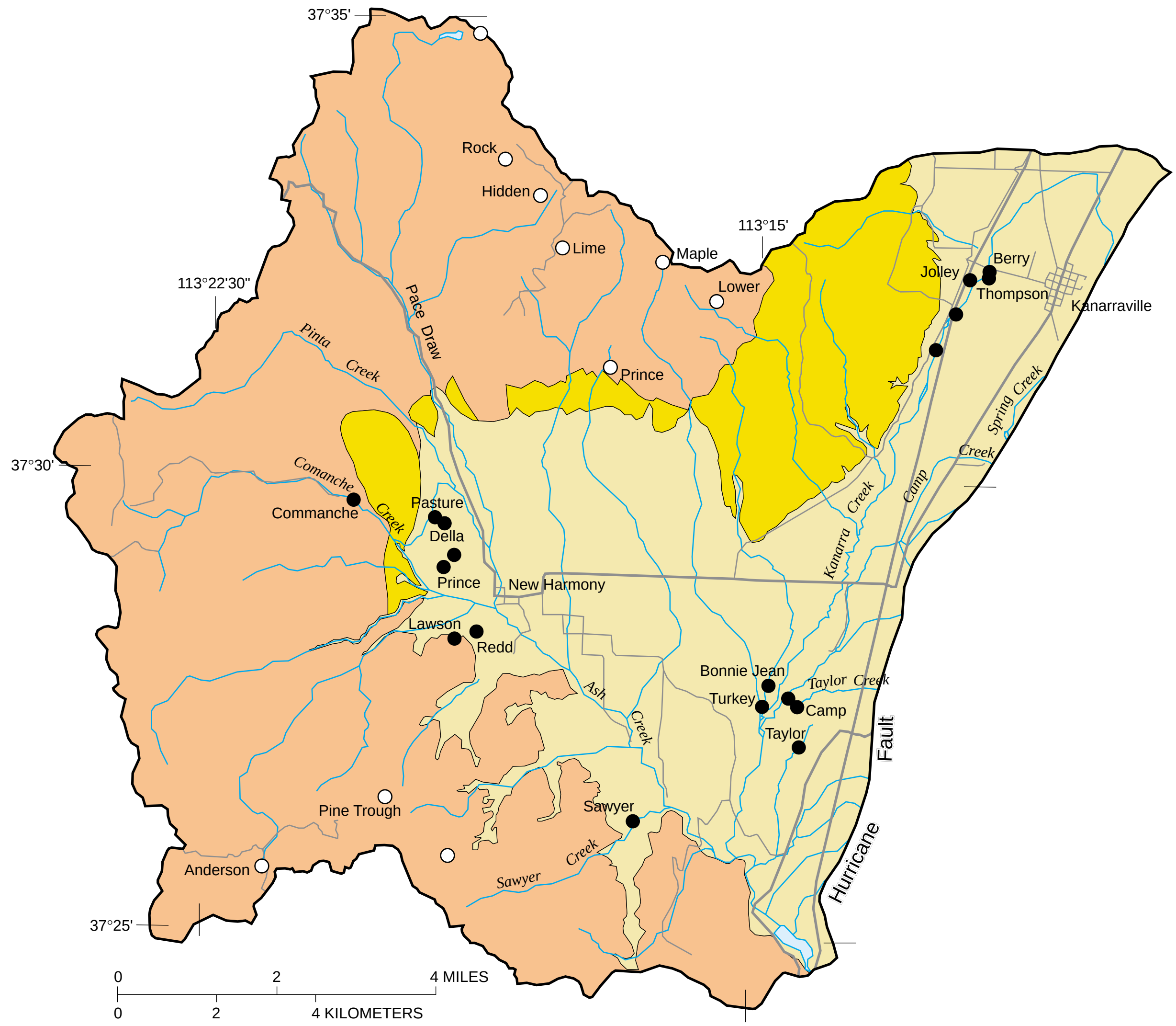

EXPLANATION

● **Springs that discharge from the regional ground-water system**

○ **Springs that discharge from localized ground-water systems**

Figure 20. Location of local and regional springs in the upper Ash Creek drainage basin, Utah.

tion of the geologic framework by Hurlow (1998), thickness and width are estimated to be about 300 ft and 5,000 ft, respectively. Hydraulic conductivity of the interbedded alluvial deposits can be estimated to be similar to the lower values of the basin-fill aquifer because of compaction and cementation. A value of about 20 ft/d was estimated. Use of these numbers in Darcy’s Law yields a maximum potential outflow of about 7,500 acre-ft/yr. Because of a general lack of information about geometry and hydraulics in this outflow area, this estimate is uncertain.

Ground-Water Budget

A compilation of potential inflow to and outflow from the upper Ash Creek drainage basin ground-water system is shown in table 9. Except for well discharge, all ground-water budget components have a large estimated range.

Navajo and Kayenta Aquifer System

The saturated parts of the Navajo Sandstone and Kayenta Formation, referred to in this section as the

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Table 9. Estimated ground-water budget for the upper Ash Creek drainage basin, Utah

Flow component	Rate, in acre-feet per year	Rate, in cubic feet per second
Recharge		
Infiltration of precipitation	2,100 to 9,200	2.9 to 12.7
Seepage from ephemeral streams	[1]3,500	4.8
Infiltration of unconsumed irrigation water	[2]0 to 5,000	0 to 6.9
Seepage from perennial streams	500 to 1,100	0.7 to 1.5
Total	6,100 to 18,800	8.4 to 25.9
Discharge		
Well discharge	1,200 to 1,500	1.7 to 2.1
Evapotranspiration	1,100 to 15,000	1.5 to 20.7
Spring discharge (excludes Sawyer Spring)	200 to 1,000	0.3 to 1.4
Seepage to Ash, Sawyer, and Kanarra Creeks (includes Sawyer Spring)	500 to 3,000	0.7 to 4.2
Subsurface outflow to lower Ask Creek drainage	0 to 7,500	0 to 10.4
Total	3,000 to 28,000	4.2 to 38.8

[1]This is likely a minimum value.
[2]Actual amount is thought to be nearer the lower end of this range.

Navajo and Kayenta aquifers, provide most of the potable water to the municipalities of Washington County, Utah. Because of large outcrop exposures, uniform grain size, and large stratigraphic thickness, these formations are able to receive and store large amounts of water. In addition, structural forces have created extensive fracture zones, enhancing ground-water recharge and movement within the aquifers. A generalized conceptualization of how water recharges to and discharges from the Navajo and Kayenta aquifers is shown in figure 21.

Aquifer System Geometry and Hydrologic Boundaries

The hydrologic boundaries of the Navajo and Kayenta aquifers are similar to the structural boundaries of the geologic formations. The aquifers are bounded to the east by the Hurricane Fault, which completely offsets these formations. Because the fine-grained fault-gouge material likely acts as a barrier to flow across the fault (discussed under “Hydrogeologic framework”), the Hurricane fault is assumed to be a lateral no-flow boundary. To conclusively determine if ground water crosses the fault into the Navajo Sandstone and Kayenta Formation to the west, it would be necessary to drill a pair of observation wells into the Navajo Sandstone south of Hurricane, just west of fault, as well as into the formations just east of the fault.

Like the Hurricane Fault, the Gunlock Fault is assumed to be a lateral no-flow boundary that divides the Navajo and Kayenta aquifers within the study area into two parts: (1) the main part, located between the Hurricane and Gunlock Faults; and (2) the Gunlock part, located west of the Gunlock Fault. Hurlow (1998) states that little or no hydrologic connection likely exists across the Gunlock Fault. The Gunlock Fault completely offsets the Navajo Sandstone and Kayenta Formations (fig. 5) along the outcrop (Hintze and Hammond, 1994, pl. 1). The offset is unknown to the north where the Navajo Sandstone is buried by younger formations. Only a small amount of ground-water recharge to the Navajo aquifer is thought to occur where it is buried by poorly permeable overlying formations. Therefore, water within the buried parts of the Navajo aquifer is most likely stagnant, with little movement across the Gunlock Fault. Additional well drilling and aquifer testing would be needed to conclusively determine the exact hydrologic characteristics of the fault.

