Table 15. Estimated ground-water budget for the main part of the Navajo and Kayenta aquifers, central Virgin River basin, Utah

Flow component	Volume, in cubic feet per second	Volume, in acre-feet per year
Recharge		
Infiltration of precipitation	10 to 30	7,200 to 21,700
Seepage from perennial streams	1.8 to 5.5	1,300 to 4,000
Seepage from ephemeral streams	.28 to 4.2	200 to 3,000
Seepage from underlying formations	0 to 4.2	0 to 3,000
Infiltration of unconsumed irrigation water	0 to 5	0 to 4,400
Total (rounded)	12 to 49	8,700 to 36,100
Discharge		
Well discharge	10 to 15	7,200 to 10,900
Spring discharge	6.9 to 8.5	5,000 to 6,200
Seepage to the Virgin River	6.5 to 7.9	4,700 to 5,700
Seepage to underlying formations	0 to 7.5	0 to 5,400
Total (rounded)	23 to 39	17,000 to 28,000

Table 16. Estimated ground-water budget for the Gunlock part of the Navajo and Kayenta aquifers, central Virgin River basin, Utah

Flow component	Volume, in cubic feet per second	Volume, in acre-feet per year
Recharge		
Infiltration of precipitation	1 to 3	700 to 2,200
Seepage from the Santa Clara River (rounded)	1 to 4	700 to 2,900
Seepage from the Gunlock Reservoir	0 to 3	0 to 2,200
Total (rounded)	2 to 10	1,400 to 7,300
Discharge		
Well discharge	4.7 to 7.6	3,400 to 5,500
Seepage to the Santa Clara River	.5	400
Total (rounded)	5 to 8	3,800 to 5,900

ary allows water to move across it at a fixed rate. A head-dependent flux-boundary allows the amount of water moving across it to vary when the head in the aquifer varies (see Franke, Reilly, and Bennett, 1987). No-flow boundaries representing the erosional and fault-controlled extend or ground-water divides in the aquifers are fairly well defined. Other boundaries, such as those representing flow to and from underlying, adjacent, and overlying formations, are not well understood. In general, the contact between the aquifers and underlying or 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 unconfined, the boundary is a free surface. A specified-flux is applied across the free-surface boundary to represent infiltration from precipitation, streams, and unconsumed irrigation water. There also are areas on the free surface boundary where head dependent fluxes are applied to simulate discharge from the system, such as spring discharge and seepage to streams.

Upper Ash Creek Drainage Basin Ground-Water System

Ground-water development in the upper Ash Creek drainage basin was negligible prior to 1995. Water-level variation in a well that has been measured since 1934 indicates no long-term effect from pumping, but seasonal and longer-term water-level changes indicate that recharge to the system is probably affected by climatic variability (fig. 31). Because there have been no long-term changes in water levels, changes in ground-water storage are negligible and the system is considered to be in steady-state. Thus, a steady-state computer model was developed to examine how the hydrologic system functions and to test and evaluate the conceptual model and test the estimated water budget. The baseline period was 1995.

A baseline simulation was developed to represent how the system is conceptualized to function. Alternative simulations, which represent variations to the conceptual model, were tested to determine which were reasonable and which were not. Because of uncertainties about the flows and properties of the hydrologic system, sensitivity analyses were done on the baseline simulation to test how variations in these parameters within reasonable limits affected simulation results.

Model Characteristics and Discretization

The model is discretized into a grid of rectangular blocks or cells, each assumed to have homogeneous properties. The ground-water flow system for the upper Ash Creek drainage basin is divided into 67 rows, 49 columns, and 3 layers with a total of 9,849 cells (fig. 32). The model grid is designed to emphasize flow in the basin-fill aquifer, for which the most information is available. All but a few cells that represent the basin-fill aquifer are 1,000 ft by 1,000 ft (about 23 acres). The southernmost cells are as much as 34 acres. Cells that represent the alluvial-fan aquifer range from 1,000 ft by 1,000 ft to 1,000 by 1,500 ft (about 34 acres). Cells that represent areas in the Pine Valley Mountains and the Pine Valley monzonite aquifer are as large as 3,000 ft by 3,000 ft (about 207 acres). The three aquifers are each represented by a model layer and the areal extent of each layer becomes larger with depth. Layer 1 represents the basin-fill aquifer and includes about 28 mi^2 and 875 active cells. Layer 2 represents the alluvial-fan aquifer and includes about 50 mi^2 and 1,251 active cells. Layer 3 represents the Pine Valley monzonite aquifer and includes about 99 mi^2 and 1,865 active cells. The Pine Valley monzonite aquifer is assumed to underlie the entire modeled area, but this is not based on fact, merely supposition. The orientation of the grid is rotated clockwise about 35 degrees from true north to better align with physical boundaries of the system and the dominant fracture orientation in the Pine Valley monozonite aquifer.

The model layers correspond to geologic units and vary in thickness. Layer 1 represents the Quaternary basin fill and ranges from less than 100 to as much as 1,500 ft thick. Layer 2 represents semiconsolidated Tertiary alluvial-fan deposits and ranges from less than 100 to as much as 1,500 ft thick. Layer 3 represents the Pine Valley monozonite aquifer and is assigned a thickness of no more than 3,000 ft. The thickness of the Pine Valley monozonite aquifer is not known, but 3,000 ft was arbitrarily chosen as a depth below which ground-water movement is negligible. Figure 32 shows the model layering used for the flow simulation.

Boundary Conditions

No-flow, specified flux, and specified-head boundaries were used to represent the hydrologic boundaries in the Ash Creek basin model (fig. 33).

Recharge Boundaries

The top of the uppermost layer throughout the modeled area represents a specified-flux recharge boundary, where simulated recharge includes infiltration of precipitation, seepage from ephemeral and perennial streamflow, and infiltration of unconsumed irrigation water. No recharge from subsurface flow was conceptualized or simulated.

Precipitation

Infiltration of precipitation is simulated with the recharge package (Harbaugh and McDonald, 1966, p. 28). The distribution of annual precipitation for the modeled area was obtained from the Utah Climate Center (1996). Initially recharge from infiltration was applied as 8.5 percent of total precipitation, but as the steady-state model was refined, the percentage was increased as total precipitation increased with altitude. The areal distribution of recharge from infiltration of precipitation is shown in figure 34.

Ephemeral Streams

Recharge from streams flowing onto the valley floor from the surrounding mountains and plateaus also is simulated as part of the recharge package but is not represented in figure 34. In the areas where Kanarra, Spring, Camp, and Taylor Creeks flow onto the valley floor the recharge package was used to apply about half the total estimated flow in these streams as infiltration into layer 1. The recharge package also was used to apply additional infiltration to cells that represent areas

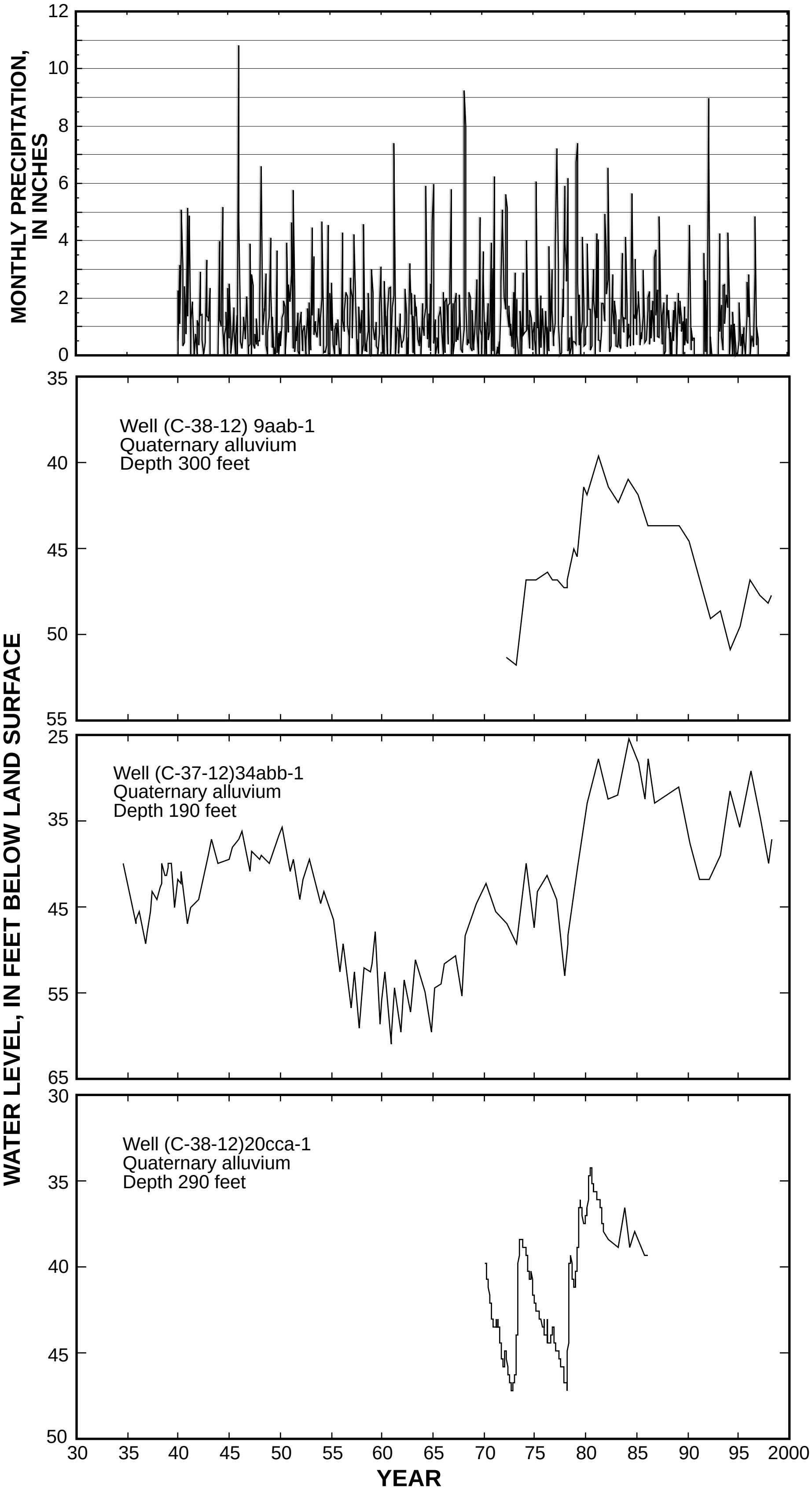


Figure 31. Water levels in three wells in the upper Ash Creek drainage basin, Utah, 1934-95.

