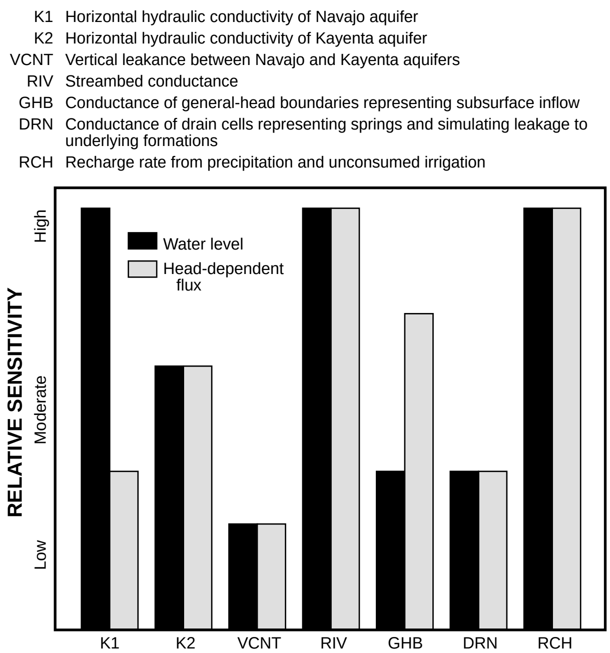


**Figure 57.** Relative sensitivity of the baseline model representing the main part of the Navajo and Kayenta aquifers to uncertainty in selected properties and flows.

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 rows, 67 columns, and 2 layers with a total of 17,688 model cells (fig. 58). The modeled area is defined by the Gunlock Fault on the east, the saturated extent of the Navajo Sandstone and Kayenta Formation on the south and west, and extends up to 4 miles north of the Carmel Formation and Navajo Sandstone contact. Model cells are 530 ft by 530 ft (0.01 $mi^2$); cell size was determined so that each well in the St. George municipal well field would be represented by an unique cell. Layer 1 represents the Navajo aquifer and includes 5,058 active cells simulating an area of about 52 $mi^2$. Layer 2 represents the Kayenta aquifer and includes 5,585 active cells that simulate an area of about 59 $mi^2$. The model grid is orientated 10 degrees east of true north so that columns run parallel to the general orientation of the Gunlock Fault. The vertical dip of both layers is about 20 degrees to the northeast, consistent with the structural geology of the area.

Vertical model discretization is referenced from the top and bottom of the Navajo Sandstone (fig. 59). The base of model layer 2 was set at 850 ft below the base of the Navajo Sandstone (table 2); where the Kayenta Formation is overlain by the Navajo Sandstone, model layer 2 is 850 ft thick. Where the Kayenta Formation is exposed, the simulated thickness of model layer 2 corresponds to model-computed water levels in the layer (200 ft to 850 ft thick). The base of model layer 1 (equivalent to the top of model layer 2) was determined from the structure contour map of the base of the Navajo Sandstone (Hurlow, 1998, pl. 5a). Where the Navajo Sandstone is exposed, the thickness of model layer 1 depends on computed water levels for the layer (200 ft to 2,400 ft). Where the Navajo Sandstone is overlain by Carmel Formation, the top of model layer 1 is based on the contour map of the top of the Navajo Sandstone (Hurlow, 1998, pl. 5b). The average thickness of the Navajo aquifer where it is overlain by the Carmel Formation is about 2,400 ft.

### Boundary Conditions

Hydrologic boundaries used in the baseline model of the Gunlock part of the Navajo and Kayenta aquifers include no-flow, specified-flux, and head-dependent (general-head) boundaries. Similar to the main part, no-flow boundaries represent the erosional extent of the aquifers and are fairly well defined. Other boundaries, such as those that represent flow to and from underlying and overlying formations, and across the Gunlock Fault, are not well defined and therefore are represented by no-flow boundaries. Where the aquifers are unconfined along the Navajo and Kayenta Formation outcrops, the water table is treated as a free surface with a specified flux recharge boundary to simulate infiltration of precipitation and seepage from Gunlock Reservoir. Model cells corresponding to the Santa Clara River include a head-dependent boundary that allows for interaction between the free surface and the river.

#### Recharge Boundaries

*Precipitation*

Recharge from precipitation is simulated with the recharge package at model cells that represent the surface exposure of Navajo Sandstone and Kayenta Formation. Where average annual precipitation is estimated to be 14 in. or less, recharge is specified as 10 percent of total precipitation. For areas where precipitation exceeds 14 in., recharge is specified as 15 percent of total precipitation. These estimated rates are based on water-budget calculations. The distribution of precipitation was derived from the 30-year average annual precipitation contours (1961-90) compiled by the Utah Climate Center (fig. 2). The distribution and amount of precipitation that becomes recharge used in the baseline model is shown in figure 60.

*Santa Clara River*

Recharge as seepage from the Santa Clara River is simulated as head-dependent flux with the streamflow package (Prudic, 1989). Properties that control the rate of simulated recharge are (1) the difference between the computed water level for the appropriate model cell and the altitude of the water surface in the Santa Clara River (stream stage), (2) the width and thickness of the alluvial streambed material that separates the Santa Clara River from the underlying Navajo Sandstone, and (3) the hydraulic conductivity of the streambed material. Altitude of the top of the streambed was determined from the appropriate USGS 1:24,000-scale topographic map, which has a contour interval of 40 ft, and surveyed altitudes at four selected sites. Width of the alluvial material is specified as 100 ft and thickness is specified at 20 ft. These dimensions are rough estimates made on the basis of field observations and correspond to values used in the analysis of the Gunlock well-field aquifer test. Hydraulic-conductivity values specified for the streambed range from 1.4 to 290 ft/day. The distribution of hydraulic conductivity is shown on figure 61, and was also made on the basis of