The southern boundaries of the Navajo Sandstone and Kayenta Formation are defined by their erosional extents (pl. 1). However, the formations are likely unsaturated along this southernmost edge, espe-

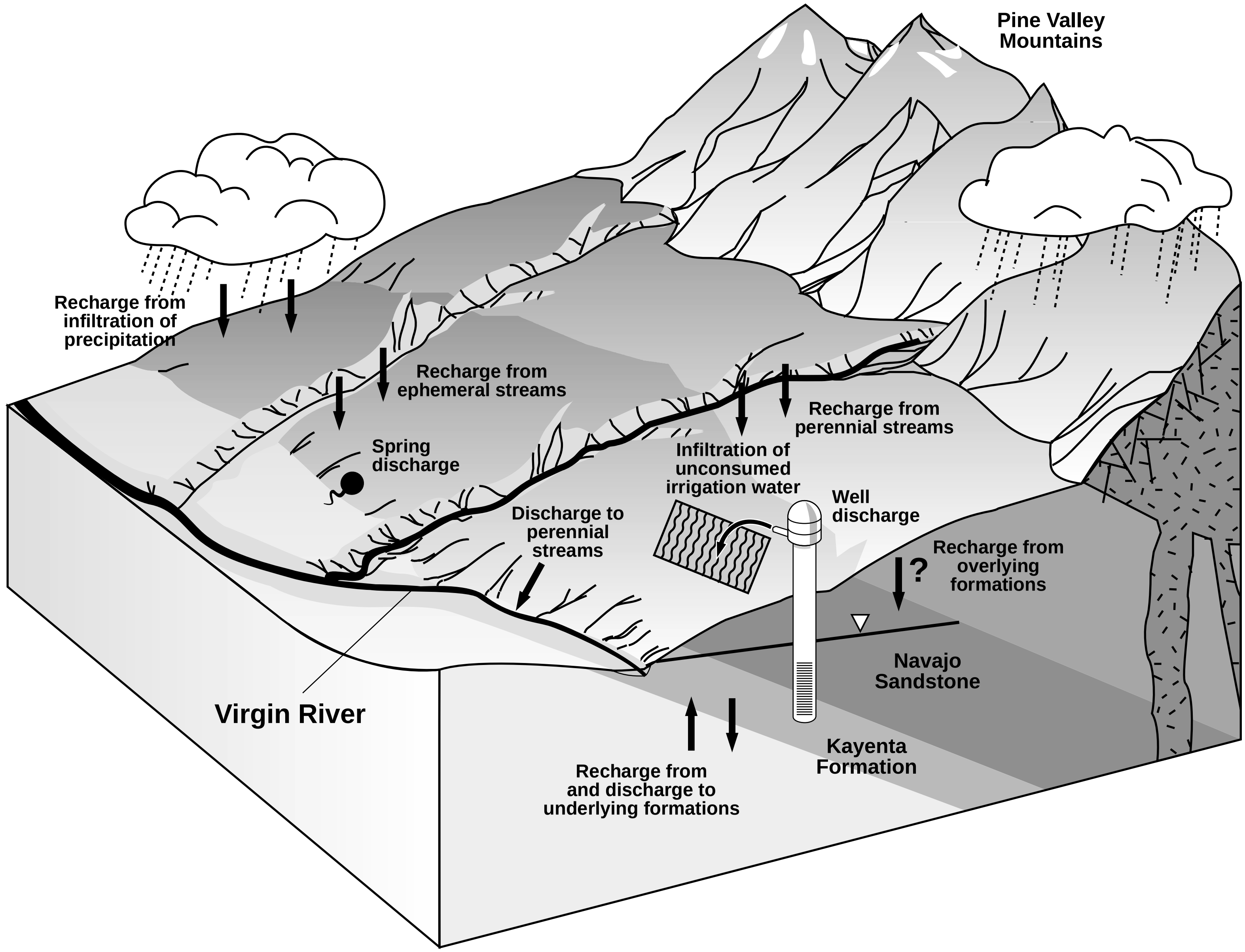

Figure 21. Generalized diagram showing sources of recharge to and discharge from the Navajo and Kayenta aquifers within the central Virgin River basin study area, Utah.

cially where they are locally uplifted, such as the southern part of the Red Mountains east of the Gunlock Fault. The Navajo Sandstone and Kayenta Formation become deeply buried toward the north. A structure contour map of the top of the Navajo Sandstone by Hurlow (1998, pl. 5B) indicates that the top of the Navajo Sandstone is about 8,000 ft below land surface (2,000 ft above sea level) in the Pine Valley Mountains. It is unknown how far to the north the Navajo Sandstone and Kayenta Formation extend under younger formations, but the ARCO Three Peaks #1 oil exploration drill hole 10 mi northwest of Cedar City (about 50 mi northeast of St. George) reached the top of the Navajo Sandstone at a depth of 6,286 ft beneath land surface (Van Kooten, 1988). Although the Navajo Sandstone and Kayenta Formation extend to the north beyond the study area, little recharge is thought to enter the aquifers where they are buried by younger formations. Therefore, it is assumed that little ground-water flow occurs in this region.

Because of the homogeneous nature of the Navajo Sandstone, the Navajo aquifer is assumed to be unconfined throughout the outcrop area. However, there may be local areas where the aquifer is confined as a result of variations in grain size, cementation, or bedding planes. One example of this is Winchester Hills well (C-41-16)24cba-1, where petrographic analysis of borehole cuttings indicated a 10-ft-thick layer of silt and clay at a depth of 850 ft. Another example is Washington County Water Conservancy District (WCWCD) Anderson Junction well (C-40-13)28dcc-1, where the driller noted that after water was reached at a depth of 190 ft, the water level rose in the borehole to a depth of 31 ft. However, such areas of confined conditions generally are not thought to be prevalent within the Navajo aquifer.

At some unknown distance north of the outcrop, the Navajo aquifer is assumed to become confined as it is buried by younger formations. A drillers' log from Dameron Valley Well (C-40-16)17dad-1 indicates that the Navajo Sandstone was reached at a depth of 440 ft with a reported water level of 1,280 ft beneath land surface (pl. 2), indicating unconfined conditions at this location about 1 mi north of the contact with younger formations. Assuming a flat potentiometric surface farther north (based on the assumption that little recharge reaches the aquifer where it is deeply buried) and a northeastward dip of the Navajo Sandstone of 3 to 10 degrees (Hurlow, 1998, pl. 5B), confined conditions may occur between 2 and 4 mi northeast of the outcrop in the Dameron Valley area. The location of the unconfined/confined boundary of the Navajo aquifer north of the contact with younger formations would vary, depending on the local dip of the Navajo Sandstone and the altitude of the water table. The saturated thickness of the aquifer would be about 2,400 ft where confined and vary from 0 to 2,400 ft in the unconfined part.

The Navajo and Kayenta aquifers are assumed to be hydraulically connected. The potentiometric gradient between the two aquifers indicates that ground water moves from the Navajo aquifer to the Kayenta aquifer (Cordova, 1978). No observation wells have been finished exclusively in the Kayenta aquifer where it underlies the Navajo aquifer. However, if the potentiometric surface from wells along the Kayenta outcrop to areas where observation wells are finished in the Navajo aquifer is extended, the estimated vertical gradient between the Navajo and Kayenta aquifers is generally downward. Water-level differences are estimated to be less than 100 ft. Cordova (1978) suggested that ground-water movement from the Navajo aquifer to the Kayenta aquifer occurs along the entire part of the outcrop within the study area. This theory is based on (1) the general direction of ground-water movement, inferred from potentiometric maps, toward the escarpment that forms the erosional extent of the Navajo Sandstone outcrop; (2) the absence of natural discharge by springs, seeps, or phreatophytes along the escarpment above the base of the Navajo Sandstone; and (3) water levels at a few wells finished in both the Navajo Sandstone and the Kayenta Formation that indicate the saturated zone is in the Kayenta Formation. If a layer with low hydraulic-conductivity separates the two aquifers, this would be manifested by substantial discharge along the contact between the Navajo Sandstone and Kayenta Formation. Rather, most of the natural discharge from the aquifer system occurs within the Kayenta Formation, which indicates a less permeable boundary at or near the base of the Kayenta Formation.

The lowest part of the Kayenta Formation consists of siltstones and mudstones (Hurlow, 1998) that are relatively impervious and most likely act as a confining layer at the base of the Navajo and Kayenta aquifer system. Evidence for this hydrologic boundary includes (1) many springs that emanate from the lower part of the Kayenta Formation between Santa Clara and St. George; (2) seepage studies that show gain in the Santa Clara River as it crosses the lower Kayenta Formation; and (3) the Sullivan flowing well (C-41-13)16bcd-1, which is an artesian well drilled along the Kayenta Formation outcrop near Sandstone Mountain but is finished in the underlying Springdale Sandstone member of the Moenave Formation (Wilkowske and others, 1998, table 1). There may be localized areas, however, where through-going fractures may act as conduits for vertical ground-water movement across this lower boundary, such as are hypothesized for (1) the higher dissolved-solids parts of the aquifer north of St. George and east of Hurricane (discussed under the "Sources of salinity to the Navajo and Kayenta aquifers" section); and (2) locations where seepage to the Santa Clara and Virgin Rivers occurs as they traverse older sedimentary layers underlying the Kayenta Formation.

Like the Navajo aquifer, the Kayenta aquifer is unconfined along its outcrop. Because of its hydraulic connection to the Navajo aquifer, the transition to confined conditions within the Kayenta aquifer likely is the same as in the Navajo aquifer—toward the north where both formations become deeply buried.

Aquifer Properties

Knowledge of aquifer properties is necessary to understand the occurrence of ground water. These properties include (1) effective porosity, (2) hydraulic conductivity or transmissivity, and (3) storage capacity. Aquifer properties are typically estimated from laboratory analyses and multiple-well aquifer testing.

Navajo Aquifer

The Navajo Sandstone is well sorted, as is shown by grain-size distribution curves (Cordova, 1978, fig. 2). Average total porosity, determined from resistivity and neutron logs of 13 boreholes in the Navajo Sandstone within the study area, is about 32 percent (Cordova, 1978, table 4). Effective porosity, determined from laboratory analysis of 12 rock samples from selected outcrops within the study area, is about 17 percent (Cordova, 1978, table 3).

Because of the uniformly well-sorted lithologic character of the Navajo Sandstone throughout the study area, variations in hydraulic conductivity are most likely caused by secondary fracturing, both vertical and along bedding planes. Laboratory analysis of rock samples from eight outcrop locations within the study area indicate that average saturated hydraulic conductivity of the Navajo aquifer is about 2.1 ft/day (Cordova, 1978). Because these outcrop samples were collected along the outcrop, the measured hydraulic-conductivity values are probably higher than the actual matrix hydraulic conductivity because of weathering. Dissolution of the cement surrounding the silica grains during weathering would likely increase the effective permeability of the rock samples.