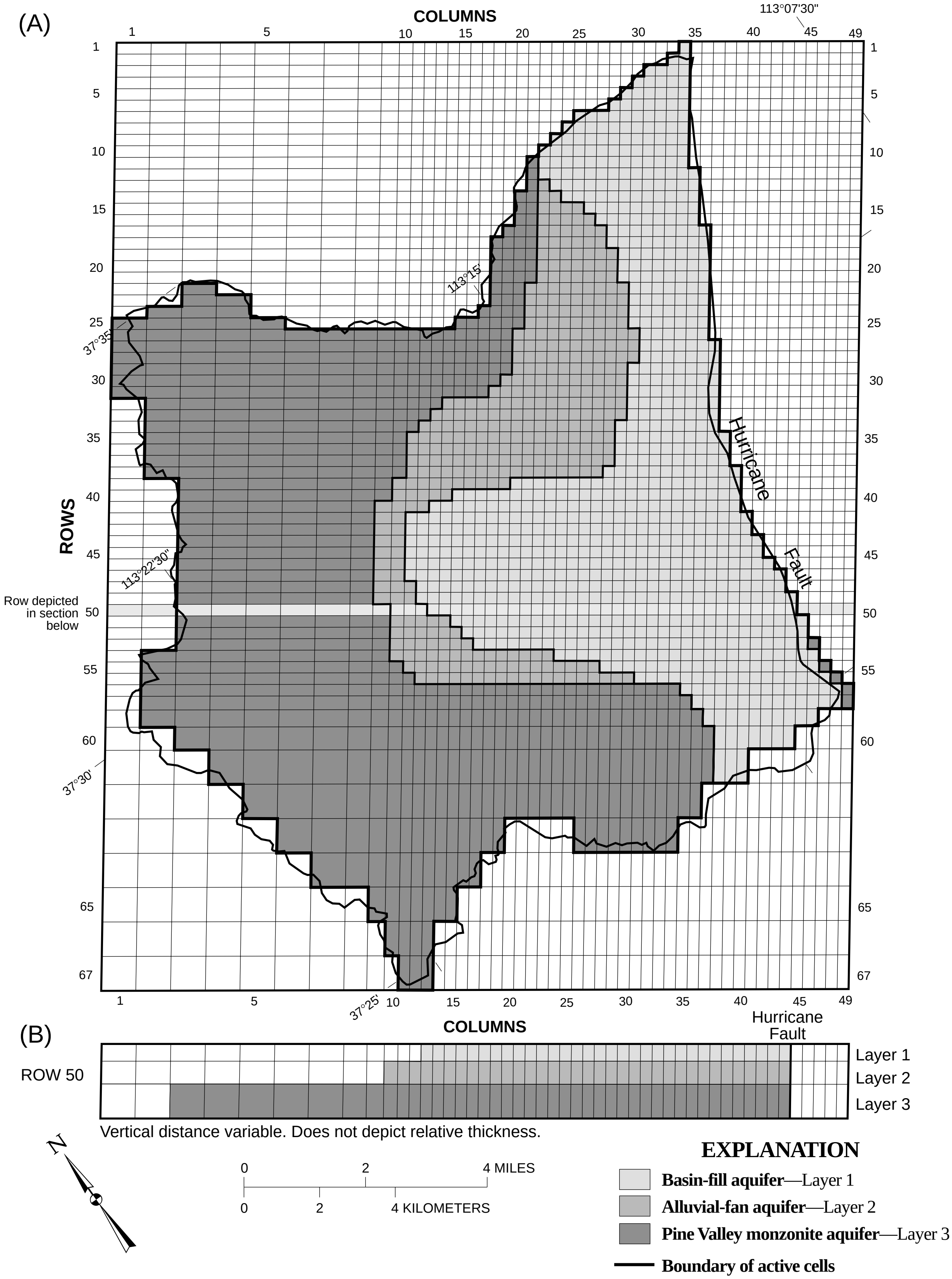
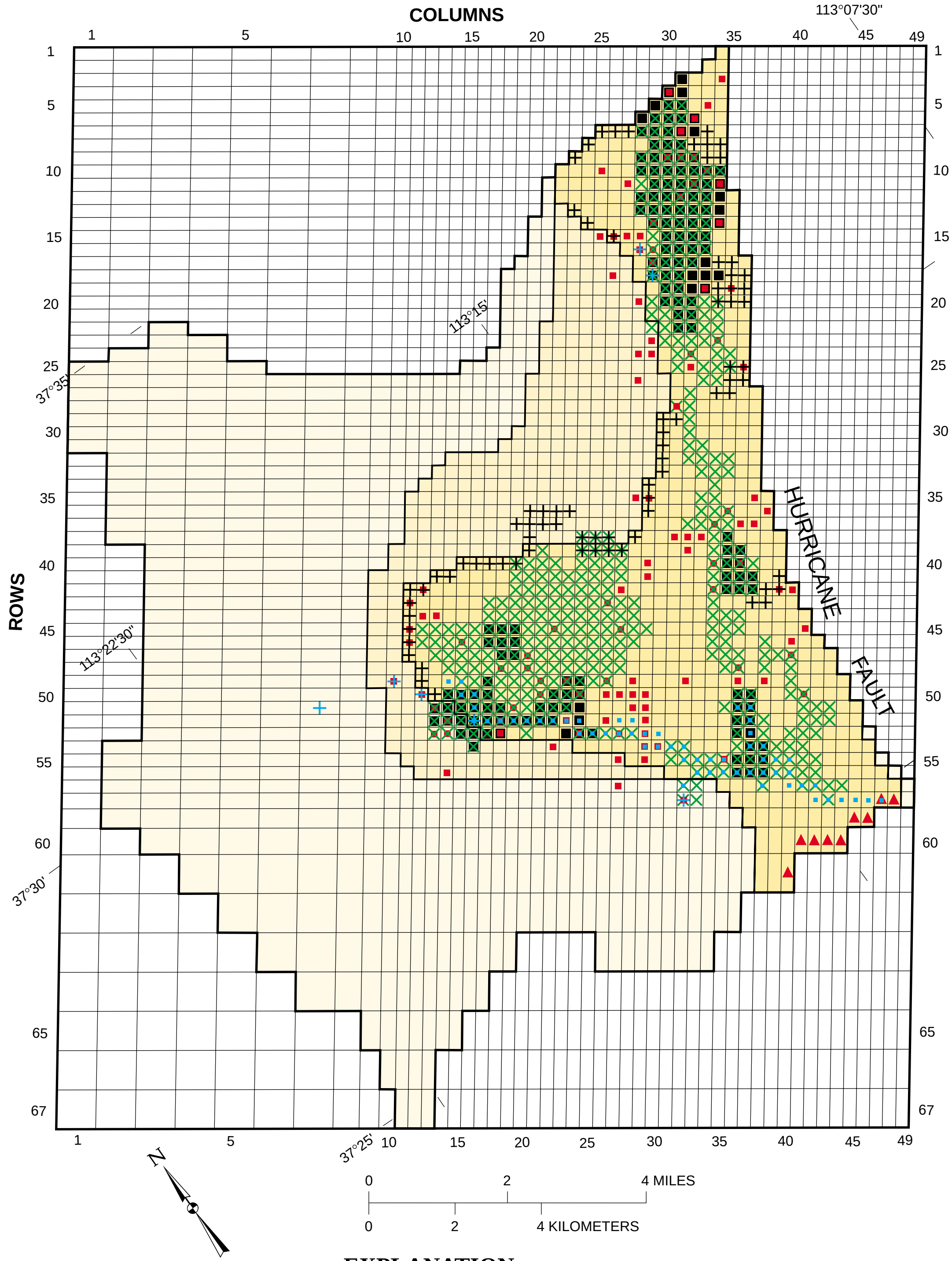


Figure 32. Map and section showing (a) finite-difference model grid and (b) layering scheme for the ground-water flow model of the upper Ash Creek drainage basin, Utah.



EXPLANATION

Active cells
- Layers 1, 2, and 3
- Layers 2 and 3
- Layer 3

Boundary of active cells

River cell—Simulates stream seepage to or from the basin

Drain cell—Simulates spring discharge

Well cell—Simulates well withdrawal

General-head cell—Simulates subsurface outflow

Areal recharge increased to simulate recharge from ephemeral stream flow

Areal recharge increased to simulate recharge from unconsumed irrigation water

ET cell—Simulates potential evapotranspiration by riparian vegetation

Figure 33. Boundary conditions and cell assignments for the ground-water flow model of the upper Ash Creek drainage basin, Utah.

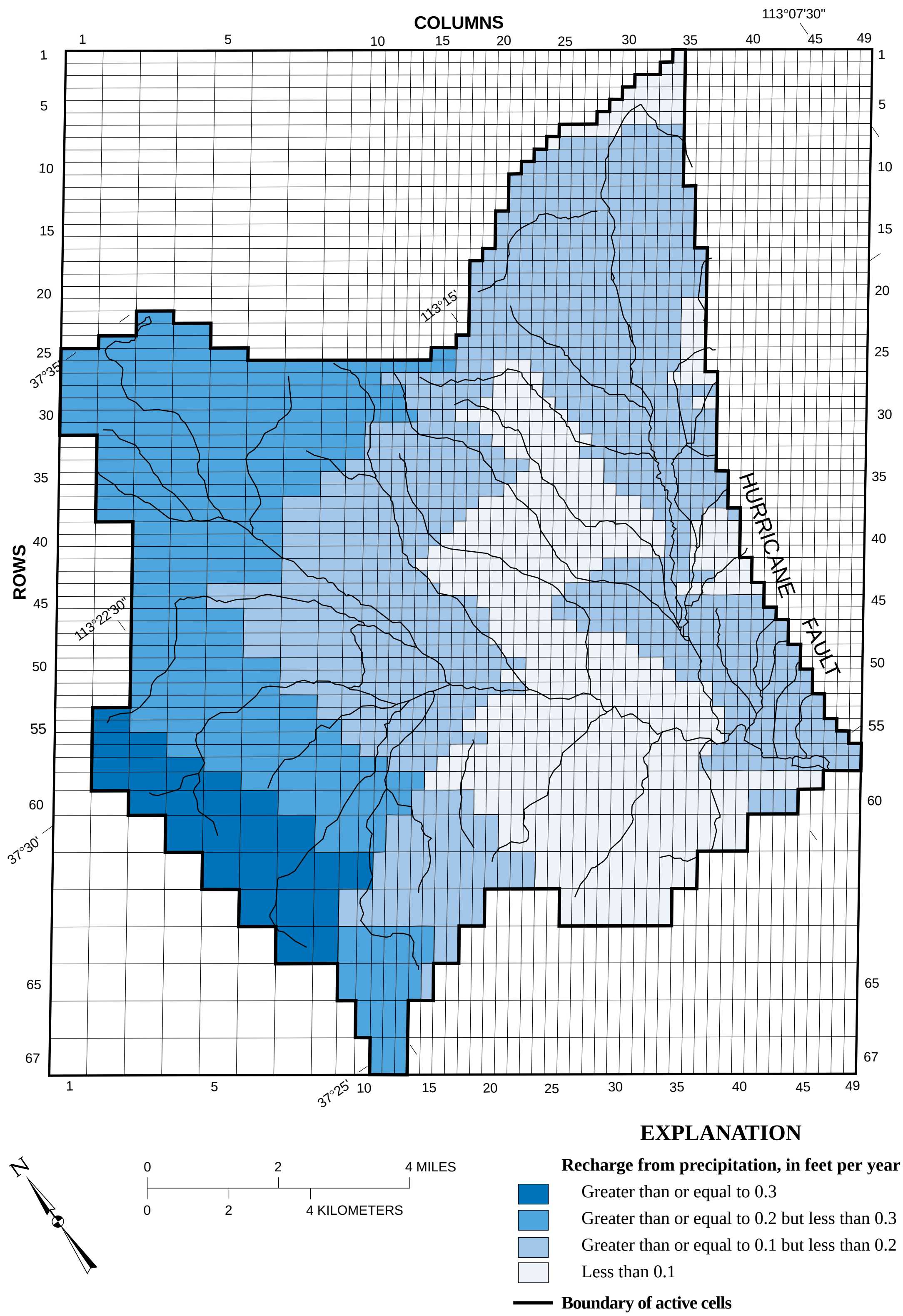


Figure 34. Areal distribution of recharge from infiltration of precipitation in the ground-water flow model of the upper Ash Creek drainage basin, Utah.

where ephemeral streams flow from the Harmony and Pine Valley Mountains onto the valley floor. The amount was arbitrary because there is no record of streamflow for these washes. The amount was adjusted during steady-state model refinement to closely approximate steady-state water levels but not beyond the estimated runoff for the drainage area represented by the wash.

