anistropy at Anderson Junction and the north-south anistropy elsewhere could be accommodated.

In summary, the alternative 1 simulation (decreased flow across faults) substantially improved water-level matches in the Anderson Junction area. Adding north-south anisotropy (alternative 2a) substantially improved water-level matches in the central and Hurricane bench areas. Unfortunately, the MODFLOW software program does not allow for variable anisotropy. However, if this capability were added to the program, a closer match to measured water levels likely could be achieved by using the alternative 1 simulation, along with increased north-south hydraulic conductivity in the central and Hurricane Bench areas, and increased east-west hydraulic conductivity in the Anderson Junction area.

Model Sensitivity

The baseline model for the main part of the Navajo and Kayenta aquifers is considered to be a reasonable, albeit simplified, representation of the ground-water flow system. It is not considered to be “calibrated.” There are numerous uncertainties about the hydrologic boundaries, the amount of water moving across these boundaries, and the geometry and properties of the aquifers. Relative sensitivity of computed water level and independent flux to variations in different parameters is shown in figure 57. It is presented to show the relative importance of the different parameters in the computer model. More detailed analyses and results of all sensitivity runs are described in Appendix B2.

Simulated water levels in the baseline model are very sensitive to variations in the horizontal hydraulic conductivity of layer 1 (Navajo aquifer), streambed conductance, and areal recharge. Simulated water levels are only slightly to moderately affected by variations in the horizontal hydraulic conductivity of layer 2 (Kayenta aquifer), vertical leakance between the Navajo and Kayenta aquifers, as well as the conductance of general-head boundary cells and drain cells.

Simulated ground-water budget components are very sensitive to streambed conductance of river cells, the conductance of general-head boundary cells, and areal recharge. Simulated ground-water budget components are only slightly to moderately sensitive to variations in horizontal hydraulic-conductivity values for layers 1 and 2, vertical leakance between the Navajo and Kayenta aquifers, and the conductance of drain cells.

Need for Additional Study

The above analysis indicates that the baseline model of the main part of the Navajo and Kayenta aquifers is very sensitive to some of the simulated parameters. A better understanding of these parameters would help to improve and refine this initial modeling effort. Suggestions for additional data collection are (1) quantify diffuse infiltration of precipitation and how it varies across the Navajo outcrop within the study area; (2) carry out additional multiple-well aquifer testing to better characterize the variation in horizontal and vertical hydraulic conductivity of the Navajo aquifer; (3) do seepage studies along the Santa Clara and Virgin Rivers upstream of their confluence to better estimate seepage to underlying and adjacent formations; (4) take additional spring measurements to better determine variation in spring discharge under different hydrologic conditions; (5) quantify recharge along the larger ephemeral stream drainages; and (6) undertake a more in-depth age-dating study, including the installation of nested piezometers for investigating vertical stratification of ground water and particle-tracking computer analysis, to better-define aquifer residence times.

In addition, periodic measurements of water levels in observation wells located away from pumping wells would provide information for the development of a transient ground-water flow model to examine shorter-term effects of drought cycles and increased well discharge. There are presently no long-term water-level data available for any Navajo or Kayenta aquifer wells.

Water-Resource Management

This preliminary simulation of ground-water flow in the main part of the Navajo and Kayenta aquifers provides a useful tool for evaluating the validity of the conceptual model and the relative importance of different hydrologic processes and hydraulic proper-