As part of the study, aquifer tests were done within the Navajo aquifer at Anderson Junction (WCWCD wells), Hurricane Bench (Winding Rivers wells), Grapevine Pass (Washington City well), and downstream from Gunlock Reservoir (St. George City wells) (table 10, appendix A). Transmissivity determined from these tests ranged from 100 to 19,000 ft^2/d, corresponding to horizontal hydraulic-conductivity values of 0.2 to 32 ft/d. Higher hydraulic-conductivity values are assumed to be associated with highly fractured parts of the aquifer. Hydraulic conductivity was highest at the Anderson Junction site and ranged from 1.3 ft/d along the north-northeast direction to 32 ft/d along the east-southeast direction. Hurlow (1998, p. 27) stated that "the Navajo Sandstone in this area is densely fractured and is cut by numerous northeast-striking faults, implying relatively high permeability." The lowest hydraulic-conductivity value of 0.2 ft/d was at Grapevine Pass. Although surface fractures are present nearby, little fracturing can be seen at the site itself (Hugh Hurlow, Utah Geological Survey, oral commun., 1997). In addition, petrographic analysis of borehole cuttings from the Grapevine Pass well showed much finer average grain size than samples from other Navajo Sandstone wells, possibly indicating a much thicker transition zone at the base of the Navajo Sandstone than at other locations (Janae Wallace, Utah Geological Survey, oral commun., 1997).

Results of the aquifer tests downstream from Gunlock Reservoir and at Anderson Junction indicate that fracture-related anisotropy can strongly influence directional permeability within the Navajo aquifer. The north-south directional anisotropy of hydraulic-conductivity values (1.0 ft/d north-south and 0.3 ft/d east-west) determined from the Gunlock Reservoir aquifer test (appendix A) is consistent with observations of large-scale fracturing aligned north-south parallel to the Santa Clara River, and with one of the three areal photograph rose diagrams from nearby outcrops. However, surface-fracture orientation data are not always consistent with the anisotropic hydraulic-conductivity values determined from aquifer tests. This is because the subsurface connectivity of fractures strongly influences anistropy in hydraulic conductivity, which can only be predicted from rose diagrams in the simplest cases. At the Gunlock test site, the scan-line rose diagrams of the outcrop and two of the three rose diagrams based on areal photographs indicate that the predominant fracture orientation generally is in the east-west

Table 10. Aquifer-test results from the Navajo aquifer, central Virgin River basin study area, Utah
(See appendix A for additional information; ±, plus or minus)

Location	Pumping well number	Number of observation wells	Pumping/ recovery period (days)	Horizontal hydraulic conductivity (feet/day)	Saturated thickness (feet)	Transmissivity (feet squared per day)	Storage coefficient
Anderson Junction	(C-40-13)28dcb-2	2	4	1.3 to 32	600	[1]800 ± 19% to 19,000 ± 21%	.0007 to .0025
Hurricane Bench	(C-42-14)12dbb-2	5	5	2.2	500	1,075	.002
Grapevine Pass	(C-41-15)28dcb-2	0 (single-well test)	1	.2	500	100	—
Downstream from Gunlock Reservoir	(C-41-17)8acc-1	6	6	.3 to 1.0	1,100	360 to 1,100	.001

[1]See figure A-8.

direction (Hurlow, 1998, pl. 6) rather than north-south direction, as indicated by aquifer testing. At Anderson Junction, the direction of maximum transmissivity indicated by aquifer testing is in the east-southeast orientation, yet the rose diagram of scan-line outcrop data indicates that the predominant orientation of surface fracturing is north-northeast. Anisotropy could not be determined from the aquifer-test results at the Hurricane Bench and Grapevine Pass sites because of the lack of observation wells.

Although there may not be a direct correlation between the direction of maximum aquifer transmissivity and the predominant orientation of surface fracturing at nearby outcrops, a strong correlation was shown between hydraulic-conductivity estimates based on specific-capacity data and the product of fracture density and average aperture (Hurlow, 1998, fig. 14). Thus, although inferring the direction of aquifer anisotropy from surface-fracture orientation data remains uncertain, other outcrop fracture data such as fracture density and aperture (fracture width) can provide a good indication of the degree of permeability enhancement caused by fracturing. Such data would be valuable in locating potentially high-yielding production wells in the Navajo aquifer.

Cordova (1978) reported the results of multiple-well aquifer tests in the Navajo aquifer at three sites: below the Gunlock Reservoir, City Creek, and Hurricane Bench. However, all of the measurements at observation wells during that study were problematic. Measurements during the Gunlock test did not include monitoring of Santa Clara River discharge. Because decreases in stream discharge were noted during this study's aquifer test in the Gunlock area, streamflow likely was induced into the aquifer. Assuming that this leakage was unaccounted for, transmissivity and storage values determined from observation-well measurements are not accurate. The aquifer test at City Creek was not a constant-drawdown test. Instead, a step-drawdown test was done, pumping first at 470 gal/min and then at 1,100 gal/min. However, an average pumping rate was used for the analysis that resulted in inaccurate determinations of transmissivity and storage. Finally, aquifer-test results at Hurricane Bench were considered inaccurate because water from the pumped well was not removed from the site and infiltrated the saturated zone, affecting observation-well drawdown measurements.

Two other aquifer tests done by Cordova (1978) at Mill Creek and City Creek did not produce drawdown at any observation wells, so the reported transmissivity values were based only on drawdown in the pumped wells. However, assuming that a constant pumping rate was maintained and the pumped water was removed sufficiently far from the site, the reported transmissivity and hydraulic-conductivity values of 2,400 ft^2/d and 3.4 ft/d for the Mill Creek site and 5,000 ft^2/d and 5.0 ft/d for the City Creek site may be reasonable.

No aquifer testing was done to determine vertical hydraulic conductivity of the Navajo aquifer within the study area. Horizontal and vertical hydraulic-conductivity values determined from laboratory analysis of Navajo Sandstone samples within the Upper Colorado River Basin were compiled by Weigel (1987, table 5). The average vertical and horizontal hydraulic conductivity of 24 samples was about 0.8 ft/d and 1.1 ft/d, respectively. The ratio of vertical to horizontal hydraulic-conductivity values for the 24 pairs of samples ranged from 0.13 to 2.7, averaging about 0.4. However, these discrete vertical samples may not be an accurate representation of the vertical hydraulic conductivity or vertical-to-horizontal anisotropy ratios for the Navajo aquifer within the study area. The lowest vertical hydraulic conductivity of a layered sedimentary formation controls the overall vertical hydraulic conductivity of that layer. Therefore, it is likely that in some regions of the Navajo aquifer, the vertical movement of ground water may be more restricted than is indicated by the average of the laboratory-determined values. Lower overall vertical hydraulic-conductivity values and vertical-to-horizontal hydraulic-conductivity ratios may result from thin, low- permeability horizontal layers that consist of fine-grained interdunal deposits or have greater-than-average cementation that may not be within the sampled zone for laboratory analyses. Conversely, vertical fracturing would greatly increase the vertical hydraulic conductivity and vertical-to-horizontal hydraulic- conductivity ratios for the aquifer above the laboratory ratios.

Storage values for the Navajo aquifer were determined from the three multiple-well aquifer tests done during this study and ranged from 0.0007 to 0.0025 (both from the Anderson Junction site). This narrow range indicates the general uniformity of storage values for the Navajo aquifer within the study area. Because storage values less than 0.001 generally indicate confined storage (Lohman, 1979), the aquifer-test results indicate that the Navajo aquifer acts as a partly confined system. However, the Navajo Sandstone, as indicated above, is generally homogeneous and well sorted. Drillers' logs and lithologic logs generally do not indicate finer grain-size layers, which normally are associated with confined conditions. One possible explanation is the existence of very thin fine-grained zones or increased cementation associated with bedding planes within the sandstone that are too small to be detected from borehole cuttings. Another explanation is that the small storage values may be a combination of short durations of aquifer testing and observation-well perforated intervals far below the water table. Although the tests showed a short-term confined response at the observation wells, longer-term drawdown observations at these wells might yield higher storage values, approaching the 17-percent effective porosity determined by Cordova (1978).

Kayenta Aquifer

No aquifer testing was done to determine the horizontal or vertical hydraulic conductivity of the Kayenta aquifer as part of this study. However, an earlier multiple-well aquifer test by Cordova (1978) at the Goddard and Savage well (C-41-13)5bbc-1 near Leeds (Wilkowske and others, 1998, table 1) indicated a transmissivity of 3,500 ft^2/d. The geology of this area is complicated by the Virgin River Anticline and associated faulting, which precludes an exact determination of the saturated thickness. However, assuming a saturated thickness of about 600 ft at the site, the estimated hydraulic conductivity is about 6 ft/d. This value is similar to the higher hydraulic-conductivity values for the Navajo aquifer and may indicate a highly fractured area within the Kayenta aquifer.

Additionally, Cordova (1972, table 11) reported a horizontal hydraulic-conductivity value of 1 ft/d on the basis of specific-capacity data from a well in St. George. The storage value estimated from this specific-capacity data is 0.006. Also, estimated horizontal hydraulic conductivity from slug tests in the Kayenta Formation near Sheep Springs, about 2 mi northwest of St. George, ranged from 0.1 to 0.6 ft/d (Jensen and others, 1997).