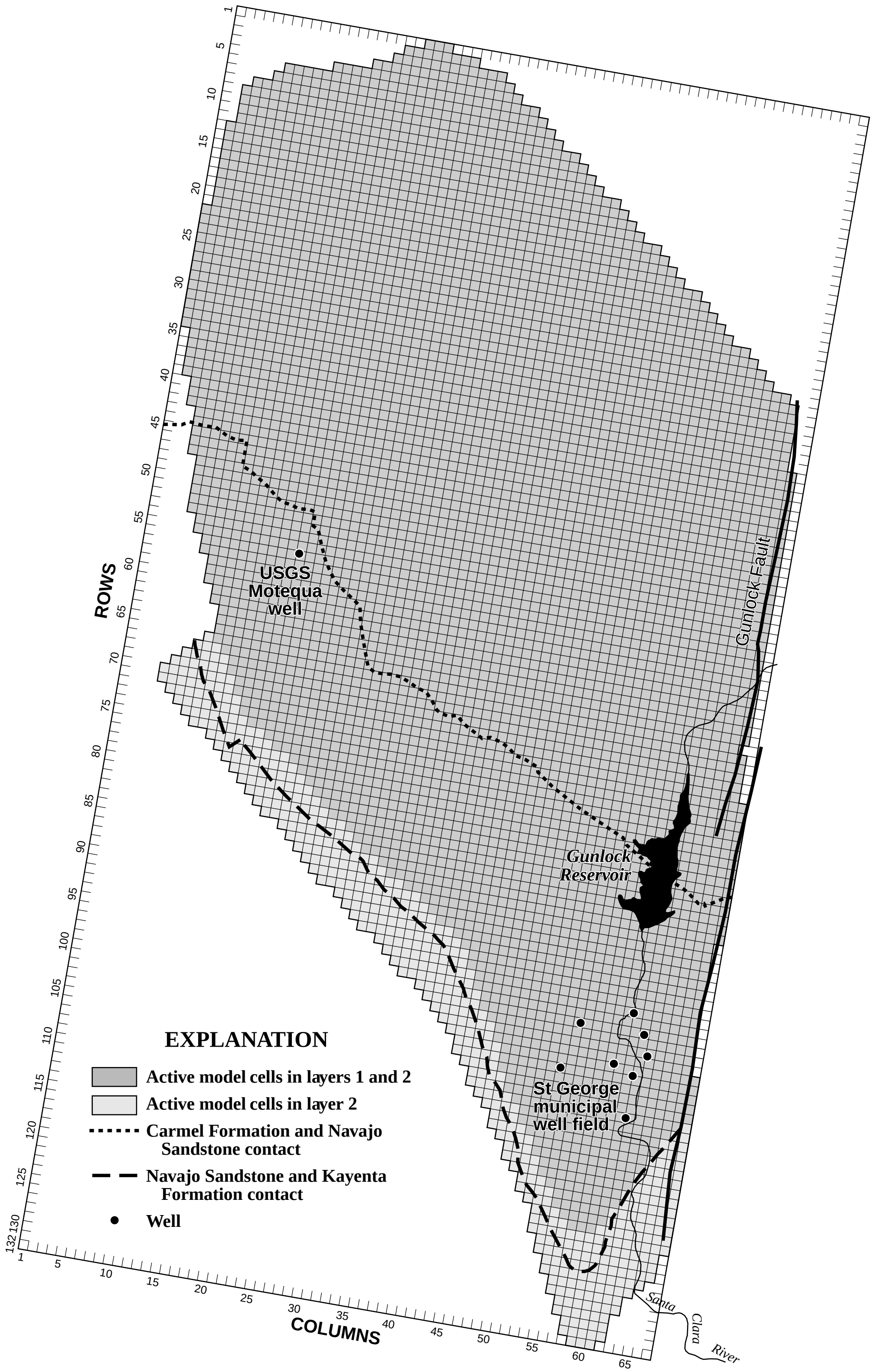


**Figure 58.** Model grid of the Gunlock part of the Navajo and Kayenta aquifers within the central Virgin River basin study area, Utah.

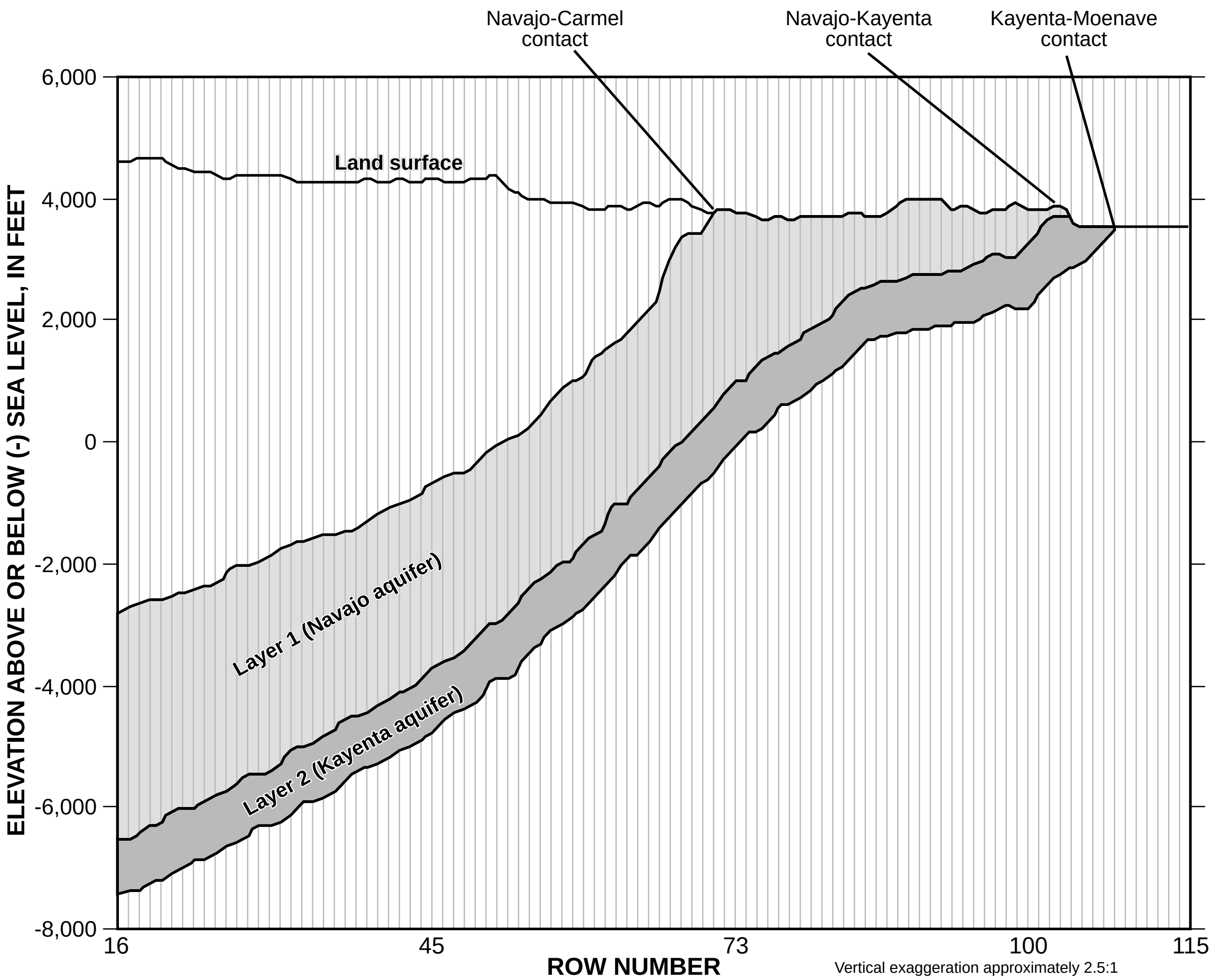


**Figure 59.** Generalized cross section along column 45 of the ground-water flow model of the Gunlock part of the Navajo and Kayenta aquifers within the central Virgin River basin study area, Utah.

the Gunlock well-field aquifer test. The degree of variability in hydraulic conductivity is large and reflects (1) averaging and uncertainty associated with the width and thickness of the streambed alluvium, and (2) heterogeneity of the underlying Navajo Sandstone that is caused by joints and fractures. The Santa Clara River alternates from running along and perpendicular to factures that exist in the Navajo Sandstone.

As mentioned, the distribution of hydraulic conductivity of the streambed alluvium was determined from results of the Gunlock well field aquifer test. However, conductivity values used in this simulation are one order of magnitude less than those from the aquifer test. This discrepancy is likely caused by the fact that simulated stream seepage in the aquifer test model is considered a combined effect from the river and release of water from storage in the alluvial streambed material (appendix A, fig. A-10). Streambed conductivities in this simulation were reduced in an attempt to replicate measured stream channel losses from the Santa Clara River.