Ash Creek

The river package (Harbaugh and McDonald, 1996, p. 26) simulates stream seepage from Ash Creek to the basin-fill aquifer (recharge). The river package represents a head-dependent flux boundary and one reach per cell is simulated (fig. 35). Stream leakage occurs whenever the water level in the aquifer is below the stage in the stream. When the stream is not in hydraulic connection with the aquifer (when there is an unsaturated zone beneath the streambed), the flux is controlled by the difference between the altitude of the stream stage and the bottom of the streambed material (RBOT) and the hydraulic conductance of the streambed. In cases where the stream is in hydraulic connection with the aquifer, the rate of leakage is controlled by (1) the difference between the altitude of the stream stage and the calculated head at the node of the cell underlying the steam reach; and (2) the conductance of the streambed (the product of vertical hydraulic conductivity and cross sectional area divided by streambed thickness). The cross sectional area is the area of streambed within each cell. Values for conductance of a small stream traversing basin fill are probably quite variable, but most were assigned a value equal to one-tenth of the horizontal hydraulic-conductivity value of the basin-fill aquifer times the length of the stream across the cell divided by a 1-ft thick streambed. The cells that represent Ash Creek Reservoir were assigned a value equal to one-hundredth of the horizontal hydraulic-conductivity value of the basin-fill aquifer times the reservoir area in the cell divided by a 1-ft thick lake bed because the reservoir bottom likely consists of much finer grained sediments than the streambed. The average altitude of the stream/lake bed was obtained from topographic maps with a contour interval of 20 ft. The stream/reservoir altitude was assigned a value 10 ft higher than the bottom altitude, thereby allowing stream or lake leakage to be driven by a hydraulic head of 10 ft. The actual driving head is probably more than 10 ft in the reservoir and less than 10 ft in the stream. A model that is intended for use as a predictive tool should be constructed so that this interaction between stream and aquifer and between reservoir and aquifer is more realistically depicted using vertical hydraulic conductivity values and varying stream/reservoir stage.

Irrigation

Irrigation areas were delineated from land-use maps developed by the Utah Division of Water Resources. Recharge of 880 acre-ft/yr was simulated with the recharge package to account for unconsumed irrigation that infiltrates to the water table (fig. 33). During steady-state model refinement, recharge rates for selected cells were adjusted within reason to obtain a better simulated match with measured water levels. The total recharge simulated for irrigation is consistent with the application method being used.

Discharge boundaries

Several types of head-dependent flux and specified-flux discharge boundaries are used in the baseline simulation (fig. 35). Evapotranspiration is simulated with the evapotranspiration package, well discharge is simulated with the well package, and discharge from springs is simulated with the drain package. Seepage to Ash, Sawyer, and the lower reach of Kanarra Creek was simulated with the river package. Subsurface flow to the south into the lower reaches of the Ash Creek drainage is simulated with the general-head package.

Evapotranspiration

Simulated evapotranspiration from the saturated zone in areas where cottonwood trees and pasture grasses grow is dependent on the depth of the water table, the average rate of consumption by each type of vegetation present, and the depth below land surface at which transpiration ceases for each type of vegetation. The evapotranspiration package simulates the effects of direct evaporation and plant transpiration by using a linear variation in the evapotranspiration rate. The maximum rate occurs when the water table is at or near land surface. The rate drops to zero when the water table is deeper than a specified extinction depth for each type of vegetation. The two dominant types of phreatophytes, cottonwood trees and pasture grasses, have different rates of water consumption and different maximum depths from which they can use ground water. The baseline numerical simulation described in this report uses extinction depths of 25 ft (Robinson, 1958, p. 62) for cottonwoods and 5 ft for pasture grass. Because of lower temperatures and density of the

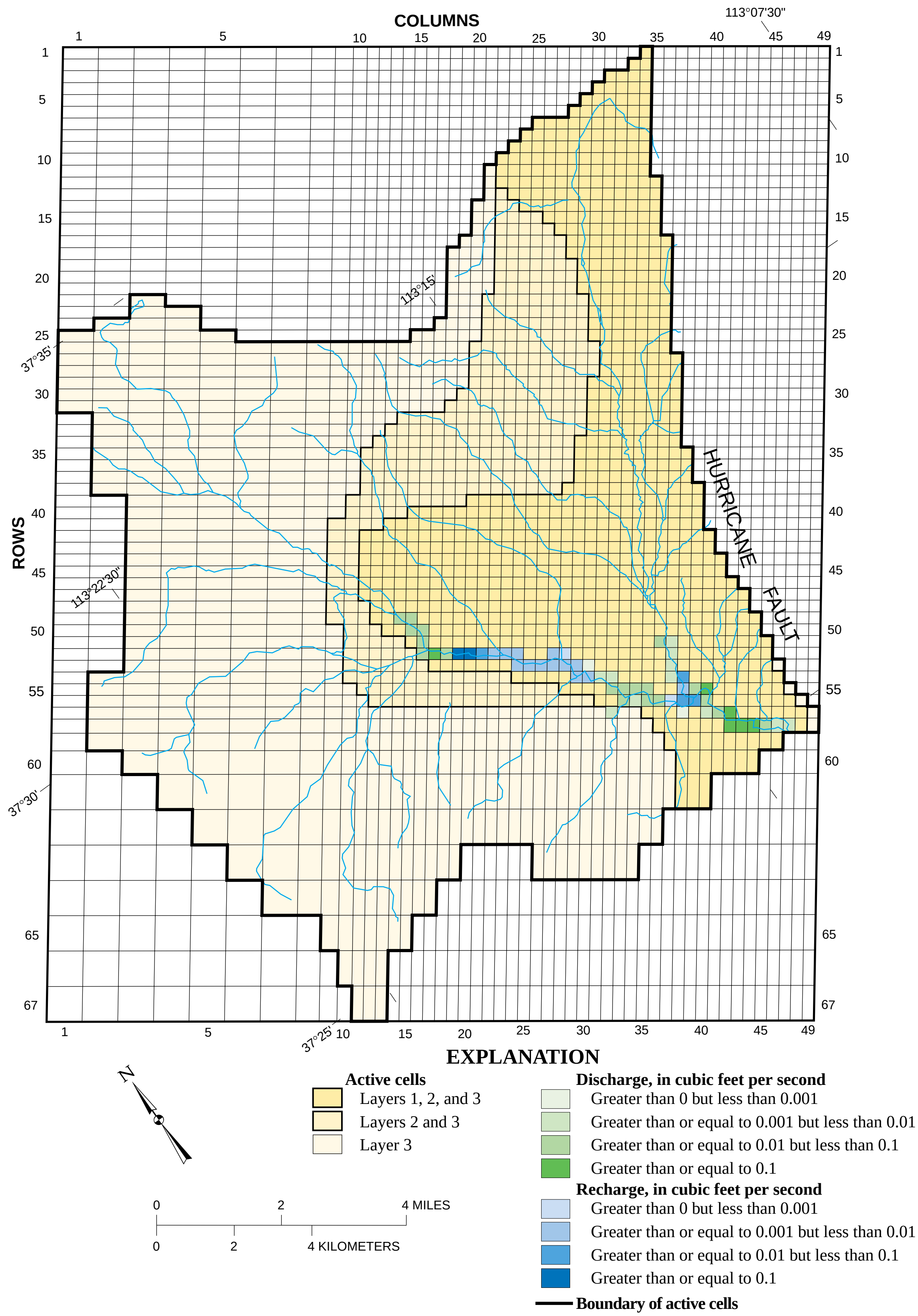


Figure 35. Simulated recharge to and discharge from the aquifers by stream seepage in the ground-water flow model of the upper Ash Creek drainage basin, Utah.

growth in the upper Ash Creek drainage, consumptive use rates were set at 3.5 ft/yr for cottonwood trees and 1.75 ft/yr for pasture grass, somewhat less than the rates from other studies. Evapotranspiration represents a head-dependent discharge boundary at the top of the saturated zone that functions only when the water-table altitude is above the extinction depth or above land surface.

Wells

Well discharge is simulated as a specified-flux discharge with the well package. Because water use for the upper Ash Creek drainage basin is not well documented, the amount of discharge simulated for each cell was estimated on the basis of type of water use, well diameter, and length of open interval. Relative to the water right, household wells were assigned a fixed discharge of 0.67 acre-ft/yr, wells used for stock were assigned a fixed discharge of 0.23 acre-ft/yr, and wells used for domestic, stock, and irrigation were assigned a fixed discharge of 3.3 acre-ft/yr. These rates combined with the rate for irrigation wells yielded a total discharge of 1,440 ft/yr. Discharge from irrigation wells was estimated based on average discharge from four irrigation wells measured with a sonic velocity device. The average discharge per square foot of screen for the four measured wells was 0.85 (gal/min)/ft^2. This factor was multiplied by the screen area of all other irrigation wells, and assuming 3 months of pumping per year, was used to obtain the estimated discharge in the baseline simulation. The distribution and magnitude for simulated well discharge is shown in figure 36.

Springs

Spring discharge is simulated with the drain package. The drain package represents a head-dependent discharge boundary for each cell to which it is assigned. The amount of discharge simulated depends on the assigned conductance value and the difference between the assigned drain altitude and the simulated water level in that cell. Drain altitudes were taken from topographic maps and were adjusted during model refinement within the accuracy of the map contour intervals. The drain simulates no discharge when the computed head is lower than the specified drain altitude. The conductance values were adjusted during the model refinement procedure to approximate the measured discharge at selected springs.