Horizontal and vertical hydraulic-conductivity values were determined from laboratory analysis of Kayenta Formation samples within the Upper Colorado River Basin, Utah and Colorado (Weigel, 1987, table 5). The average horizontal hydraulic-conductivity value of 12 core samples was about 0.5 ft/d and ranged from 8.2×10^{-4} to 1.4 ft/d. The vertical hydraulic-conductivity value of two samples ranged from 8.2×10^{-4} to 0.5 ft/d. The large range in values reflects the alternating siltstone, silty mudstone, and sandstone layers within the formation. The ratio of vertical-to-horizontal hydraulic conductivity for these two samples ranged from 0.36 and 1.0. As with laboratory analyses of core samples from the Navajo aquifer, these discrete vertical samples may not be an accurate representation of the hydraulic conductivity or vertical-to-horizontal anisotropy ratios for the Kayenta aquifer. Also, hydraulic properties of the Kayenta aquifer may vary regionally between the Upper Colorado River Basin and the central Virgin River basin.

As in the Navajo aquifer, fracturing within the Kayenta Formation is thought to enhance the permeability of the aquifer. Sheep Springs, which emanate from a fracture zone in the Kayenta Formation, is evidence of this. In the vicinity of Sheep Springs, the predominant joints are orientated north-south and have a near-vertical dip (Jensen and others, 1997, fig. 21, 22). This is similar to the predominant north-south direction and vertical dip of the Navajo Sandstone fractures at nearby outcrops between City Creek and Snow Canyon (Hurlow, 1998, pl. 6). Therefore, it generally is assumed that directional anisotropy of hydraulic conductivity within the Kayenta aquifer is similar to that in the Navajo aquifer.

Recharge

The Navajo and Kayenta aquifers are recharged primarily by infiltration of precipitation on the Navajo Sandstone and Kayenta Formation outcrop and seepage from streams crossing the outcrop. Additional sources of recharge include seepage from overlying and underlying formations, infiltration of unconsumed irrigation water, and seepage from Gunlock Reservoir. The total amount of recharge for the main and Gunlock parts of the aquifer is estimated to range from 12 to 49 ft^3/s (about 8,700 to 36,100 acre-ft/yr) and from 2 to 10 ft^3/s (about 1,400 to 7,300 acre-ft/yr), respectively.

Precipitation

Infiltration of precipitation as either rain or snow on the Navajo Sandstone and Kayenta Formation outcrop is thought to be the largest source of recharge to the main aquifer but not the Gunlock part of the aquifer. The total average annual precipitation on the outcrop is estimated to be about 205 ft^3/s (148,800 acre-ft/yr) and 18.5 ft^3/s (13,400 acre-ft/yr), respectively, for the main and Gunlock parts of the aquifers. The percentage of precipitation that moves through the unsaturated zone to the water table is assumed to vary widely based on such factors as topographic slope, density of fractures extending to the surface, surficial material on the outcrop, season, vegetation, and storm intensity.

The topography of Navajo Sandstone and Kayenta Formation outcrops within the study area ranges from steep escarpments to nearly flat surfaces. Rapid runoff and potentially lower infiltration rates are characteristic of the steeper sloped areas, whereas slower runoff and potentially higher infiltration rates are characteristic of the more flatter areas. The outcrop surface consists of areas of consolidated rock, unconsolidated sand, and fractured basalt. The exposed sandstone and siltstone along the outcrop varies from highly fractured to relatively unfractured. Fractures that are exposed along the outcrop can greatly enhance recharge by providing conduits for rapid transport of water to the saturated zone (Pruess, 1998). Also, infiltration rates likely are higher where thin surficial deposits of sand and basalt cover the outcrop. Sand deposits can trap and temporarily store precipitation that would otherwise run off of unfractured areas of the outcrop, allowing more time for infiltration into the consolidated rock outcrop (Dincer and others, 1974). Likewise, fractured basalt can rapidly transmit water beneath the evapotranspiration zone and result in more available recharge.

Once infiltration to the subsurface occurs, evaporation from the shallowest part of the unsaturated zone can occur and reduce recharge, especially during the warmer seasons. Similarly, in areas of thick vegetative cover, much of the potential recharge to the aquifer can be intercepted within the evapotranspiration (root) zone during the warmer seasons. The frequency and intensity of precipitation also are important factors that affect the amount of recharge. Recharge from short-lived storms with small amounts of precipitation is probably minimal, with most of the water intercepted in the shallow subsurface by evapotranspiration. However, long-lasting storms of high precipitation intensity, especially during the winter months when evaporation and evapotranspiration effects are minimal, likely account for a large part of recharge to the aquifer. The increased soil-moisture content during longer precipitation events greatly increases the effective permeability of the unsaturated sandstone and its ability to transmit water downward toward the saturated zone.

Recharge to the Navajo and Kayenta aquifers is estimated to be from 5 to 15 percent of precipitation on the outcrop, and ranges from about 10 to 30 ft^3/s (7,200 to 21,700 acre-ft/yr) for the main part and from about 1 to 3 ft^3/s (700 to 2,200 acre-ft/yr) for the Gunlock part. No measurements of the infiltration rates were taken during this study. The minimum estimated infiltration rate is based on a study site in New Mexico in fine-grained soils (Scanlon, 1992). The infiltration rate from tritium analysis of unsaturated-zone pore water was estimated to be about 4.8 percent of the 8-in. average annual precipitation. This infiltration rate is assumed to be at the low end of recharge to the outcrop in the study area because (1) average annual precipitation on the outcrop ranges from 8 to 19 in. and the rate of infiltration is generally assumed to increase in areas of higher precipitation; (2) the study area has lower average annual temperatures and lower potential soil-water evaporation than the New Mexico site; and (3) the surficial material along the outcrop (sand dunes, fractured basalt, and fractured sandstone) may capture and transport water to the saturated zone more readily than the soils at the New Mexico study sites. The maximum 15-percent infiltration rate is based on estimated recharge along consolidated-rock outcrops in Tooele County, Utah, where average annual precipitation ranges from 16 to 20 in/yr (Hood and Waddell, 1968, table 5). Also, a study of recharge beneath the Dahna sand dunes in Saudi Arabia, where annual precipitation is much less, indicated infiltration rates of as much as29 percent (Dincer and others, 1974). The measured infiltration rate in Saudi Arabia may be higher than along sand dunes overlying the Navajo aquifer because the Dahna sand is coarser grained.

Streams

Seepage from streams traversing the Navajo Sandstone and Kayenta Formation outcrop is another important source of ground-water recharge to the Navajo aquifer. Six of the seven perennial streams that traverse the outcrop in the study area had a net loss of water from the stream into the Navajo aquifer. Also, numerous ephemeral washes traverse the outcrop and most likely are an additional source of recharge to the Navajo aquifer.

Perennial Streams

All six perennial streams which originate in the Pine Valley Mountains and traverse the outcrop recharge the Navajo aquifer. These streams include South Ash Creek, Wet Sandy Creek, Leeds Creek, Quail Creek, Cottonwood Creek/Heath Wash, and the Santa Clara River (fig. 22). Total recharge to the Navajo aquifer from these perennial streams was estimated from seepage studies to range from 1.8 to 4.4 ft^3/s (1,300 to 3,200 acre-ft/yr) and from 0.78 to 4.1 ft^3/s (570 to 3,000 acre-ft/yr) for the main and Gunlock parts of the Navajo and Kayenta aquifers, respectively. The Virgin River, which traverses the outcrop near Sand Mountain, is the only perennial stream that did not show net seepage to the aquifer during seepage studies.

Reconnaissance-level seepage studies were done along all of the perennial creeks that originate in the Pine Valley Mountains and traverse the outcrop. These studies were done from October through December 1995, during base-flow conditions when little or no evapotranspiration was occurring. Therefore, measured loss in streamflow was assumed to be recharge to the Navajo aquifer. Streamflow was measured in the Santa Clara River, Leeds Creek, and Quail Creek where the streams first cross the contact between the Navajo Sandstone and the overlying Carmel Formation, and again where the streams cross the contact between the Navajo Sandstone and the Kayenta Formation. The downstream measurement in South Ash Creek was at the contact with unconsolidated Quaternary sediments, about 0.7 mi upstream from the contact between the Navajo Sandstone and the Tertiary formations (pl. 1). The downstream measurement in Wet Sandy Creek was at the contact with unconsolidated Quaternary sediments about 2 mi upstream from where it was noted to be dry as the wash crosses underneath highway I-15. Streamflow was measured in Cottonwood Creek (and the Heath Wash tributary) at the Navajo Sandstone/Carmel Formation contact, and the stream was observed to be dry at the Navajo Sandstone/Kayenta Formation contact. Estimated recharge from perennial streams on the basis of the seepage studies is shown in table 11. The estimated recharge to the Navajo aquifer from perennial streams may be low because the seepage studies were done during base-flow conditions. Higher flow conditions would increase the stage and width of the stream and should increase recharge from the stream to the aquifer.