In addition to simulating interaction with the Gunlock aquifer, the streamflow package also accounts for surface flow in the Santa Clara River; surface flow changes in accordance with seepage losses from the river. Streamflow in the Santa Clara River, at the point where water is released from Gunlock Reservoir, is specified at 6.0 $ft^3/s$ (4,300 acre-ft/yr). Surface flow in successive stream reaches is determined by the computer model. Stream stage for the Santa Clara River is specified at 1 ft above the top of the streambed, on the basis of field observations made at several locations along the stream. The location and course of the Santa Clara River also was determined from the 1:24,000-

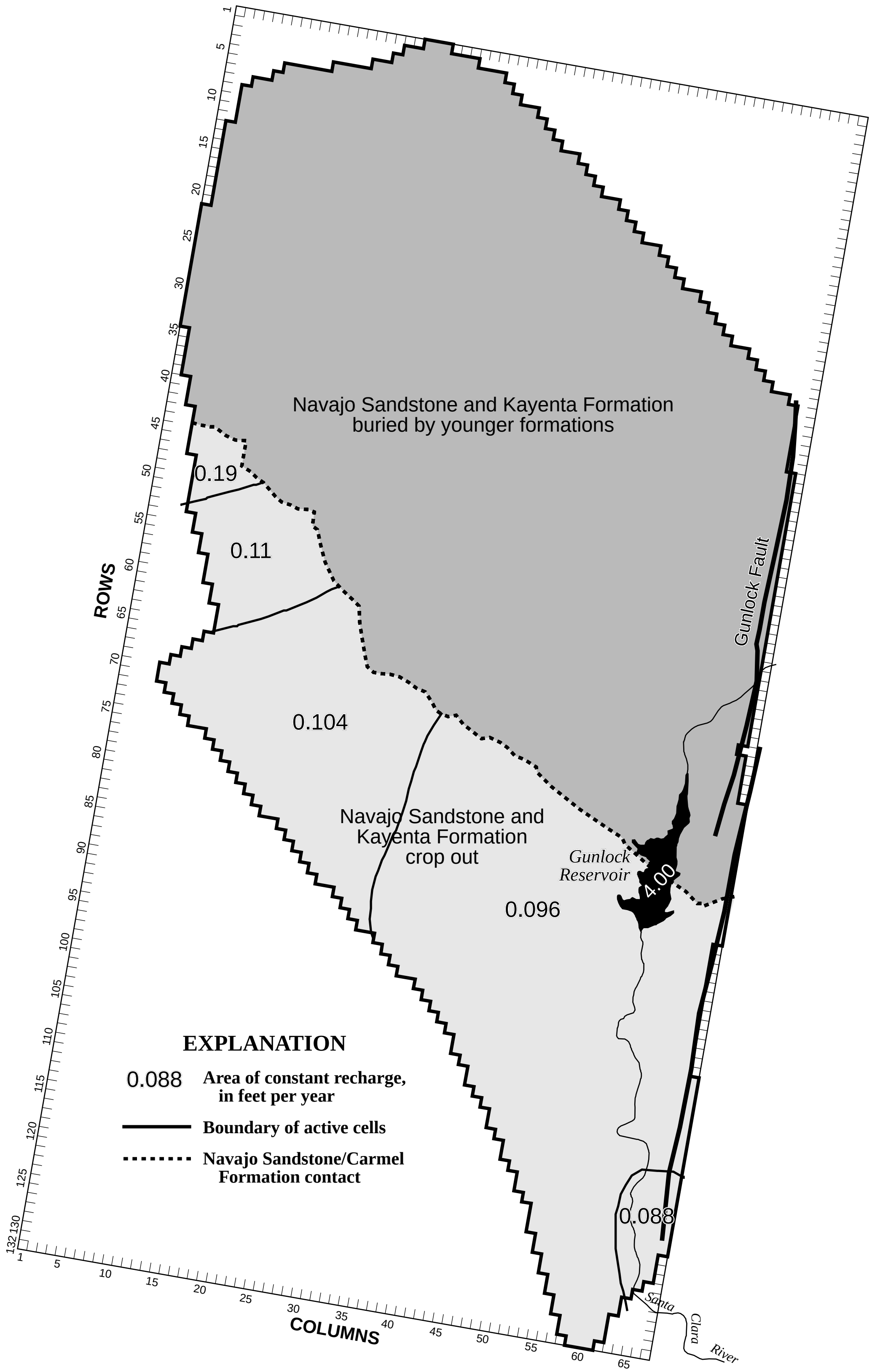


**Figure 60.** Distribution of recharge from infiltration of precipitation and reservoir leakage simulated in the ground-water flow model of the Gunlock part of the Navajo and Kayenta aquifers within the central Virgin River basin study area, Utah.

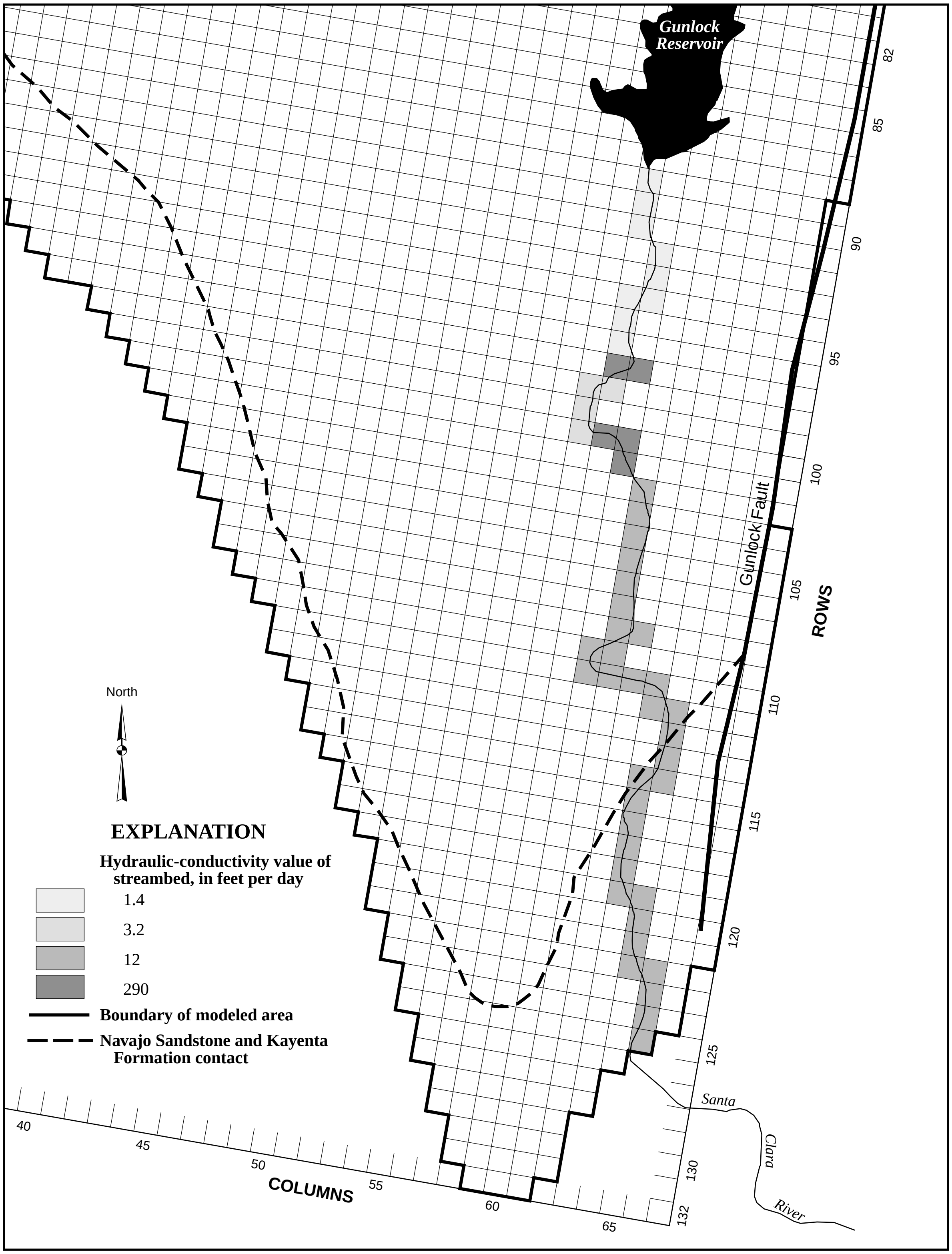


**Figure 61.** Distribution of streambed hydraulic conductivity that simulates seepage from the Santa Clara River in the ground-water flow model of the Gunlock part of the Navajo and Kayenta aquifers within the central Virgin River basin study area, Utah.

scale topographic map. Seventy-six model cells are used to simulate the river.