Ash and Kanarra Creeks

Discharge from the aquifer into the perennial reaches of Ash and Kanarra Creeks is simulated with the river package (fig. 33). The river package represents a head-dependent boundary at the contact between perennial streams and the uppermost saturated zone. Discharge from the ground-water system to the streams is controlled by (1) the difference between the simulated head in a river cell and the altitude of the stream or lake bottom, (2) the streambed area in each cell, and (3) the assigned conductance value for the streambed. The streambed area in each cell and the assigned conductance values are explained above in the “Ash Creek” section.

Subsurface Flow to Lower Ash Creek Drainage

Subsurface flow from the upper Ash Creek drainage basin ground-water system to the south into the lower Ash Creek drainage (fig. 33) is simulated with the general-head package. This package represents a head-dependent boundary between the assigned cells and a fixed-head boundary outside of the modeled area. When the fixed head is lower in altitude than the simulated water-level altitude in the general-head cells, discharge from those cells is simulated. The amount of discharge simulated depends on the simulated head difference and the assigned conductance value. The conductance value is approximated by dividing the product of the horizontal hydraulic conductivity of the material and the cross-sectional area by the distance traveled through that material. This value is somewhat speculative for the area south of Ash Creek Reservoir because the hydraulic properties of the material through which ground water moves are uncertain. Values of conductance assigned for the baseline simulation were 20 ft^2/d for the basin-fill and Pine Valley monzonite aquifers and 15 ft^2/d for the alluvial-fan aquifer. A fixed head of 3,850 ft was assigned to represent a well 3.5 mi to the south.

No-Flow Boundaries

It is conceptualized that no ground water enters or exits the upper Ash Creek drainage basin at the drainage-basin boundaries or at the Hurricane Fault. The model was developed so that the appropriate layer boundaries terminate at the drainage-basin boundaries and the fault. No flow was simulated for all lateral boundaries except at the general head cells south of Ash Creek Reservoir. Also, no flow was simulated for the base of the Pine Valley monzonite aquifer (layer 3).

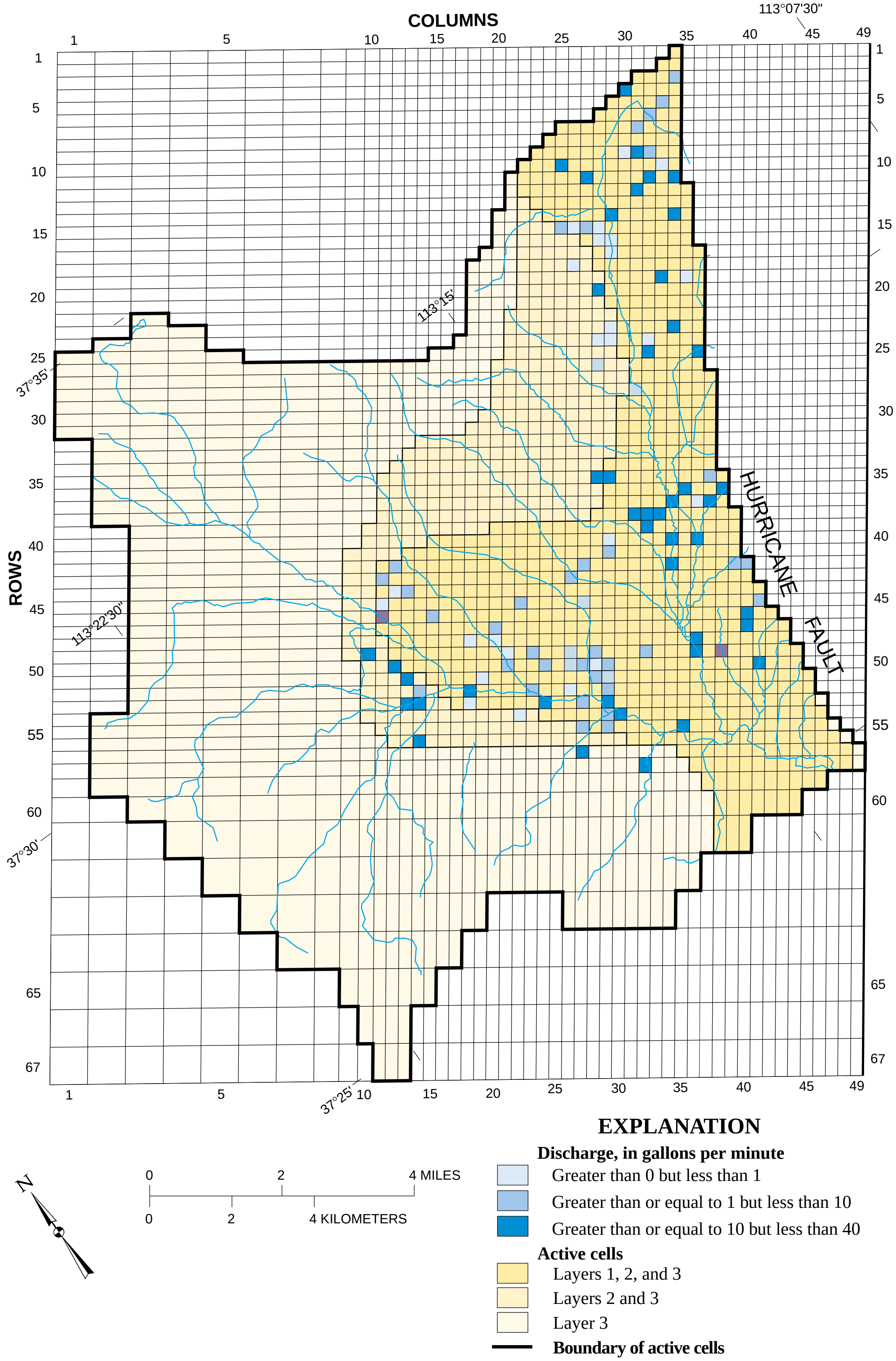


Figure 36. Location and magnitude of simulated well discharge in the ground-water flow model of the upper Ash Creek drainage basin, Utah.

Ground-Water Divide

The ground-water divide between the upper Ash Creek drainage basin and Cedar Valley ground-water systems represents a no-flow boundary whose position varies with time. Withdrawals from the Cedar Valley ground-water system to the north apparently have moved this boundary 2 mi farther south since the mid-1940s. These withdrawals were not simulated in the upper Ash Creek drainage basin.

Faults

A no-flow boundary is simulated for the Hurricane Fault. Cross sections from geologic mapping indicate that the offset of the fault is many thousands of feet. Water levels and streamflow measurements indicate that there is little or no ground water moving through the fault system into the basin-fill aquifer.

Underlying Formations

The nature of the material that underlies the Pine Valley monzonite aquifer is not known. As stated previously, this aquifer is thought to be more than 2,000 ft thick. The bottom of the aquifer was chosen to be at 3,000 ft below land surface. This allows the simulated transmissivity to be calculated from the product of hydraulic conductivity and saturated thickness. Compaction and cementation associated with deeper burial are presumed to have resulted in low hydraulic conductivity, so that no ground water is moving from depth up into the aquifer; thus, it is simulated as a no-flow boundary.

Divides

The surface drainage divide for the Ash Creek drainage basin was assumed to be a ground-water divide and thus is simulated as a no-flow boundary.

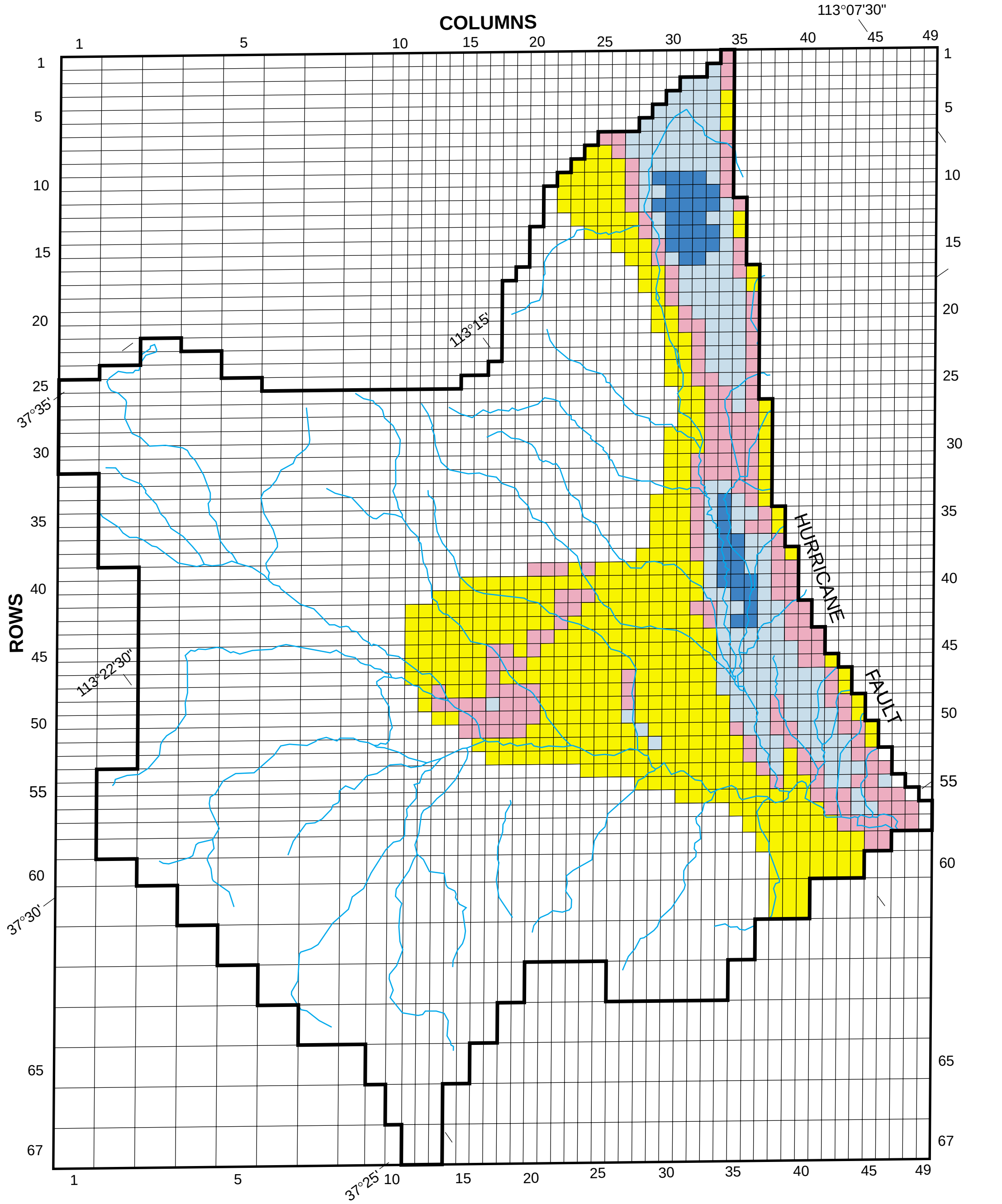
Distribution of Aquifer Characteristics

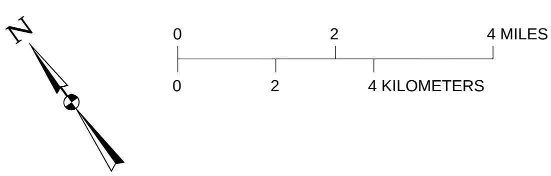
Each model layer represents a different aquifer and is assigned hydrologic properties on the basis of aquifer-test results reported in the literature, specific-capacity tests, and lithologic descriptions from drillers' logs. Available data with which to estimate aquifer properties are scant. The initial distribution of transmissivity for layer 1, the basin-fill aquifer, was developed by comparing the values reported from a few aquifer tests with values from specific-capacity tests done by drillers. A rough map of the most likely values and their areal distribution was created and appropriate values for aquifer top, bottom, and hydraulic conductivity were assigned to the cells that represent that aquifer. Transmissivity in the model is calculated from the product of the hydraulic conductivity and the saturated thickness. The distribution for layers 2 and 3 was determined in the same way but is based on fewer data.