Decreases in streamflow were measured for all perennial streams that cross the outcrop (fig. 22). Upper Cottonwood, Quail, Wet Sandy, and South Ash Creeks had measured seepage losses of 0.47 ft^3/s (360 acre-ft/yr), 0.19 ft^3/s (140 acre-ft/yr), 0.37 ft^3/s (270 acre-ft/yr), and 1.38 ft^3/s (1,000 acre-ft/yr), respectively (table 11). Although seepage studies along Leeds Creek on 10/07/95 and 12/07/95 showed small net gains in streamflow as the creek crossed the outcrop, these gains were within the error limitations of the measurement equipment. Therefore, these two seepage studies were determined to be inconclusive. An earlier seepage study by Cordova (1978) indicated a seepage loss from Leeds Creek to the Navajo aquifer of 0.22 ft^3/s (160 acre-ft/yr).

Downstream from the Navajo Sandstone outcrop, Wet Sandy and South Ash Creeks flow along Quaternary alluvial deposits that overlie the Navajo Sandstone (pl. 1). During the October 1995 seepage study, discharge in Wet Sandy Creek decreased along this reach of coarse alluvium from 0.63 ft^3/s, eventually drying

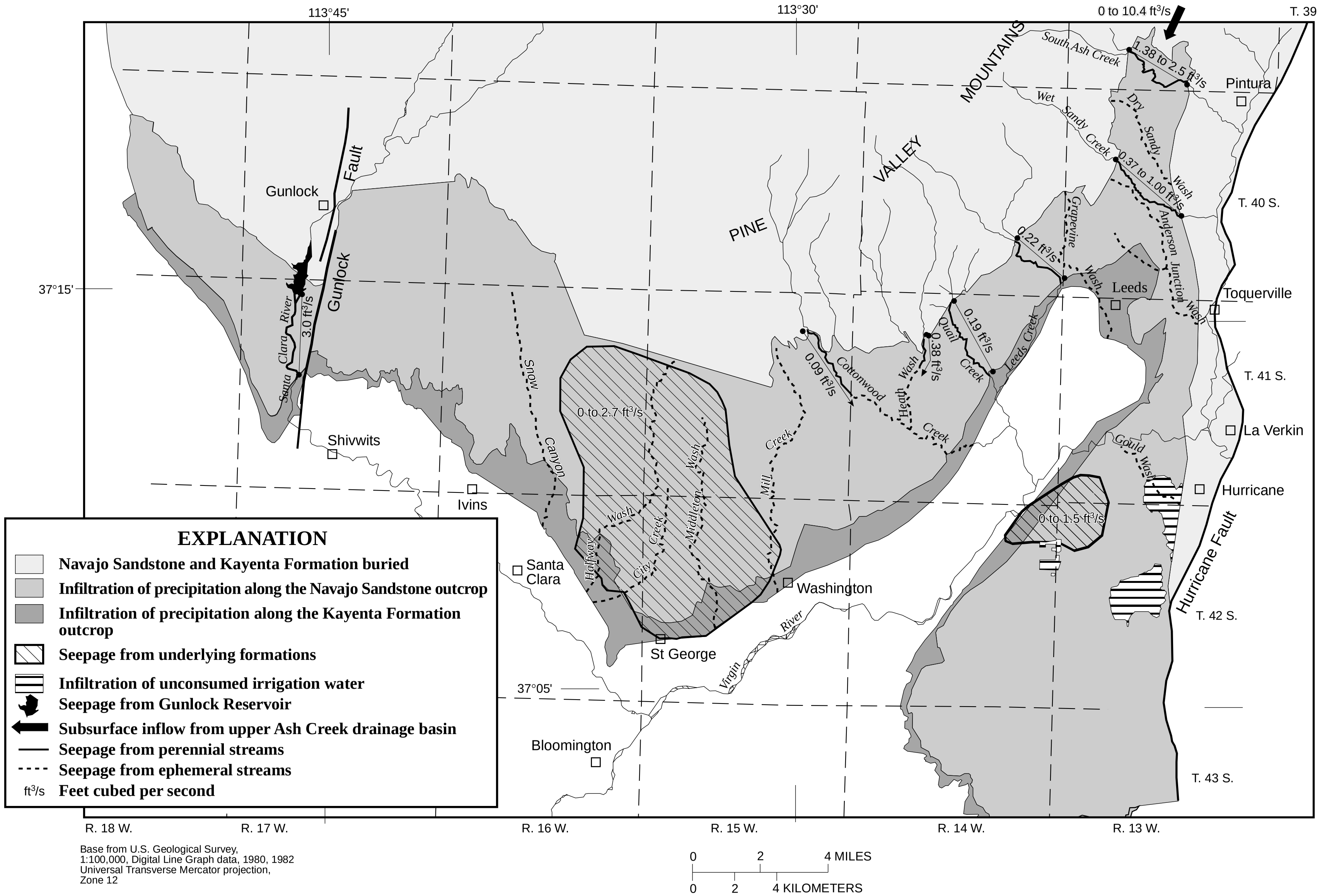

Figure 22. Potential sources of recharge to the Navajo and Kayenta aquifers in the central Virgin River basin study area, Utah.

Table 11. Seepage measurements and estimated recharge from perennial streams to the Navajo aquifer in the central Virgin River basin, Utah

[acre-ft/yr, acre-feet per year; ft^3/s, cubic feet per second; NA, not available]

Stream	Average annual discharge from streamflow-gaging stations (acre-ft/yr)	Date	Upper discharge measure-ment, (ft^3/s)	Lower discharge measure-ment, (ft^3/s)	Measured seepage from stream, (ft^3/s)	Estimated recharge to aquifer, in ft^3/s (acre-ft/yr)
Main part of Navajo aquifer[1]						
Cottonwood Creek (upper)[2]	NA	10/08/95	.47	0	.47	.47 (360)
Quail Creek	NA	10/24/95	[3].537	.345	.19	.19 (140)
Leeds Creek	[4]5,610	12/07/95	4.99	5.27	[5]NA	0 to[6].22 (160)
Wet Sandy	NA	10/06/95	1.00	.63	.37	.37 to [7]1.00 (270 to 720)
South Ash Creek	[8]5,000	10/09/95	3.58	2.20	1.38	[6].48 to[9]3.6 (350 to 2,600)
Total (rounded)						**1.5 to 5.5 (1,300 to 4,000)**
Gunlock part of Navajo aquifer						
Santa Clara River	[10]17,170	12/06/95	18.8	14.7	4.1	[11].78 to 4.1 (570 to 3,000)
		02/15/96	.78	0	.78	

[1] Combination of discharge in Bitter Creek and Heath Wash.
[2] A seepage study was done for upper Cottonwood Creek, however, it is only a perennial stream along the upper part of Navajo Sandstone outcrop.
[3] Combination of discharge in Quail Creek and Water Canyon.
[4] Based on measurements from USGS streamflow-gaging station 0940800 for water years 1965-1996 (Herbert and others, 1997).
[5] Because of possible measurement error (as much as 10 percent), the upper contact and lower contact discharge values are too close to quantify seepage.
[6] Based on a USGS seepage study reported by Cordova (1978, p. 17).
[7] Assumes all seepage to the subsurface through alluvial deposits recharges the Navajo aquifer.
[8] Based on measurements from USGS streamflow-gaging station 09406700 for water years 1966-82 (ReMillard and others, 1982).
[9] Assumes all seepage to the subsurface through alluvial deposits recharges the Navajo aquifer.
[10] Based on USGS streamflow-gaging station 09410100 for water years 1973-96 (Herbert and others, 1997).
[11] Average annual recharge is estimated to be 3.0 cubic feet per year based on a seepage rate of 4.1 ft^3/s for 8 months per year and 0.78 ft^3/s for 4 months per year.

out before the reach crossed under Interstate I-15. Therefore, in addition to the measured 0.37 ft^3/s seepage loss along Wet Sandy Creek as it traversed the outcrop, it is probable that there was 0.63 ft^3/s of seepage to the Navajo aquifer through overlying alluvial deposits. Similarly, the flow in South Ash Creek decreased from 2.2 ft^3/s along Quaternary alluvial deposits downstream of the outcrop, eventually drying out before the reach crossed under Interstate I-15. Therefore, in addition to the measured 1.38 ft^3/s seepage loss along South Ash Creek as it traversed the outcrop, it is possible that there was up to 2.2 ft^3/s of seepage to the Navajo aquifer through overlying alluvial deposits. Thus, total recharge to the Navajo aquifer during these base-flow conditions was up to 1.00 ft^3/s (720 acre-ft/yr) along Wet Sandy Creek and 3.6 ft^3/s (2,600 acre-ft/yr) along South Ash Creek.

Because the city of St. George diverts several large springs that previously flowed into Cottonwood Creek, this once perennial stream flows year round only in the upper section of its reach along the outcrop. On the basis of a 15-year record from the city of St. George, an average of 2,500 acre-ft/yr of water from springs is diverted from the upper Cottonwood Creek drainage. During the seepage study, the creek bed was dry along the lower two-thirds of its reach as it traverses the outcrop. Therefore, it is assumed that the base-flow component of the creek is removed by diverting the springs, effectively shortening its perennial reach. Observations by local residents indicate that after a precipitation event, Cottonwood Creek remains flowing longer than other nearby ephemeral drainages (Morgan Jenson, Washington County Water Conservancy District, oral commun., 1998). This is consistent with the assumption that Cottonwood Creek was perennial along the entire reach that traverses the Navajo Sandstone prior to spring development by the city of St. George.