*Gunlock Reservoir*

Recharge as seepage from Gunlock Reservoir is specified with the recharge package at cells where the reservoir overlies the Navajo Sandstone (fig. 53). Total simulated recharge beneath the reservoir is 1.4 $ft^3/s$ (1,000 acre-ft/yr), as determined from Darcy's law and seepage estimates discussed in the conceptual description of the Gunlock area. Because seepage from the reservoir is treated as a specified flux, recharge is independent of water levels in the Navajo aquifer and the pool altitude in the reservoir.

### Discharge Boundaries

*Wells*

Discharge from eight wells in the St. George municipal well field is simulated with the well package. These wells are located in a cluster about 1 to 2 miles south of Gunlock Reservoir. The discharge rate used in the baseline simulation, 5.8 $ft^3/s$, is based on water-use information compiled by the city of St. George and represents the 1987-96 average. During that time, total discharge rates from the eight wells ranged from 4.1 to 7.1 $ft^3/s$. The location of the wells is shown in figure 51. All well discharge is simulated from the Navajo aquifer (model layer 1).

*Santa Clara River*

Discharge as seepage to the Santa Clara River is simulated as head-dependent flux with the streamflow package. Discharge is simulated when the model-computed water level for the aquifer is higher than the stream stage of the river. On the basis of field observations, seepage to the Santa Clara River occurs where the river flows across the southern extent of the Navajo Sandstone and across the Kayenta Formation. Model parameters required for the streamflow boundary and the methods used to estimate them are explained in the section titled "Recharge boundaries." Hydraulic conductivity of the streambed material where it is underlain by the Kayenta Formation was estimated at 12 ft/d (fig. 61). This value was not determined directly but was extrapolated from the hydraulic conductivity assigned to the southern most streambed material included in the Gunlock well-field aquifer test.

### No-Flow Boundaries

No-flow boundaries are used to represent (1) the base of the Kayenta Formation, (2) the lateral extent of the Navajo and Kayenta aquifers to the south, west, east, and north, and (3) the top of the Navajo Sandstone where it is overlain by Carmel Formation. This boundary condition is based on the conceptual assumptions that (1) there is no hydraulic connection between the Kayenta aquifer and underlying formations, (2) there is no hydraulic connection across the Gunlock Fault with the main part of the Navajo and Kayenta aquifers, and (3) there is no ground-water recharge from the overlying Carmel Formation to the Navajo aquifer.

### Distribution of Aquifer Characteristics

The Navajo and Kayenta aquifers are simulated as individual layers in the baseline model. Each layer is assigned a set of aquifer characteristics on the basis of aquifer tests and simulation results for the main part of the Navajo and Kayenta aquifers. Data describing the spatial distribution of aquifer properties are not available; therefore, both layers are considered homogeneous. Aquifer properties include horizontal hydraulic conductivity, vertical hydraulic conductivity, and anisotropy. These properties are assigned to all active cells in the modeled area. In conjunction with boundary conditions, aquifer properties determine the amount and pattern of simulated ground-water flow. Values assigned to each layer are listed in table 24.

The horizontal hydraulic conductivity of layer 1 (the Navajo aquifer) is specified as 0.33 ft/d and the east-west to north-south horizontal anisotropy ratio is specified as 3.0. This results in a simulated hydraulic conductivity of 0.33 ft/d in a generally east-to-west direction (along rows) and 1.0 ft/d in a generally north-to-south direction (along columns). Anisotropy and horizontal hydraulic conductivity of the Navajo aquifer are based on values determined from the Gunlock well-field aquifer test. A vertical hydraulic-conductivity value of 0.25 ft/d is specified for layer 1 and was calculated by multiplying the east-west horizontal-conductivity value by 0.75. This multiplier is the same as that used in the baseline simulation of the main part of the Navajo and Kayenta aquifers and is in agreement with laboratory hydraulic testing of Navajo Sandstone.

The horizontal hydraulic-conductivity value of layer 2 (the Kayenta aquifer) is specified as 0.25 ft/d. Initially, the conductivity value assigned to layer 2 was 0.085, which resulted in the same ratio of layer 1:layer 2 horizontal conductivity specified in the baseline sim-

**Table 24.** Hydraulic-conductivity values used in the baseline simulation of the Gunlock part of the Navajo and Kayenta aquifers, central Virgin River basin, Utah

| | Navajo aquifer (layer 1), in feet per day | Kayenta aquifer (layer 2), in feet per day |
|---|---|---|
| East-west to north-south anisotropy | [1]3.0 | [1]3.0 |
| East-west horizontal hydraulic conductivity | .33 | .25 |
| North-south horizontal hydraulic conductivity | 1.00 | .75 |
| Vertical hydraulic conductivity | .25 | .125 |

[1]Anisotropy is unitless.

ulation of the main part of the Navajo and Kayenta aquifers. The final value of 0.25 ft/d results in a better match to measured and estimated water levels and fluxes. The vertical hydraulic conductivity of layer 2 is specified as 50 percent of the horizontal value, maintaining the horizontal-to-vertical conductivity ratio specified in the baseline simulation of the main part. The Kayenta Formation contains zones of silts and clays, most likely causing overall conductivity values to be less than those estimated for the Navajo Sandstone. Assuming that fracture density and orientation within the Kayenta aquifer are similar to the Navajo aquifer, the anisotropy for layer 2 was specified at 3.0, the same value as in layer 1.

#### Conceptual Model and Numerical Simulation

Two factors were used to determine how closely the baseline numerical simulation matched the conceptual model: (1) a comparison of conceptual and model-computed ground-water budgets, and (2) a comparison of computed and measured water levels in wells (table 25). The computed ground-water budget indicates that simulated seepage from the Santa Clara River to the aquifers are at the upper limit of the range estimated in the conceptual model. Simulated seepage to the Santa Clara River from the aquifers is several times the estimated amount, although the excess represents less than 15 percent of the total ground-water budget. Other components of the simulated budget are specified and not computed by the model. The direction of ground-water movement depicted by the baseline simulating (fig. 62) is similar to that depicted in figure 26, indicating flow from recharge areas toward the Santa Clara River.

Water levels indicate considerable variation between simulated and measured values (table 25). Although differences in excess of 25 ft occur only at wells 3 and 4, the root mean square error (a measure of overall error) indicates that the numerical simulation does not accurately simulate the detailed shape of the water table in the area of the municipal well field. Several factors may explain this, including the use of pumping wells as observation wells, and steep ground-water gradients (drawdown cones) near pumping wells. The overall hydraulic gradient from northwest to southeast in the Navajo aquifer, as measured by the difference in water levels at the USGS Motoqua well and well 3 (figs. 26 and 58) is reasonably represented. The measured difference is 240 ft; the simulated difference is 263 ft.