While trying to match measured and model-computed water levels and estimated and model-computed flows, initial distributions were altered within reasonable limits to obtain the best match between measured and computed values. Final distributions of transmissivity are shown in figure 37. The distribution values for layer 2 are 10 times smaller than values in the other layers. This is speculative and was based on the relative differences in a few specific-capacity values. The distribution for layer 3 is largely uncertain for all areas except south of New Harmony, where several irrigation wells have been drilled. Layer 3 for the Harmony and Pine Valley Mountains and where the monzonite aquifer is at depth under basin fill, was assigned a small transmissivity value. A line of cells across the Harmony structural basin also were assigned a small value to simulate the potential impedance of west-to-east ground-water movement across the fault zone mapped by Hurlow (1998). Slightly higher values were assigned to a zone of cells that represent a more structurally disturbed transition from Pine Valley monzonite to the Quichapa Group and Claron Formation, roughly along the stream course of Comanche Creek.

Vertical-Head Gradients

No wells with multiple completions are finished in any of the three aquifers; however, anomalous water levels in some closely spaced wells indicate possible vertical-head gradients within and between aquifers (discussed in "Ground-water movement" section). To simulate vertical-head differences, the values for vertical conductance between layers must be small enough to create an impedance to vertical ground-water movement. Laterally uniform values are used for the baseline simulation and were chosen during model development to approximate measured water levels. Final vertical-conductance values were 1×10^{-4} (ft/d/)ft between layers 1 and 2 and 1 (ft/d)/ft between layers 2 and 3. This simulates little or no vertical impedance to flow between layers 2 and 3 and substantial impedance between layers 1 and 2. Because of the uncertainty in the values for aquifer properties and geometry, vertical-conductance values were assigned during model refinement, not on the basis of calculations of vertical hydraulic conduc-





EXPLANATION

Transmissivity in feet squared per day—Layer 1, basin-fill aquifer

- Less than or equal to 500
- More than 500 but less than or equal to 1,000
- More than 1,000 but less than or equal to 5,000
- More than 5,000

Boundary of active cells

Figure 37. Final distribution of transmissivity simulated in the ground-water flow model of the upper Ash Creek drainage basin, Utah.

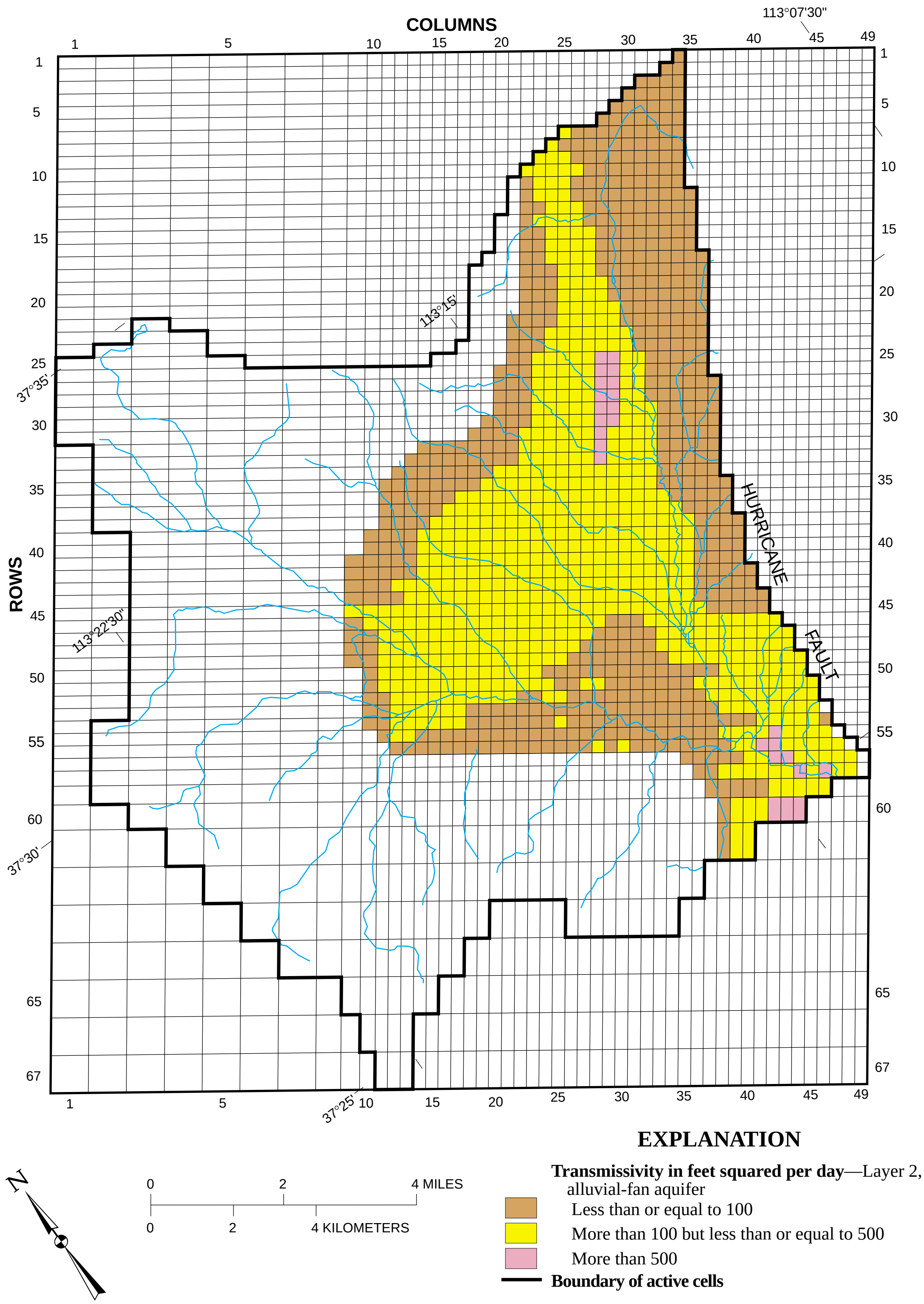


Figure 37. Final distribution of transmissivity simulated in the ground-water flow model of the upper Ash Creek drainage basin, Utah—Continued.

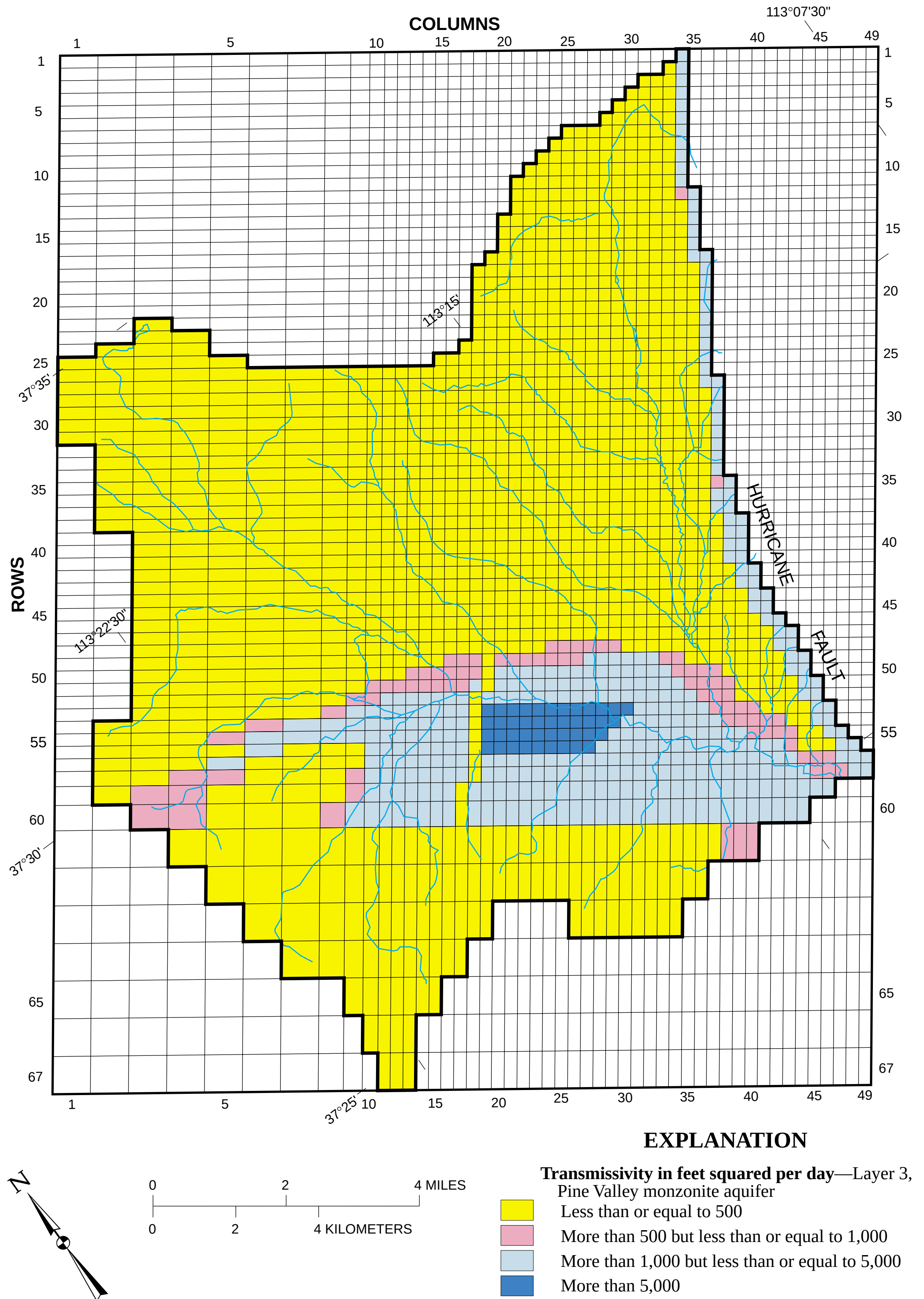


Figure 37. Final distribution of transmissivity simulated in the ground-water flow model of the upper Ash Creek drainage basin, Utah—Continued.

tivity multiplied by cross sectional area divided by distance between the center of layers.