Discharge in the Santa Clara River traversing the Navajo Sandstone and Kayenta Formation outcrop is controlled by releases from Gunlock Reservoir. Discharge records from the Gunlock Reservoir outlet beginning in 1971 (Utah State Division of Water Rights, written commun., 1998) indicate that water is released from the reservoir for about 8 months per year. Discharge from the reservoir averages about 20 ft^3/s during this period (Rodney & Helen Leavitt, written commun., 1998). When the reservoir release valve is closed (for about 4 months per year), about 0.8 ft^3/s seeps from the base of the dam into the stream channel. Two seepage studies were done on the Santa Clara River during winter when little or no evapotranspiration is thought to occur. The first seepage study, during which 18.8 ft^3/s was being released from the reservoir, indicated that 4.1 ft^3/s of seepage loss occurred. The second seepage study, during which the release valve was shut and streamflow was 0.78 ft^3/s, indicated that 0.78 ft^3/s of seepage loss occurred because the stream stopped flowing a few miles downstream from the dam. If the higher seepage rate of 4.1 ft^3/s occurs on average 8 months per year and the lower seepage rate to occur on average 4 months per year, the average annual seepage rate from the Santa Clara River into the Navajo aquifer is estimated to be about 3.0 ft^3/s (table 11). A seepage study done by the USGS in 1974 (Cordova, 1978) indicated a seepage gain into the river along the same reach of about 1.5 ft^3/s. This indicates that a reversal of head gradient between the aquifer and the river has occurred since 1974, most likely as a result of increased discharge at the St. George municipal well field.

Geochemical evidence also indicates that most of the water that recharges the St. George municipal well field in the Gunlock part of the Navajo aquifer (west of the Gunlock Fault) originates as seepage from the Santa Clara River. A trilinear plot of major-ion chemistry of water from both the Santa Clara River and the St. George municipal well field near Gunlock is shown in figure 23. With the exception of the water sample of St. George City Gunlock Well #2, the ground-water samples have a geochemical signature very similar to that of Santa Clara River water sampled near Gunlock and Windsor Dam. This indicates that most of the recharge to the municipal well field is from seepage from the Santa Clara River and Gunlock Reservoir where they cross the Navajo Sandstone and Kayenta Formation outcrop. Gunlock Well #2, located about 1,500 ft from the Santa Clara River, contains water with higher dissolved-solids concentrations than the other wells, including higher concentrations of sulfate and chloride (fig. 15; Wilkowske and others, 1998, tables 1 and 4). This well, located farther from the Santa Clara River than the other St. George City municipal wells, was drilled closer to the base of the Navajo Sandstone and Kayenta Formation than the other wells. Thus, it may receive part of its recharge from infiltration of precipitation or upward movement of water from underlying formations.

CFC data also indicate that the Santa Clara River is a source of recharge to the Navajo aquifer. Seven wells in the Gunlock part of the Navajo aquifer and four surface-water sites along the Santa Clara River were sampled for CFCs (fig. 24). Average CFC-12 concentrations from Gunlock Wells #7 and #8, east of the Santa Clara River, were about 0 and 0.11 pmoles/kg, respectively, indicating apparent recharge ages from pre-1950 to 1958 (table 4; fig. 25). These values are much lower than for wells adjacent to the Santa Clara River on the west side. Gunlock Wells #3, #4, and #5, west of the Santa Clara River, had measured CFC-12 concentrations of about 0.35, 0.42, and 1.14 pmoles/kg, respectively, indicating apparent recharge ages from 1966 to 1977 (table 4; fig. 25). The average CFC-12 concentration at four sites along the Santa Clara River was about 1.5 pmoles/kg (table 4). The analysis of the CFC-12 data indicates that in the area of the St. George municipal well field, the Santa Clara River recharges the Navajo aquifer to the west. This is consistent with (1) general-chemistry data that show that the Santa Clara River is likely the principal source of recharge to this part of the Navajo aquifer, (2) seepage studies along the Santa Clara River that show it to be a losing reach in the area of the well field, and (3) contoured water-level data from the well field that show the direction of ground-water flow from northeast to southwest under the river (fig. 26).

Ephemeral Streams

Two methods for estimating recharge to the Navajo aquifer along ephemeral streams in Washington County, Utah, have been developed. In the first method, a theoretical average annual discharge in ephemeral streams is calculated and recharge to the aquifer is assumed to be a percentage of this amount. In the second method, an experimentally determined rate of infiltration per unit length of ephemeral stream is applied to calculate recharge. Both methods were applied to ephemeral streams with drainage-basin areas greater

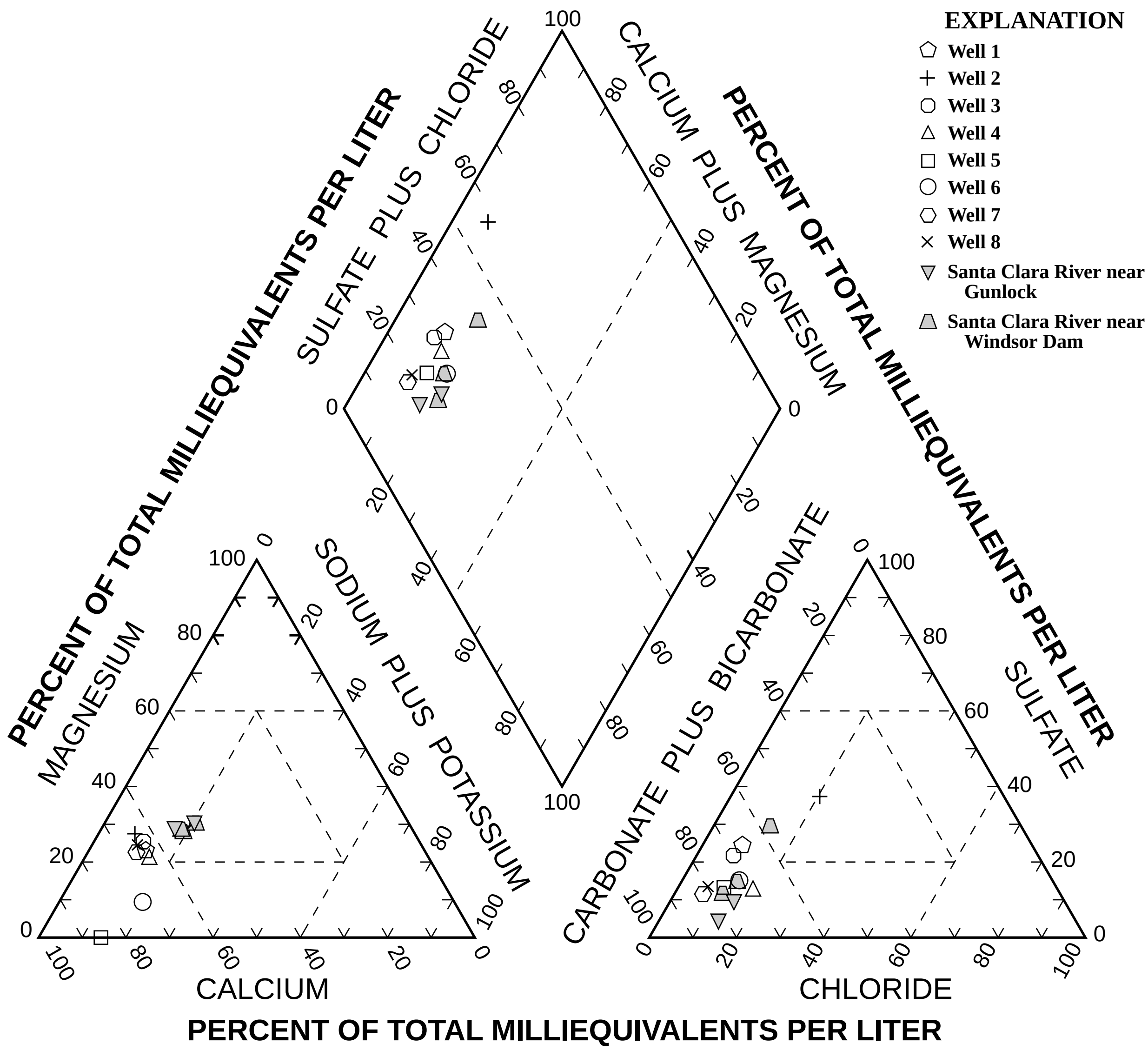

Figure 23. Chemical composition of water from the Santa Clara River and the St. George municipal well field in the Gunlock part of the Navajo aquifer within the central Virgin River basin study area, Utah.

than 5 mi^2 that cross the main part of the outcrop. No ephemeral streams with drainage basin areas greater than 5 mi^2 cross the Gunlock part of the outcrop. The drainage-basin area for the perennial and larger ephemeral streams that recharge the Navajo aquifer in the study area are shown in figure 27. Recharge to the main part of the Navajo aquifer from ephemeral streams is estimated to range from 0.28 to 6.3 ft^3/s (200 to 3,000 acre-ft/yr).