#### Model Applicability

The baseline model represents the conceptual understanding and available data for the Gunlock part of the Navajo and Kayenta aquifers. However, as is the case for the upper Ash Creek drainage basin ground-water system and the main part of the Navajo and Kayenta aquifers, other possible numerical simulations might match the recharge fluxes, discharge fluxes, and water-level distribution observed and estimated for the Gunlock aquifers. Because available data are limited and certain hydrologic boundaries of the Gunlock aquifers are not well defined, the baseline model should not be considered a “calibrated” model. Although other combinations of aquifer properties and fluxes may yield a similar or improved match to measured and estimated hydrologic properties, the baseline model is a viable representation that can be used as a tool for testing alternative combinations of aquifer properties and fluxes.

.

**Table 25.** (a) Conceptual and simulated ground-water budgets and (b) simulated versus measured water-level differences in the Gunlock part of the Navajo and Kayenta aquifers, central Virgin River basin, Utah

**(a) Ground-water budget[1]**

| Flow component | Conceptual | Baseline simulation[1] (rounded) |
|---|---|---|
| **Recharge, in acre-feet per year** | | |
| Infiltration of precipitation | 700 to 2,200 | 1,400 |
| Seepage from Gunlock Reservoir | 0 to 2,200 | 1,000 |
| Seepage from the Santa Clara River | 700 to 2,900 | 2,900 |
| Total | 1,400 to 7,300 | 5,300 |
| **Discharge, in acre-feet per year** | | |
| Well discharge | 3,400 to 5,500 | 4,200 |
| Seepage to the Santa Clara River | 400 | 1,100 |
| Total | 3,800 to 5,900 | 5,300 |

[1] Budget amounts listed in italics were specified fluxes. All others are head-dependent fluxes determined by the model.

**(b) Measured and simulated water levels, in feet above sea level**

| Well identifier | Measured water level | Simulated water level | Difference[3] |
|---|---|---|---|
| Well #1[1] | 3,341 | 3,348 | 7 |
| Well #2[1] | 3,343 | 3,356 | 13 |
| Well #3[2] | 3,326 | 3,290 | -36 |
| Well #4[1] | 3,351 | 3,318 | -33 |
| Well #5[1] | 3,419 | 3,418 | -1 |
| Well #6[1] | 3,352 | 3,376 | 24 |
| Well #7[1] | 3,411 | 3,410 | -1 |
| Well #8[1] | 3,407 | 3,400 | -7 |
| Motoqua Well[1] | 3,566 | 3,549 | -17 |
| Root mean square error, in feet | | | 20 |

[1] Water level measured in February 1996, when pump in well was not operating. Motoqua well contains no pump.
[2] Water level measured in February 1997, when pump in well was not operating.
[3] (-) indicates simulated water level is lower than measured water level.

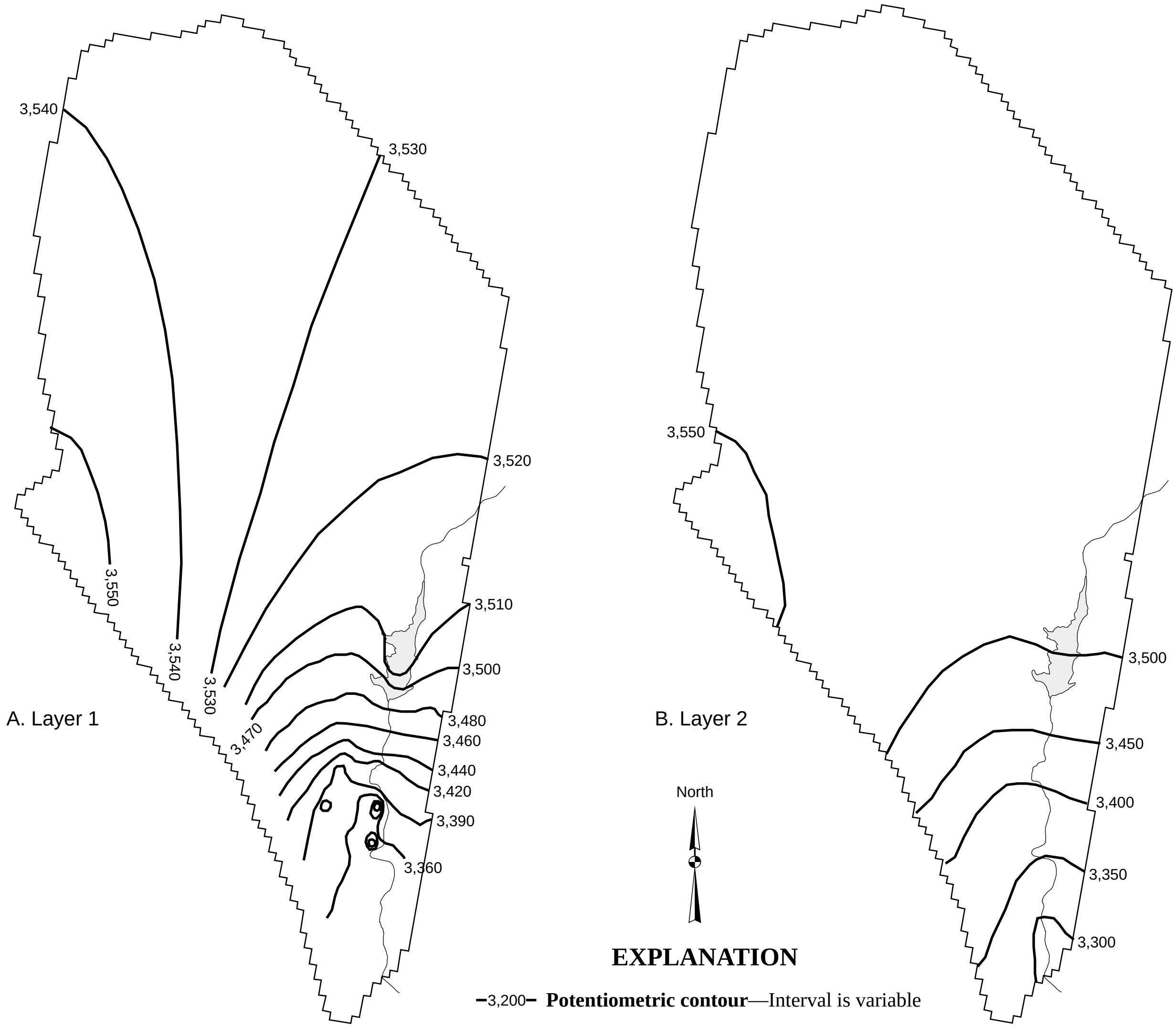


**Figure 62.** Simulated potentiometric contours for (a) layer 1 and (b) layer 2 of the baseline simulation of the Gunlock ground-water flow model.

#### Alternative Simulations

Conceptually, the Gunlock part of the Navajo and Kayenta aquifers is not considered to be hydraulically connected to underlying formations, nor to the main Navajo and Kayenta aquifers east of the Gunlock Fault. Reflecting that, the baseline model simulates the bottom of the Kayenta aquifer and the Gunlock Fault as no-flow boundaries. Only seepage to and from the Santa Clara River was simulated as being dependent on hydrologic conditions within the aquifers. To examine the effects of other hydraulically connected boundaries, two alternative simulations were tested.

*Alternative 1—Seepage Across the Gunlock Fault.*

In the baseline model, the Gunlock Fault is represented as a no-flow boundary. Because the fault has created a vertical offset between the main part of the Navajo and Kayenta aquifers and the aquifers of the Gunlock part. However, no direct evidence or field observations substantiate this concept. To explore the possible effects of ground-water flow across the fault, the no-flow baseline boundary was replaced with a head-dependent flow boundary with the general-head boundary package.