Conceptual Model and Numerical Simulations

Two factors are typically used to determine how closely a numerical simulation compares to a conceptual ground-water flow model: (1) comparison of computed and measured water levels in wells, and (2) comparison of the model's volumetric-balance calculation and the estimated ground-water budget. Although there are similarities between the budgets, computed water levels in layer 3 of the upper Ash Creek drainage basin model are substantially higher than measured water levels, and there is considerable variation among the four computed and measured water levels for layer 2 (table 17). These comparisons indicate that although the conceptual model could be correct, there are many details about aquifer-property distribution and system heterogeneity that are not accurately represented by this baseline simulation. The direction of ground-water movement depicted by the baseline simulation (fig. 38a, b, and c) is similar to that depicted in figure 18, indicating flow from recharge areas in the surrounding mountains to discharge points at springs and streams.

Model Applicability

The model was developed to help understand the ground-water flow system in the upper Ash Creek

Table 17. (a) Conceptual and simulated ground-water budgets and (b) simulated versus measured water-level differences for the upper Ash Creek drainage basin ground-water system, Utah

(a) Ground-water budget		
Flow component	**Conceptual**	**Baseline simulation[1] (rounded)**
Recharge, in acre-feet per year		
Infiltration of precipitation	2,100 to 9,200	10,410
Seepage from ephemeral streams	1,000 to 6,000	2,650
Infiltration of unconsumed irrigation water	0 to 5,000	880
Seepage from perennial streams	500 to 1,100	380
Total	3,600 to 21,300	14,320
Discharge, in acre-feet per year		
Well discharge	1,200 to 1,500	1,440
Evapotranspiration	1,100 to 15,000	8,410
Spring discharge	200 to 1,000	340
Seepage to Ash, Sawyer, and Kanarra Creeks	500 to 3,000	1,630
Subsurface outflow to lower Ash Creek drainage	0 to 7,500	2,500
Total	3,000 to 28,000	14,320

[1]Budget amounts in italics are specified and not computed by the model.

(b) Difference between simulated and measured water levels, in feet			
Water-level comparison	**Layer 1 basin fill**	**Layer 2 alluvial fan**	**Layer 3 Pine Valley monzonite**
Number of water levels compared	18	4	8
Maximum computed above measured, in feet	54	51	97
Maximum computed below measured, in feet	-36	-110	-35
Mean of differences, in feet	-.8	-4.4	34.0
Root mean square error, in feet	24	63	57

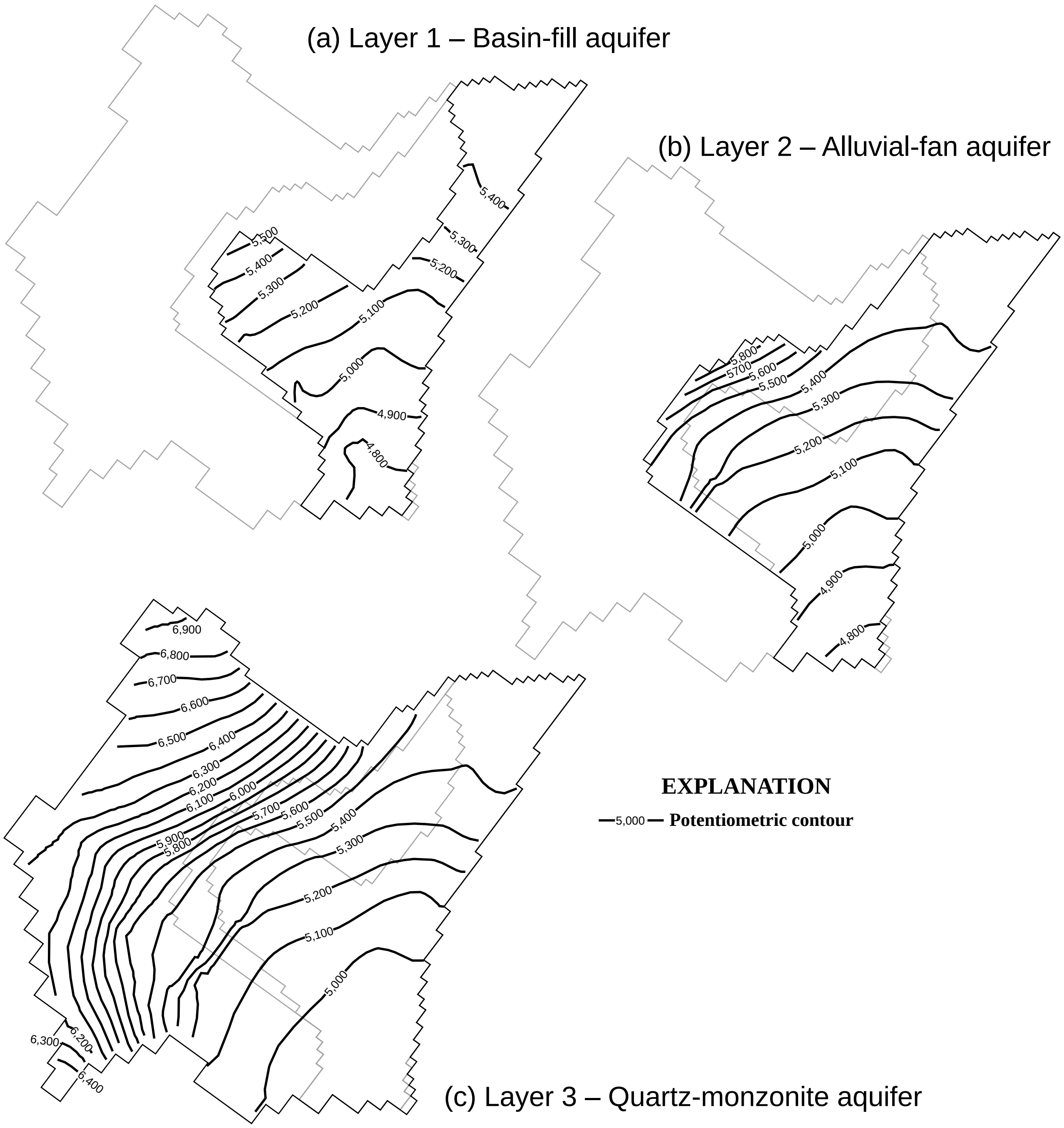


Figure 38. Simulated potentiometric contours in (a) layer 1, (b) layer 2, and (c) layer 3 from the baseline simulation of the upper Ash Creek drainage basin, Utah. [New figure]

drainage basin. It is the first computer simulation of the upper Ash Creek drainage basin. Because of the many uncertainties regarding boundaries, geometry, and aquifer properties, it is not considered a “calibrated” steady-state model. It should be thought of as a tool to use to explore the viability of alternative conceptualizations about the flow system.

Alternative Conceptualizations

Numerous alternative conceptual models might match the measured ground-water budget components and water levels. Much more hydrologic data are needed before a calibrated model can be developed. This model is the mathematical representation of one of those conceptual models. This numerical model was used to explore the validity of other conceptualizations about the upper Ash Creek drainage basin ground-water system. Four different conceptualizations were simulated.

Alternative 1—Flow Across the Hurricane Fault

On the basis of the relation between recharge and average annual precipitation in excess of 8 in. defined for the basin-fill aquifers of Nevada and Utah (Harrill and Prudic, 1998), about 1,000 acre-ft/yr of “mountain-front” recharge could be generated by precipitation on the Markagunt Plateau east of the Hurricane Fault. If this amount of recharge were added as inflow to the basin-fill aquifer at the eastern boundary of the upper Ash Creek drainage basin, water levels in all three layers would rise along the boundary by 5 to 15 ft. Water levels in the area around Ash Creek Reservoir and New Harmony would increase by less than 2 ft. Most of the increase in recharge would be counterbalanced by an increase in evapotranspiration, which would be well within conceptual estimates. Seepage to Ash Creek, discharge at springs, and underflow to the lower Ash Creek drainage area would also increase slightly. Seepage from Ash Creek would decrease by less than 1 acre-ft/yr.

In summary, the alternative 1 simulation did not improve the water-level match for layers 1 and 2 and slightly improved the match for layer 3 (table 18). Recharge along the east boundary across the Hurricane Fault is plausible, but not an improvement over the baseline simulation. Simulated ground-water movement through the system did not change substantially in this alternative (fig. 39a, b, and c).

Alternative 2—No Subsurface Outflow to Lower Ash Creek Drainage

Because no physical evidence of ground-water seepage to lower Ash Creek drainage has been observed, an alternative simulation without this seepage was tested. Simulating no subsurface outflow to the lower Ash Creek drainage was done by changing the conductance values for these general-head boundary cells to zero in the baseline model. The budget components in Alternative 2 were within reasonable ranges; seepage into Ash Creek and spring discharge were increased to values that were closer to those initially conceptualized. The match between measured and simulated water levels were about the same for layer 1 and layer 2. The layer 3 water-level match was slightly worse than in the baseline simulation. Simulated water levels rose as much as 98 ft, but no measured water levels are available for the area where these increases occurred (table 19). The configuration of the potentiometric surfaces was not substantially different than that of the baseline simulation (fig. 40).

Alternative 3—Increased Transmissivity of the Pine Valley Monzonite Aquifer

The hydrologic character of the Pine Valley monzonite aquifer is largely unknown, especially in the mountains and beneath the main part of the alluvial basin between Kanarraville and Ash Creek Reservoir. The aquifer is assumed to have low transmissivity everywhere except south of New Harmony where irrigation wells have high yields. Transmissivity values for these unknown areas were increased to about 10 times the values used in the baseline simulation. Higher transmissivity values for layer 3 could not be numerically simulated. The model would not converge to the prescribed closure criteria and water-level declines caused numerous cells in layer 2 to be eliminated from the simulation because water levels fell below the defined bottom of the aquifer. This was likely caused by the conductive vertical connection simulated between layers 2 and 3. Increasing the transmissivity of layer 3 likely is not a viable conceptualization.