Method 1

Average annual discharge for streams in southern Utah can be estimated by using two equations developed by Christensen and others (1985, tables 3 and 4):

Southwestern plateaus region: $Q = 7.02 + .583\,A$ (2)

Central plateaus region: $Q = 4.13 \times 10^{-4} A^{.709} P^{1.46} S^{.554}$ (3)

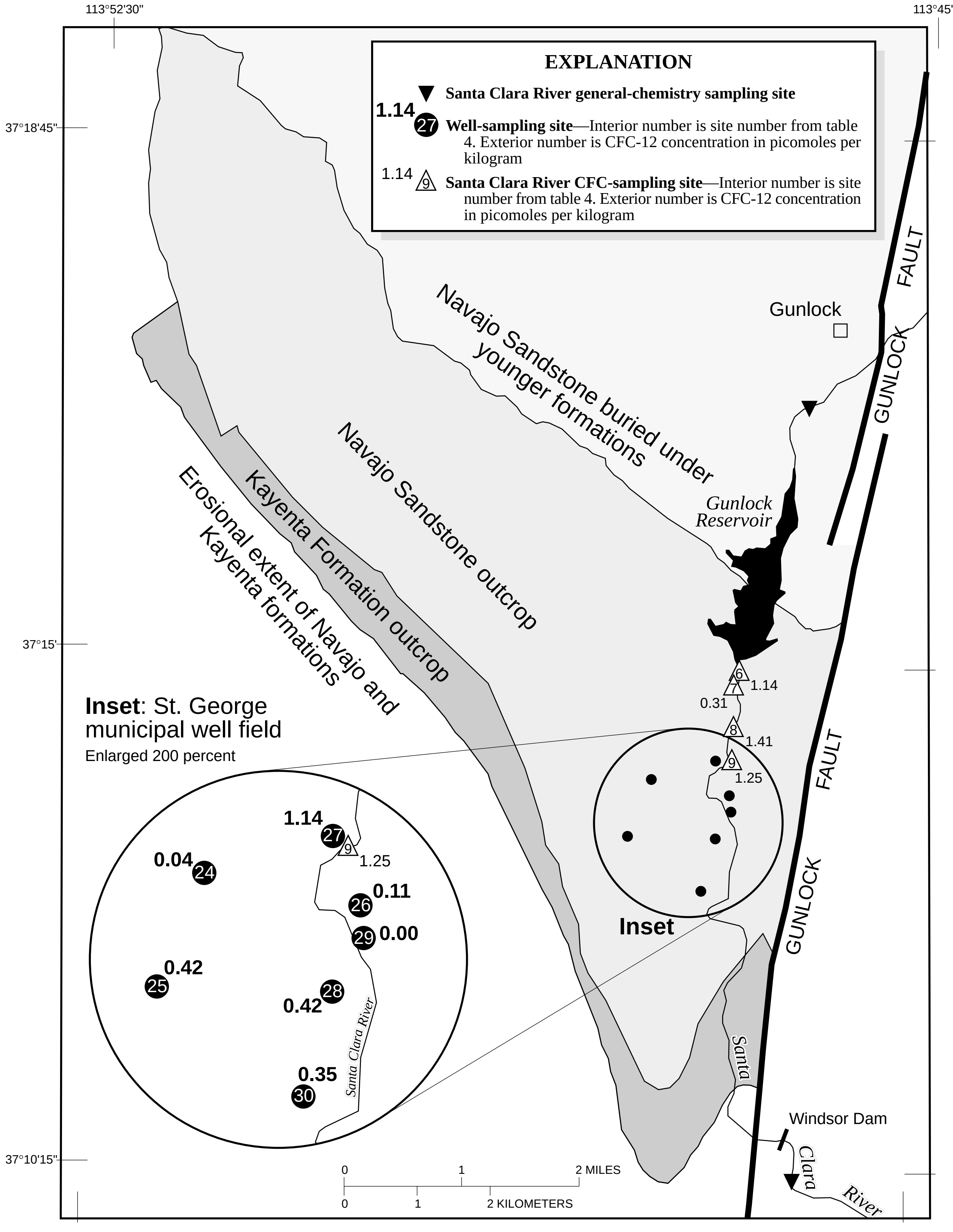

Figure 24. Location of general-chemistry sampling sites and CFC-12 sampling sites in the Gunlock part of the Navajo aquifer, central Virgin River basin study area, Utah.

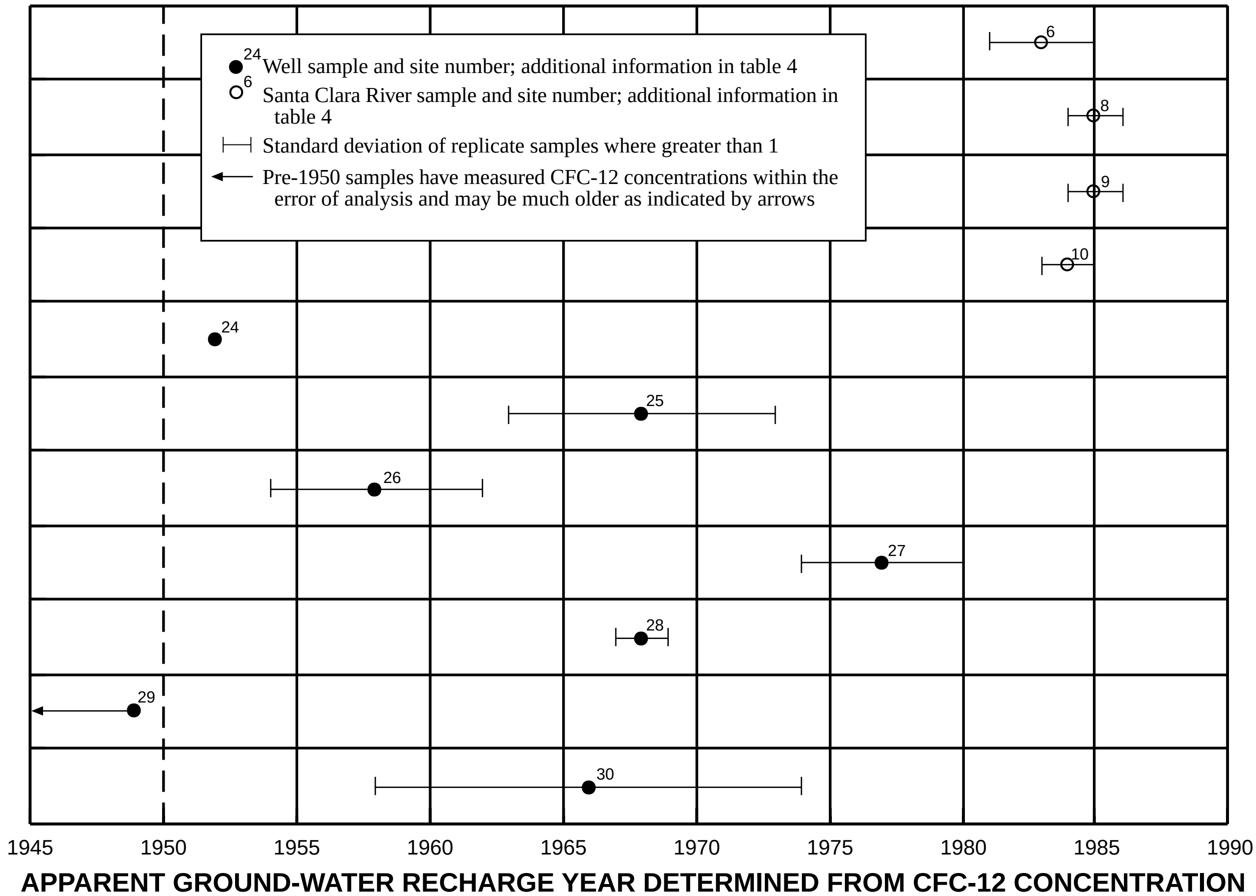

Figure 25. Apparent ground-water recharge year determined from CFC-12 concentration at Santa Clara River sites and in water from wells in the Gunlock part of the Navajo aquifer within the central Virgin River basin study area, Utah.

where

Q is discharge in acre-ft/d,
A is the area of the drainage basin in mi^2,
P is average annual precipitation in., and
S is the main channel slope in ft/mi.

Equation 2 was developed for streams in the southwestern plateaus region of Utah and was calibrated with perennial streams including South Ash Creek and Leeds Creek. Equation 3 was developed for the central plateaus region of Utah. The ephemeral streams in the central part of the study area southwest of and including Cottonwood Creek and along Hurricane Bench have quite different characteristics from South Ash Creek and Leeds Creek. These streams receive little or no gain from snowmelt runoff; therefore, it is believed that the equation developed for the central plateaus region more accurately predicts discharge of these lower-altitude streams. The parameters for each of the drainage basins are reported in table 12.

Only the higher altitude ephemeral stream basins northeast of Cottonwood Creek are assumed to be affected by snowmelt runoff. These streams, labeled “E2” in table 12, are similar to Leeds and South Ash Creeks, upon which the southwestern plateaus region discharge equation, equation 3, was based (Christensen and others, 1985, tables 3 and 4). Ephemeral streams that drain the Pine Valley Mountains to the southwest of and including Cottonwood Creek are probably not affected by snowmelt runoff and are similar to streams in the central plateaus region. Discharge in these streams is calculated by using equation 3 and is labeled “E3” in table 12. The last column of the table shows the estimated average annual discharge for both the ephemeral and perennial creeks that cross the outcrop. Discharge for the perennial streams is calculated by using equation 2.