Required input parameters for the general-head boundary include hydraulic conductivity of the boundary and water-level altitude outside of the modeled area. Computed flow across the boundary is directly proportional to the difference between computed water levels inside the model area and the water levels assigned outside the model area. The general-head boundary was placed in model layer 1 at cells that correspond to the segment of the Gunlock Fault with the vertical offset between the main and Gunlock aquifers.

To simulate seepage across the fault, the following assumptions were made: (1) the vertical face of the boundary is set to the 2,400-ft measured thickness of the Navajo Sandstone west of the Gunlock Fault; (2) the water level on the east side of the fault (3,345 ft) is the average water level simulated for the main part of the Navajo Sandstone at the fault; (3) the fault zone is 300 ft wide; and (4) the hydraulic conductivity of the fault zone is the average horizontal hydraulic-conductivity value of the Navajo Sandstone (1.2 ft/d) used in the main and Gunlock parts. Data are not available to describe the hydrology of the fault zone, and these assumptions are hypothetical.

Given the conditions listed above, the computer model simulated ground-water flow out of the Gunlock aquifers across the Gunlock Fault (fig. 63, table 26). This outflow has a moderate effect on the simulated interaction between the Navajo aquifer and the Santa Clara River. Seepage from the river increased from 2,900 to 3,400 acre-ft/yr. Seepage to the river decreased, from 1,100 to 900 acre-ft/yr, and is a closer match to measured seepage. Overall, simulated water levels at the St. George municipal well field decreased. This simulation indicates that some flow across the fault toward the main aquifer is plausible. However, only one of many possible representations of the fault is explored.

#### *Alternative 2—Inflow from Underlying Formations*

The formations underlying the Kayenta aquifer contain fine-grained material and are generally considered to have poor water-bearing characteristics. Because of this, the base of the Kayenta aquifer is treated as a no-flow boundary in the baseline model. However, as is the case with the Gunlock Fault, no direct hydrologic evidence substantiates the no-flow concept. Depending on the vertical extent of fractures, some ground-water flow across the base of the Kayenta aquifer is possible. Such flow could be induced or enhanced if water levels in the Navajo and Kayenta aquifers declined. Higher dissolved-solids concentrations at St. George Gunlock Well 2, (C-41-17)7ddb-1 (Wilkowske and others, 1998, table 4) indicate that there may be some upward movement of ground water from underlying formations at the municipal well field. To explore this possibility, the no-flow boundary at the base of the Kayenta Formation was replaced with a head-dependent flow boundary, with the general-head boundary package.

The general-head boundary was arbitrarily assigned to cells defining a 1-$mi^2$ area at the base of the Kayenta aquifer and centered at St. George Gunlock Well 2. The following assumptions were made for this alternative: (1) the water-level altitude in the underlying formation near St. George Gunlock Well 2 is about 100 ft higher than the average water level of 3,340 ft estimated for the area (fig. 26); (2) the point at which this water level exists in the underlying formation is 300 vertical feet below the base of the Kayenta aquifer; and (3) the vertical hydraulic conductivity of the underlying formations is about three orders of magnitude less than the estimated vertical hydraulic conductivity of the Kayenta aquifer. These values are consistent with the values specified to simulate flow from underlying formations in the main part of the Navajo and Kayenta aquifers. No data are available to determine the characteristics of this boundary with certainty.

Using the conditions stated above, the alternative model simulated about 300 acre-ft/yr of ground-water inflow from underlying formations (table 27). This inflow has a small effect on the simulated interaction between the Navajo aquifer and the Santa Clara River. Seepage from the river decreased slightly, from about 2,900 to 2,700 acre-ft/yr. Seepage to the river increased by about the same amount, from about 1,100 to 1,200 acre-ft/yr. Simulated water levels at the St. George municipal well field generally rose, increasing at seven wells and remaining the same at one well (table 27). The simulated water level at the Motoqua well increased by 6 ft. The direction of ground-water movement depicted by this alternative simulation (fig. 64a and b) is similar to the baseline simulation, but water levels are slightly higher in the northern part of the simulated area. Given the above conditions, the alternative of allowing a small amount of inflow to the area from underlying formations is plausible.

### Model sensitivity

Although the baseline model is not “calibrated,” it is a viable tool for analysis of general concepts of ground-water flow for the Gunlock part of the Navajo and Kayenta aquifers. To get a feel for the relative importance of the aquifer properties and fluxes that

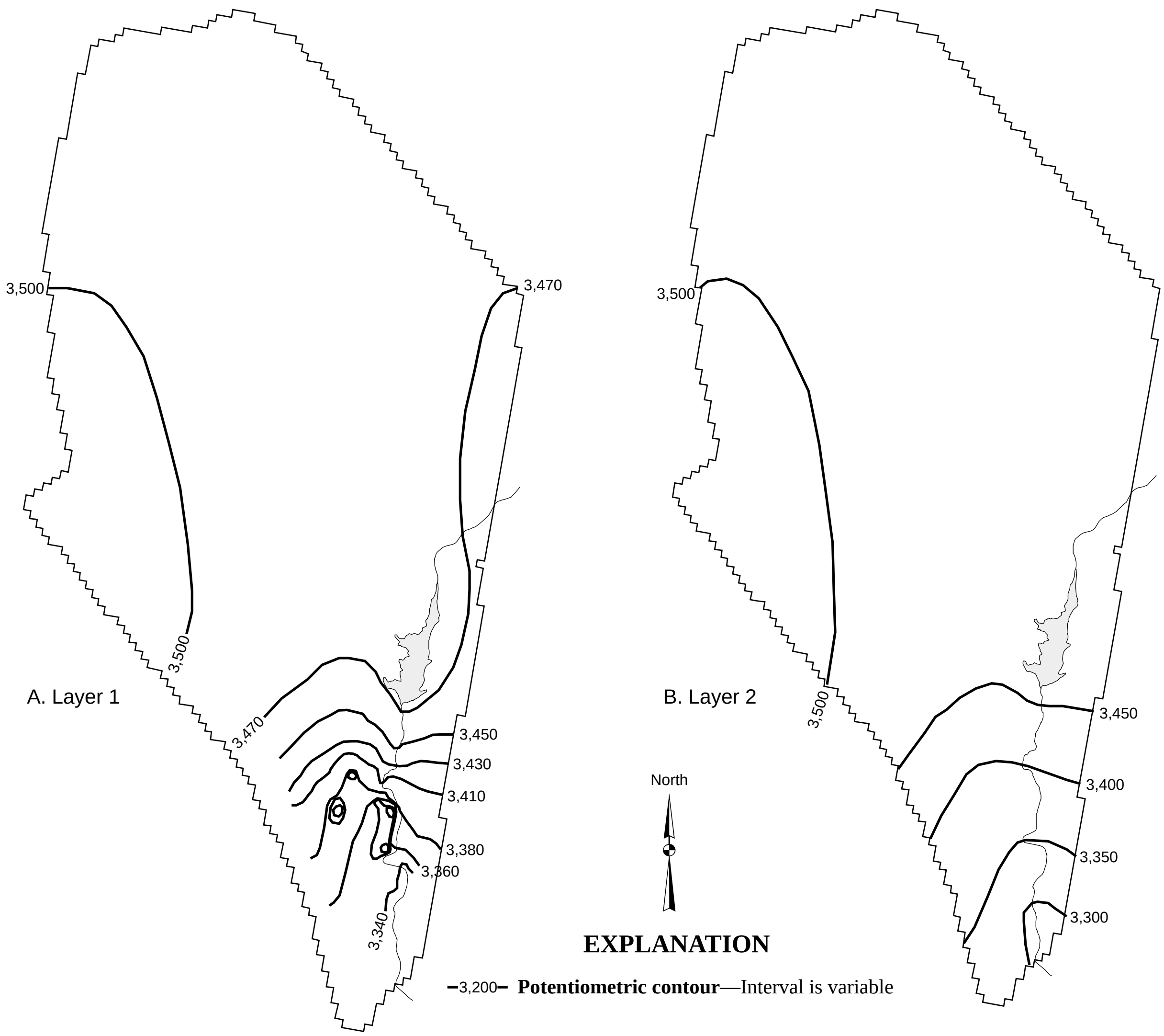


**Figure 63.** Simulated potentiometric contours for (a) layer 1, and (b) layer 2 of the alternative simulation depicting flow across the Gunlock Fault, Gunlock ground-water flow model.