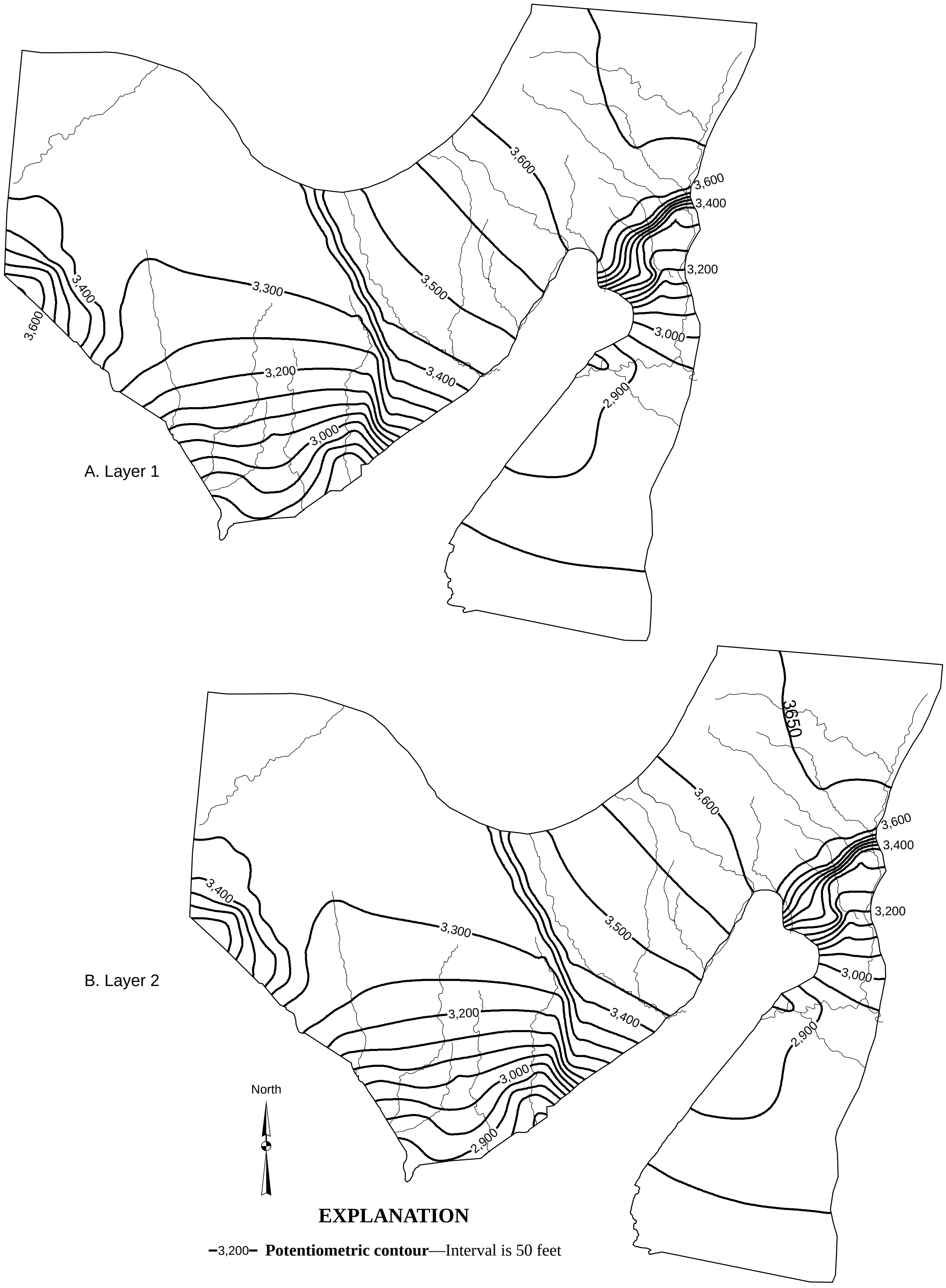

Figure 56. Simulated potentiometric contours for (a) layer 1, and (b) layer 2 of the alternative depicting effects of faulting and east-west anisotropy of the main Navajo aquifer ground-water flow model.