Alternative 4—Variation in anisotropy of the Pine Valley Monzonite Aquifer

The Pine Valley monzonite contains numerous fractures in outcrops (Hurlow, 1998, p. 29) and the primary orientation of these fractures has been observed to be generally north-south. An anisotropy ratio for hydraulic conductivity of 1.5-to-1 along the column direction (south-southwest to north-northeast) was used

Table 18. (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 Hurricane Fault in the upper Ash Creek drainage basin ground-water system, Utah

(a) Ground-water budget

Flow component	Conceptual	Baseline simulation (rounded)	Hurricane Fault simulation (rounded)
Recharge, in acre-feet per year			
Infiltration of precipitation	2,100 to 9,200	10,410	10,410
Seepage from ephemeral streams	1,000 to 6,000	2,650	2,650
Infiltration of unconsumed irrigation water	0 to 5,000	880	880
Seepage from perennial streams	500 to 1,100	380	370
Underflow across Hurricane Fault	≠—	—	950
Total	3,600 to 21,300	14,320	15,260
Discharge, in acre-feet per year			
Well discharge	1,200 to 1,500	1,440	1,440
Evapotranspiration	1,100 to 15,000	8,410	9,320
Spring discharge	200 to 1,000	340	350
Seepage to Ash, Sawyer, and Kanarra Creeks	500 to 3,000	1,630	1,650
Subsurface outflow to lower Ash Creek drainage	0 to 7,500	2,500	2,500
Total	3,000 to 28,000	14,320	15,260

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

Water level	Layer 1 basin fill		Layer 2 alluvial fan		Layer 3 Pine Valley monzonite	
	Baseline simulation	Hurricane Fault simulation	Baseline simulation	Hurricane Fault simulation	Baseline simulation	Hurricane Fault simulation
Number of water levels compared	18		4		8	
Maximum computed above measured, in feet	54	64	51	54	97	92
Maximum computed below measured, in feet	-36	-34	-110	-108	-35	-37
Mean of differences, in feet	-0.8	3.9	-4.4	-.3	34.0	29.3
Root mean square error, in feet	24	26	63	63	57	54

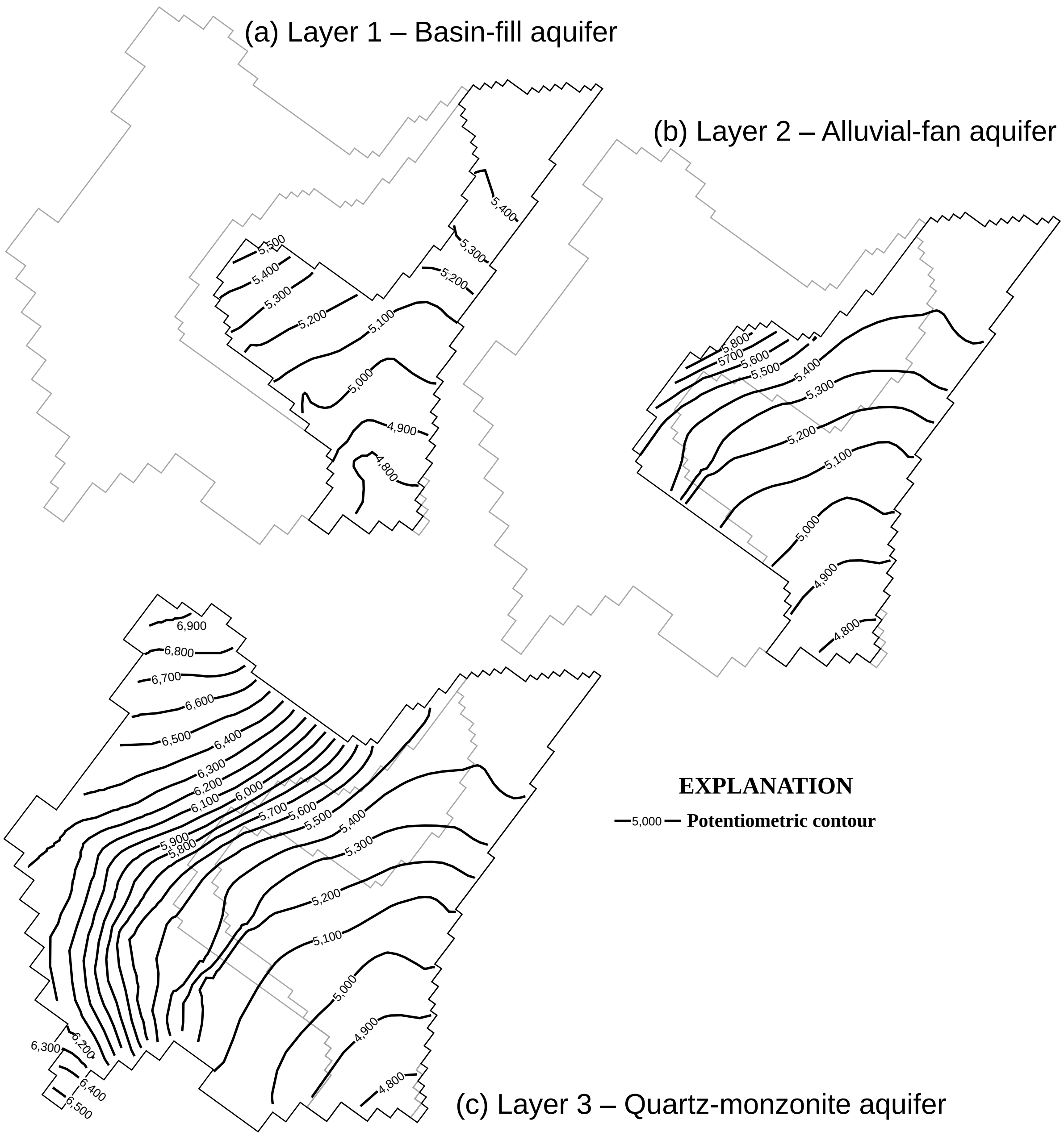


Figure 39. Simulated potentiometric contours in (a) layer 1, (b) layer 2, and (c) layer 3 from alternative simulation depicting flow across the Hurricane Fault, the upper Ash Creek drainage basin, Utah.

Table 19. (a) Conceptual and simulated ground-water budgets and (b) simulated versus measured water-level differences for the baseline simulation and the simulation of no subsurface outflow to the lower Ash Creek drainage basin, Utah

(a) Ground-water budget

Flow component	Conceptual	Baseline simulation	No subsurface outflow simulation
Recharge, in acre-feet per year			
Infiltration of precipitation	2,100 to 9,200	10,410	10,410
Seepage from ephemeral streams	1,000 to 6,000	2,650	2,650
Infiltration of unconsumed irrigation water	0 to 5,000	880	880
Seepage from perennial streams	500 to 1,100	380	350
Total	3,600 to 21,300	14,320	14,290
Discharge, in acre-feet per year			
Well discharge	1,200 to 1,500	1,440	1,440
Evapotranspiration	1,100 to 15,000	8,410	10,290
Spring discharge	200 to 1,000	340	390
Seepage to Ash, Sawyer, and Kanarra Creeks	500 to 3,000	1,630	2,170
Subsurface outflow to lower Ash Creek drainage	0 to 7,500	2,500	0
Total	3,000 to 28,000	14,320	14,290

(b) Difference between simulated and measured water levels

Water level	Layer 1 basin fill		Layer 2 alluvial fan		Layer 3 Pine Valley monzonite	
	Baseline simulation	No under-flow simulation	Baseline simulation	No under-flow simulation	Baseline simulation	No underflow simulation
Number of water levels compared	18		4		8	
Maximum computed above mea-sured, feet	54	54	51	51	97	98
Maximum computed below mea-sured, in feet	-36	-36	-110	-110	-35	-35
Mean of differences, in feet	-0.8	-0.4	-4.4	-4.4	34.0	35.3
Root mean square error, in feet	24	24	63	63	57	58

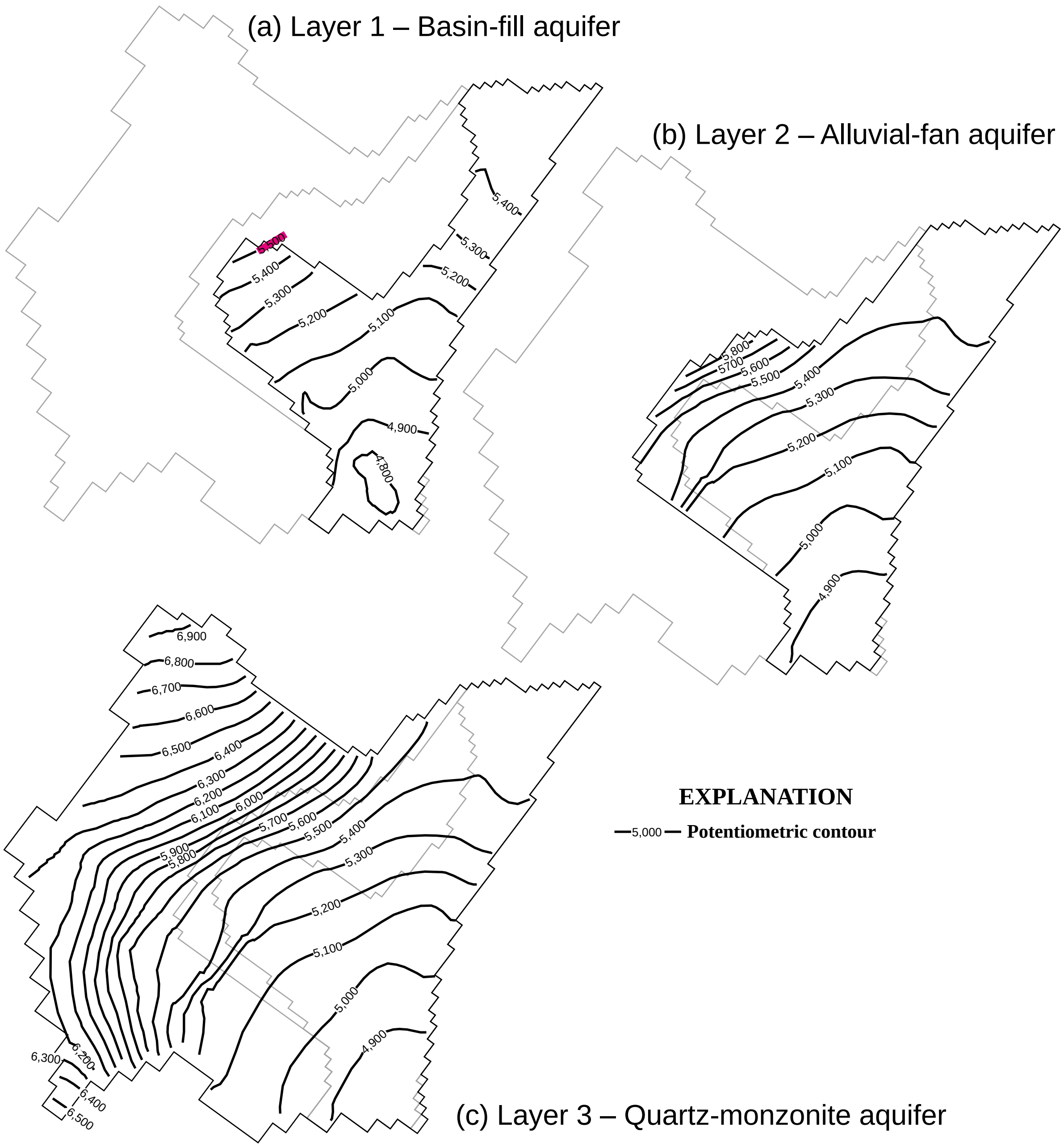


Figure 40. Simulated potentiometric contours in (a) layer 1, (b) layer 2, and (c) layer 3 from alternative simulation depicting no outflow from the basin near Ash Creek reservoir, upper Ash Creek drainage basin, Utah.

in the baseline simulation; however, this ratio is speculative. Because of uncertainty about the relative magnitude of hydraulic conductivity in the direction of primary fracture orientation, the anisotropy ratio conceptually could be lower or higher than the value used in the baseline model. To test this alternative, the anisotropy ratio was increased from 1.5-to-1 to 3-to-1, and then decreased to 1-to-1.