make up the Gunlock aquifers, a sensitivity analysis of the baseline simulation was performed. A sensitivity analysis identifies which model parameters have the greatest influence on model simulations. Although there is no direct correlation between model sensitivity and the natural system, model sensitivity is useful when considering additional analysis or data collection.

The sensitivity of the baseline model to different parameters is shown in figure 65. The height of each bar is subjective and based on an evaluation of how variations in the parameter affected computed water-levels and fluxes. A more detailed analysis and the quantitative results of all sensitivity runs are described in appendix B.

Computed water levels in the baseline model are highly sensitive to both increases and decreases in horizontal anisotropy (the ratio between east-west and north-south horizontal hydraulic conductivity) and the distribution of infiltration of precipitation. Decreased horizontal hydraulic conductivity in the north-south orientation caused computed water levels in all parts of the modeled area to decrease dramatically. Increased anisotropy caused increased head-dependent flux into and out of the Santa Clara River. Changes in the distribution of infiltration of precipitation had the greatest affect on water levels in areas away from the Santa Clara River. Both seepage to and from the Santa Clara River are moderately sensitive to changes in streambed properties. Computed water levels were moderately

**Table 26.** (a) Conceptual and simulated ground-water budgets and (b) simulated versus measured water-level differences for the baseline simulation and the simulation testing flow across the Gunlock Fault in the Gunlock part of the Navajo and Kayenta aquifers, central Virgin River basin, Utah

**(a) Ground-water budget[1]**

| Flow component | Conceptual | Baseline simulation | Gunlock Fault flow simulation |
|---|---|---|---|
| **Recharge, in acre-feet per year** | | | |
| Infiltration of precipitation | 700 to 2,200 | 1,400 | 1,400 |
| Seepage from Gunlock Reservoir | 0 to 2,200 | 1,000 | 1,000 |
| Seepage from Santa Clara River | 700 to 2,900 | 2,900 | 3,400 |
| Total | 1,400 to 7,300 | 5,300 | 5,800 |
| **Discharge, in acre-feet per year** | | | |
| Well discharge | 3,400 to 5,500 | 4,200 | 4,200 |
| Seepage to Santa Clara River | 400 | 1,100 | 900 |
| Flow across Gunlock Fault | 0 | 0 | 600 |
| Total | 3,800 to 5,900 | 5,300 | 5,700 |

[1] Budget amounts listed in italics were specified fluxes. All others are head-dependent fluxes determined by the model.

**(b) Difference between simulated and measured water levels, in feet**

| Well identifier | Baseline simulation | Gunlock Fault flow simulation |
|---|---|---|
| Well #1 | 7 | 2 |
| Well #2 | 13 | -2 |
| Well #3 | [1]-36 | [1]-38 |
| Well #4 | -33 | -35 |
| Well #5 | -1 | -2 |
| Well #6 | 24 | 8 |
| Well #7 | -1 | -3 |
| Well #8 | -7 | -9 |
| Motoqua well | -17 | -62 |
| Root mean square error | 20 | 27 |

[1] Difference determined from water level measured in February 1997; all other water levels measured in February 1996.

**Table 27.** (a) Conceptual and simulated ground-water budgets and (b) simulated versus measured water-level differences for the baseline simulation and the simulation testing inflow from underlying formations in the Gunlock part of the Navajo and Kayenta aquifers, central Virgin River basin, Utah

**(a) Ground-water budgets[1]**

| Flow component | Conceptual | Baseline simulation | Underlying-formation inflow simulation |
|---|---|---|---|
| **Recharge, in acre-feet per year** | | | |
| Infiltration of precipitation | 700 to 2,200 | 1,400 | 1,400 |
| Seepage from Gunlock Reservoir | 0 to 2,200 | 1,000 | 1,000 |
| Seepage from Santa Clara River | 700 to 2,900 | 2,900 | 2,700 |
| Flow from the Moenave | 0 | 0 | 300 |
| Total | 1,400 to 7,300 | 5,300 | 5,400 |
| **Discharge, in acre-feet per year** | | | |
| Well discharge | 3,400 to 5,500 | 4,200 | 4,200 |
| Seepage to Santa Clara River | 400 | 1,100 | 1,200 |
| Total | 3,800 to 5,900 | 5,300 | 5,400 |

[1] Budget amounts listed in italics were specified fluxes. All others are head-dependent fluxes determined by the model.l

**(b) Differences between simulated and measured water levels, in feet**

| Well identifier | Baseline simulation | Underlying-formation inflow simulation |
|---|---|---|
| Well #1 | 7 | 11 |
| Well #2 | 13 | 27 |
| Well #3 | [1]-36 | [1]-34 |
| Well #4 | -33 | -32 |
| Well #5 | -1 | -1 |
| Well #6 | 24 | 33 |
| Well #7 | -1 | 0 |
| Well #8 | -7 | -6 |
| Motoqua | -17 | -11 |
| Root mean squared error | 20 | 22 |

[1] Difference determined from water level measured in February 1997; all other water levels measured in February 1996.