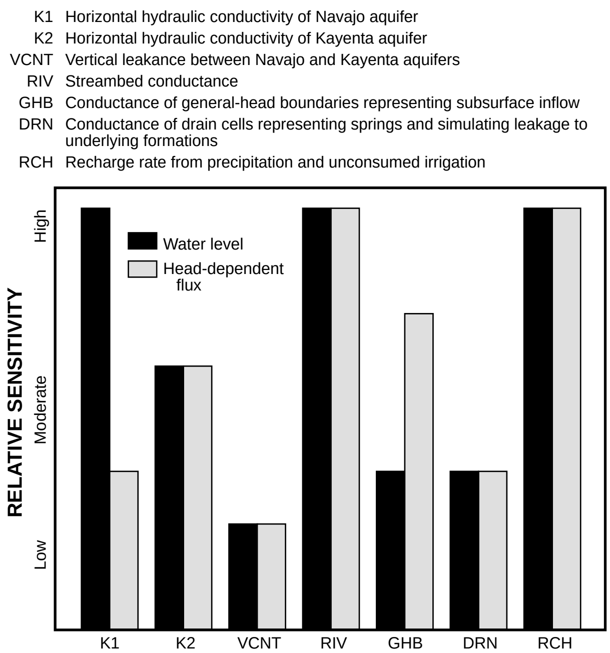

Figure 57. Relative sensitivity of the baseline model representing the main part of the Navajo and Kayenta aquifers to uncertainty in selected properties and flows.

ties. Although the model was constructed with all available hydrologic information, many unknown or poorly-defined hydrologic parameters need to be further investigated. In its present state, the model should not be used as a ground-water management tool, but rather to illustrate the interdependence of hydrologic processes and potential effects of climate change or water use.

Model Limitations

As previously stated, the alternative 1 simulation is considered to be a reasonable approximation to the aquifer system of the main part of the Navajo and Kayenta aquifers. However, it is evident from both aquifer testing and computer modeling of anisotropic conditions that aquifer properties vary throughout the study area. Because of sparse hydraulic-property data and limitations of the modeling software, such variability was not simulated. Likewise, important ground-water fluxes, such as recharge from precipitation and ephemeral streams, were only estimated; the spatial location and rates of recharge may vary substantially from the simulated fluxes. Therefore, the model is a reasonable representation of the aquifer system on a regional scale but may not accurately represent hydrologic conditions at particular locations. Thus, the model should be used as a tool for testing general cause-and-effect scenarios rather than evaluating site-specific processes.

In addition, the model simulates steady-state conditions based on the underlying assumption that hydrologic data collected during 1995 and 1996 are representative of average conditions. If either natural or man-induced stresses to the hydrologic system substantially change different ground-water budget components, these components would need to be revised in the computer model. Subsequently, the revised model's ability to accurately represent the hydrologic system would need to be reevaluated. Finally, because the model is a steady-state simulation, it can only indicate the ultimate effects of imposed changes rather than the changing effects over time. For example, if the effect of a new well field were to be evaluated, the model would only show the potential ultimate decrease in ground-water levels, rather than year-to-year declines.

Gunlock Part of the Navajo Aquifer

The Gunlock part of the Navajo and Kayenta aquifers is defined by the Gunlock Fault on the east and the erosional extent of the Kayenta Formation on the south and west. These aquifers are in hydrologic contact with the Santa Clara River and stores a major portion of the potable water supply of St. George. To examine the hydrologic characteristics of the Gunlock aquifers, a steady-state baseline ground-water flow model was developed. The flow model was used to study pumping at the St. George municipal well field, flow in the Santa Clara River, and alternative hydrologic boundaries. The steady-state simulation incorporates an average recharge and discharge for the system. Simulated well discharge is the 1987-96 average; simulated precipitation recharge represents the 1961-90 average.

Model Characteristics and Discretization

The ground-water flow model presented here is an initial effort at simulating hydrologic conditions in the Gunlock part of the Navajo and Kayenta aquifers. Most model parameters were not adjusted from initial estimates and the model is not considered to be "calibrated." Limited data are available to describe conditions in the Gunlock part and a determination of whether adjusted model parameters result in a more acceptable or "better" simulation of the system than initial values is difficult to make.

The 59-mi^2 area that represents the Gunlock part of the Navajo and Kayenta aquifers is divided into 132