The simulations (table 20) indicate that an anisotropy of 3-to-1 in layer 3 is a plausible hydrologic conceptualization. This ratio, however, did not provide as close a match to measured water levels in layers 1 and 2 as an anisotropy ratio of 1.5-to-1. An anisotropy ratio of 1-to-1 in layer 3 also is a plausible hydrologic conceptualization. Water-budget discharge to springs and streams was within the desired range, and simulated water levels were closer to measured values for layers 2 and 3. The configuration of the potentiometric surfaces was not substantially different than that of the baseline simulation.

Model Sensitivity

Sensitivity analyses are an important part of developing ground-water flow models. They help to understand which properties and budget components are most important to simulation results, and thus, which should be given the highest priority when considering additional analysis or data collection. The upper Ash Creek drainage basin ground-water flow model described in this report is considered the most plausible and probable representation of the ground-water flow system for 1995 conditions. It is not considered to be "calibrated." There are numerous uncertainties about the hydrologic boundaries, the amount of water moving across these boundaries, and about the geometry and properties of the aquifers. Relative sensitivity of the baseline model to variations in different parameters is shown in figure 41. The height of each bar is subjective and is based on an overall evaluation of how variations in the parameters affected computed water levels and head-dependent flux. More detailed analyses and results of all sensitivity runs are in appendix B.

The baseline model was acutely sensitive to variations in the water transmitting properties of the layers that represent the basin-fill and the Pine Valley monzonite aquifers and of the vertical conductance in the basin fill. The model appears to be insensitive to vertical conductance between the alluvial-fan and Pine Valley monzonite aquifers, but this was a result of setting the baseline value for conductance high. If conductance values were decreased to those for the basin-fill aquifer, the model would indicate a comparable sensitivity to this value. The amount of water simulated as recharge from unconsumed irrigation and as direct infiltration from precipitation also affected baseline model results. Other parameters such as transmissiveness of the alluvial-fan aquifer, streambed conductance, and recharge attributed to ephemeral stream flow affected results moderately to slightly.

Need for Additional Study

On the basis of model sensitivity to selected parameters, collection of specific types of data would help refine the present hydrologic conceptualization. Data needed to update this preliminary model might include the amount of (1) water applied for irrigation, (2) water used by different crops, (3) applied water that evaporates, and (4) applied water that runs off into drainage channels. Recharge from precipitation and how it is distributed laterally throughout the upper Ash Creek drainage basin also warrants additional attention.

Appropriately designed multiple-observation-well aquifer testing is needed for the basin-fill and Pine Valley aquifers. The variability in transmissivity of the basin-fill aquifer, created by variations in thickness and lithologic character, needs to be well delineated to decrease the uncertainties in this important parameter. Additional data on the variability of transmissivity in the monzonite aquifer are equally needed. Water from snowmelt and precipitation infiltrating into the surrounding mountains eventually moves from this fractured crystalline aquifer into shallow alluvial deposits where it is discharged by evapotranspiration, springs, wells, and seepage to streams. Better understanding of the flow paths through the fractured monzonite aquifer and how water moves from fractured crystalline rock to unconsolidated sediments are critical to developing accurate numerical simulations of this flow system.

Water-Resource Management

Probably the most important aspects of effectively managing the surface- and ground-water resources of the upper Ash Creek drainage basin are the amount of water that moves through the system from year to year and where, why, and how that water is being used within the system. Much of that information has been documented by observations, measurements, and development of a preliminary simulation. The simulations described herein should not be used to manage

Table 20. (a) Conceptual and simulated ground-water budgets and (b) simulated versus measured water-level differences for the baseline simulation and the simulation testing anisotropy in the Pine Valley monzonite aquifer in the upper Ash Creek drainage basin ground-water system, Utah

(a) Ground-water budget

Flow component	Conceptual model	Baseline simulation (anisotropy 1.5:1)	Higher-anisotropy simulation (3:1)	No-anisotropy simulation (1:1)
Recharge, in acre-feet per year				
Infiltration of precipitation	2,100 to 9,200	10,410	10,410	10,410
Seepage from ephemeral streams	1,000 to 6,000	2,650	2,650	2,650
Infiltration of unconsumed irrigation water	0 to 5,000	880	880	880
Seepage from perennial streams	500 to 1,100	380	360	370
Total	3,600 to 21,300	14,320	14,300	14,310
Discharge, in acre-feet per year				
Well discharge	1,200 to 1,500	1,440	1,440	1,440
Evapotranspiration	1,100 to 15,000	8,410	8,150	8,550
Spring discharge	200 to 1,000	340	450	260
Seepage to Ash, Sawyer, and Kanarra Creeks	500 to 3,000	1,630	1,730	1,570
Subsurface outflow to lower Ash Creek drainage	0 to 7,500	2,500	2,530	2,490
Total	3,000 to 28,000	14,320	14,300	14,310

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

Water level	Layer 1 basin fill			Layer 2 alluvial fan			Layer 3 Pine Valley monzonite		
	Baseline simulation	Higher anisotropy simulation (3:1)	No anisotropy simulation (1:1)	Baseline simulation	Higher anisotropy simulation (3:1)	No anisotropy simulation (1:1)	Baseline simulation	Higher anisotropy simulation (3:1)	No anisotropy simulation (1:1)
Number of water levels compared	18			4			8		
Maximum computed above measured, in feet	54	47	57	51	48	52	97	96	90
Maximum computed below measured, in feet	-36	-38	-36	-110	-120	-104	-35	-41	-36
Mean of differences, in feet	-0.8	-5.9	0.5	-4.4	-13.6	-0.8	34.0	32.2	27.4
Root mean square error, in feet	24	24	25	63	65	61	57	56	53

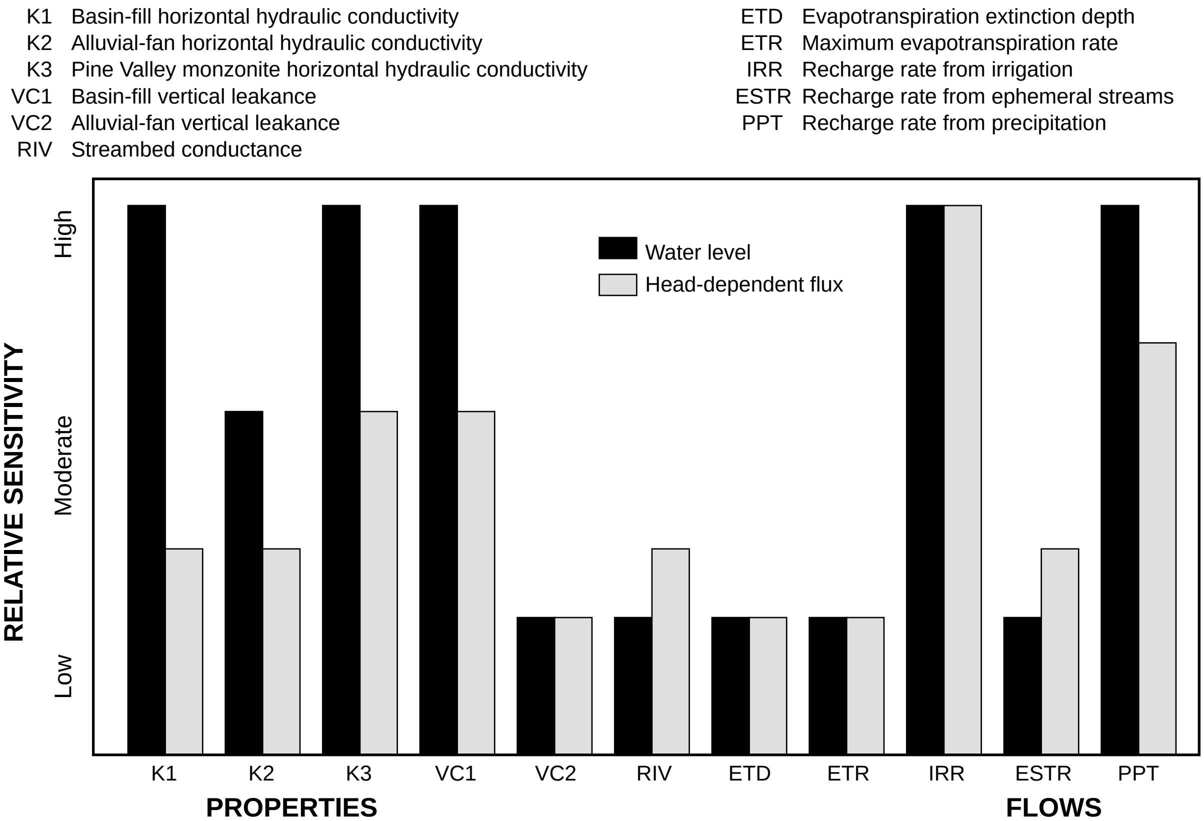


Figure 41. Relative sensitivity of the baseline model representing the upper Ash Creek drainage ground-water flow system to uncertainty in selected properties and flows.

the basin's ground water, but only to visualize the interdependencies of hydrologic processes and the possible effects of climate change or human-caused change.

Model Limitations

The limitations of the model have been implied in previous sections. The baseline simulation is considered to be the most reasonable representation for the upper Ash Creek ground-water system, but because the model has no storage component, it can only simulate the ultimate result of changes in stress on aquifer properties. Other representations may also be realistic, and thus the baseline simulation may need to be revised after additional hydrologic or geologic data about the system become available.

Alternate steady-state simulations could be devised to show the potential effect of (1) decrease in areal recharge because of drought, (2) removal of riparian vegetation, or (3) increased or decreased pumpage, but simulations such as these should not be used to manage the water resources but rather to better understand interaction of hydrologic processes.

Navajo and Kayenta Aquifer System

Because the Gunlock Fault completely offsets the Navajo Sandstone and Kayenta Formation outcrops (pl. 1), two separate ground-water flow models were developed for the main and Gunlock parts of the Navajo and Kayenta aquifers. The two computer models share similar aquifer properties and boundary conditions; for example, a shared no-flow boundary represents the Gunlock Fault. They were developed independently on the basis of the conceptual model ground-water budgets presented earlier (tables 15 and 16). Recharge to and discharge from the aquifers varies both seasonally and yearly as a result of both climatic changes and water use; however, there has generally been little overall water-level change at wells measured both in 1974 and as part of this study (fig. 42). Although at least 30 ft of water-level decline was measured at three of the Gunlock wells, those measurement were at productions