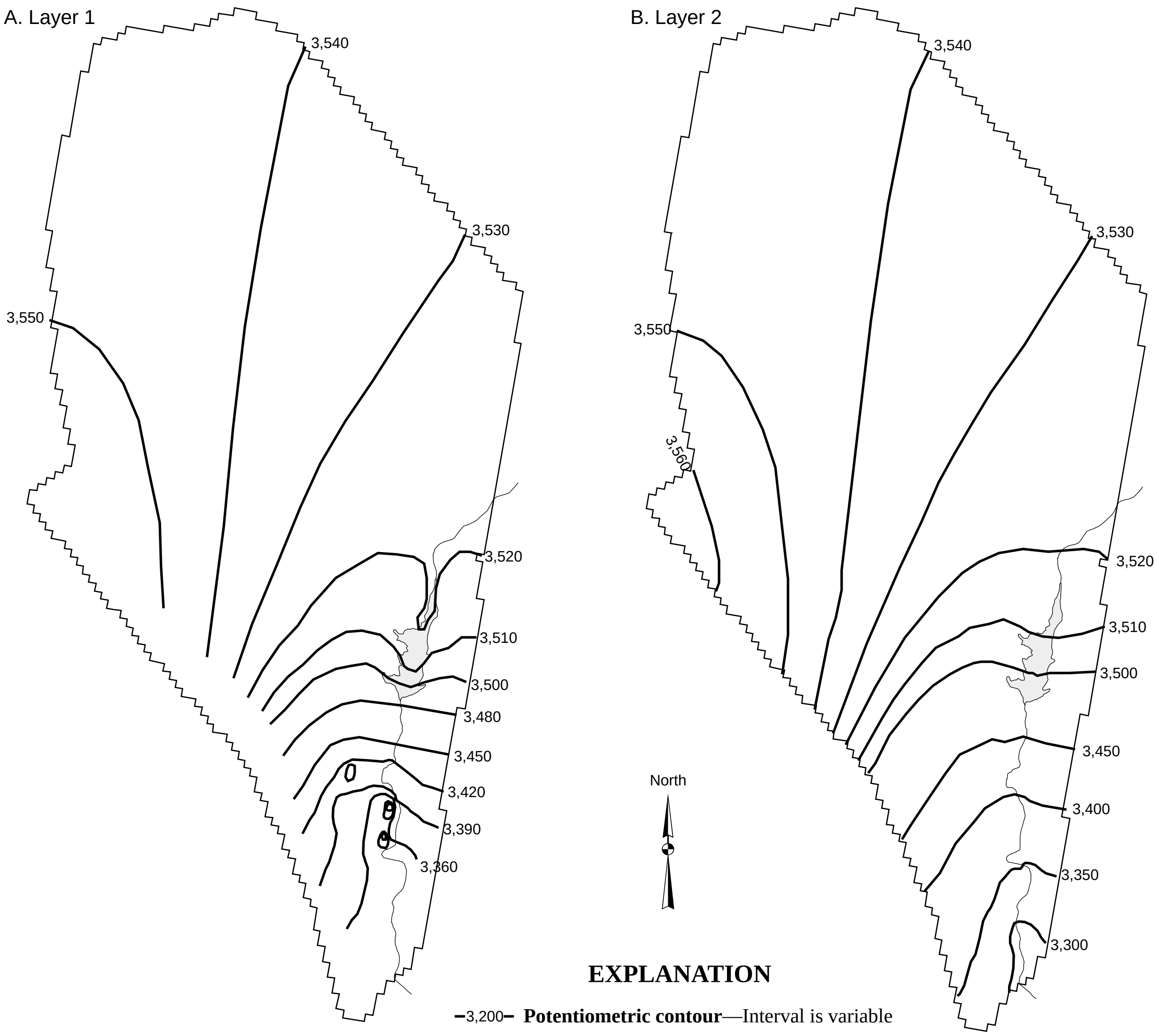


**Figure 64.** Simulated potentiometric contours for (a) layer 1, and (b) layer 2 of the alternative simulation depicting inflow from underlying formations, Gunlock ground-water flow model.

sensitive to changing aquifer properties of layer 1 near the Gunlock Fault. The baseline simulation is not very sensitive to changes in hydraulic properties of the Kayenta aquifer.

#### Need for additional study

On the basis of the alternative simulations and sensitivity analysis of the baseline model of the Gunlock part of the Navajo and Kayenta aquifers, the need for additional data became apparent. Better quantification of the hydrologic properties associated with the Gunlock Fault is needed to determine whether ground-water flow occurs across the fault, and the direction and amount of that flow. Design of an aquifer test with observation wells located on both sides of the fault would answer some of those questions. Additional information regarding the interaction between the Santa Clara River and adjacent Navajo aquifer also would improve the conceptual model. Specifically, identifying aquifer properties associated with the streambed material would be helpful and could be determined with an appropriately designed multi-well aquifer test.

To better define the general shape and hydraulic gradient of the water table, water-level observation wells need to be constructed in areas away from the St. George municipal well field. Annual, seasonal, or monthly monitoring of water levels at observation wells

A1 Anisotropy
K1 Horizontal hydraulic conductivity of the Kayenta aquifer
V1 Vertical hydraulic conductivity of the Kayenta aquifer
S1 Streambed hydraulic conductivity
K2 Hydraulic conductivity near the Gunlock Fault
R1 Recharge from Gunlock Reservoir
I1 Infiltration of precipitation

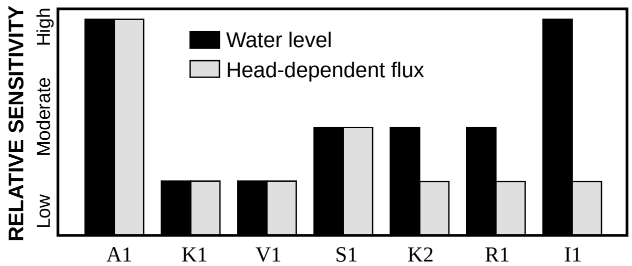


**Figure 65.** Relative sensitivity of the baseline model of the Gunlock part of the Navajo and Kayenta aquifers to uncertainty in selected properties and flows.

would help identify temporal variations in the potentiometric surface of the aquifers. Long-term water-level trends would help determine whether natural recharge to the aquifers is in balance with well discharge and seepage to the Santa Clara River.

#### Water-resource management

For the Gunlock part of the Navajo and Kayenta aquifers, the most important hydrologic parameter is the ground-water/surface-water interaction between the Santa Clara River and Navajo aquifer. Interaction is a function of aquifer boundaries and the hydraulic properties of the Navajo aquifer and streambed materials. Effective water-resource management must consider the effects of pumping at the St. George municipal well field on ground-water/surface-water interaction. The baseline model is a tool that can be used to better illustrate the role of pumping on streamflows.

### Model Limitations

The ground-water flow model of the Gunlock part of the Navajo and Kayenta aquifers required simplification and, thus, could not accurately represent the actual heterogeneity of the system. Rarely are model simulations in perfect agreement with observations and field measurements. These factors are even more relevant for the baseline model, which, because of limited data, is not calibrated to reproduce a specific set of hydrologic conditions. Also, the model simulates steady-state conditions and does not account for the effects associated with any changes in the amount of water stored in the aquifers. Although this model simulates the Gunlock aquifers reasonably well, the solution is not unique. Other numerical simulations could yield similar results. Model results should only be used for verifying concepts and indicating generalized effects associated with the hydrologic stresses that are simulated. Results should not be used to evaluate absolute water levels and flows at specific locations. The ability of this model to represent actual ground-water conditions could be better evaluated when additional data are collected and the system is observed under other stress conditions.

A specific limitation of the baseline model concerns flow at specified-flux boundaries. Because the model contains only one head-dependent flux boundary (the Santa Clara River), any change in specified flux will be exactly compensated for at the head-dependent flux boundary. For example, an increase in simulated pumping rates will be compensated for by a net increase in seepage from the Santa Clara River. Pumping cannot be increased beyond the point where seepage from the stream exceeds total streamflow, which is specified at 6.0 $ft^3/s$. Therefore, any increase in pumping rates beyond that will result in the complete dewatering of the model area. Although this is consistent with the conceptual model, it represents a simplification that may not accurately reflect the natural system.

## SUMMARY

This study focused on the two main ground-water reservoirs within the central Virgin River basin: the upper Ash Creek basin ground-water system and the Navajo and Kayenta aquifer system. On the basis of measurements, estimates, and numerical simulations of reasonable values for all inflow and outflow components, total water moving through the upper Ash Creek drainage basin ground-water system is estimated to be about 14,000 acre-ft/yr. Recharge to the upper Ash Creek drainage basin ground-water system primarily enters the system as infiltration of precipitation and seepage from ephemeral and perennial streams. The main source of discharge is assumed to be evapotranspiration; however, subsurface discharge near Ash Creek Reservoir also maybe important. The character of two of the hydrologic boundaries of the upper Ash Creek drainage basin ground-water system is speculative. The eastern boundary represented by the Hurricane Fault is assumed to be a no-flow boundary. Likewise, it is assumed that the principal drain for the system is subsurface outflow beneath Ash Creek Reservoir along the