The estimated discharge in acre-ft/yr is shown in the first column of table 13. Average annual discharge, estimated by using equation 2 for Leeds Creek, is 5,770

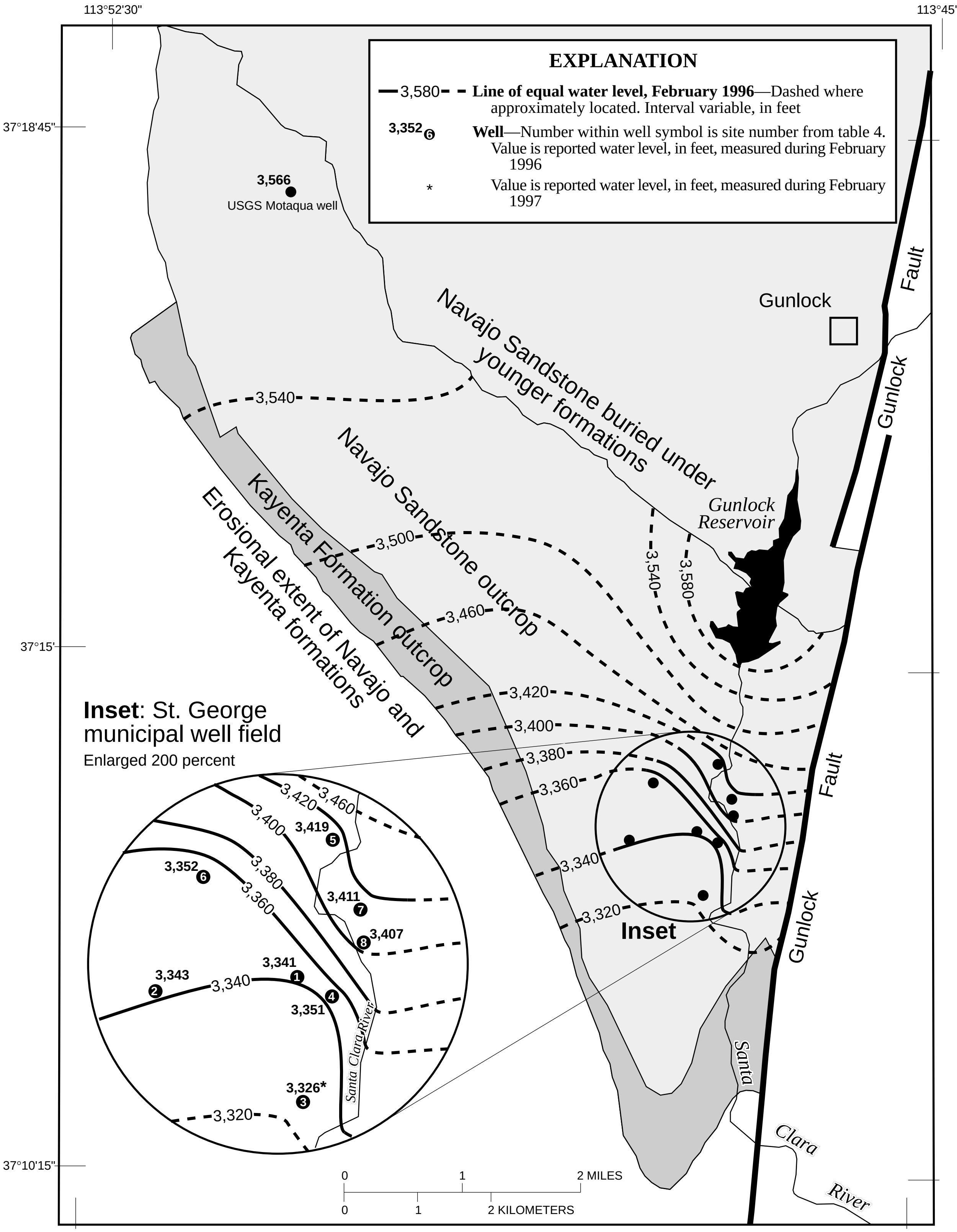

Figure 26. Approximate potentiometric surface in the Gunlock part of the Navajo aquifer within the central Virgin River basin study area, Utah, February 1996.

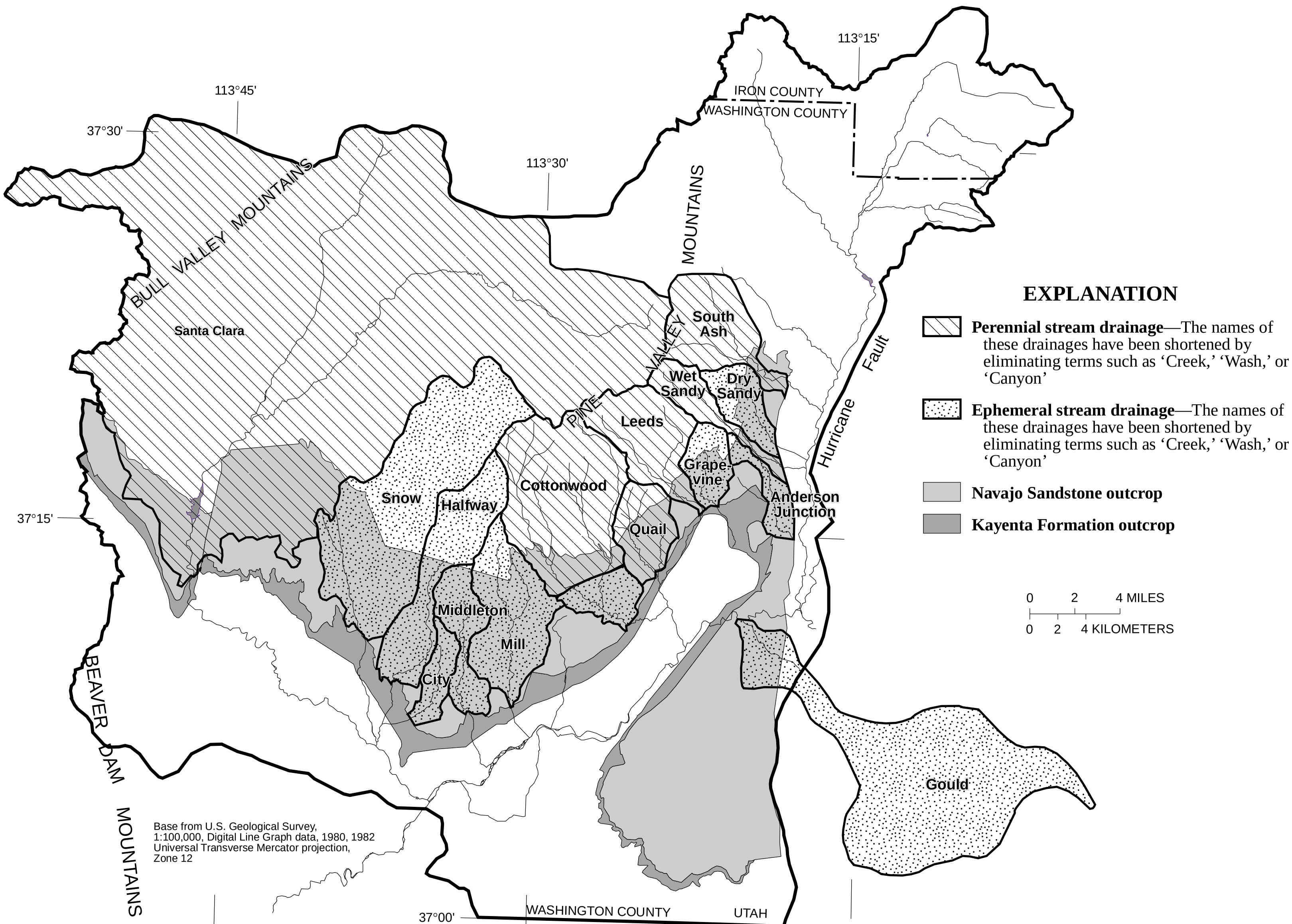

Figure 27. Drainage-basin areas for perennial and ephemeral streams that recharge the Navajo and Kayenta aquifers in the central Virgin River basin study area, Utah.

Table 12. Drainage-basin parameters for perennial and ephemeral streams that recharge the Navajo aquifer in the central Virgin River basin, Utah

Stream type: E2 indicates an ephemeral stream located northeast of Cottonwood Creek with discharge calculated using equation 2; E3 indicates an ephemeral stream located southwest of, and including, Cottonwood Creek and along Hurricane Bench, with discharge calculated using equation 3; P indicates a perennial stream with discharge calculated using equation 2.

Drainage basin	Stream type	Drainage area (square miles)	Average annual precipitation (inches)	Main channel slope (feet per mile)	Estimated average annual discharge (acre-feet per day)	Estimated average annual discharge (acre-feet per year)
Ephemeral streams:						
Snow Canyon	E3	49	14.7	180	5.9	2,140
Halfway Wash	E3	19	12.7	260	3.0	1,080
City Creek	E3	5	9.14	130	0.48	180
Middleton Wash	E3	9	10.5	150	.97	360
Mill Creek	E3	19	11.0	330	2.7	1,000
Gould Wash	E3	62	14.0	78	4.1	1,480
Cottonwood Creek	E3	40	16.1	250	7.0	2,540
Grapevine Wash	E2	6	13.0	210	10.5	3,830
Anderson Junction Wash	E2	5	12.2	220	9.9	3,610
Dry Sandy Wash	E2	7	16.6	610	11.1	4,050
Perennial streams:						
Quail Creek	P	9	12.9	340	12.3	4,490
Leeds Creek	P	15	19.0	410	15.8	5,770
Wet Sandy	P	7	19.8	570	11.1	4,050
South Ash Creek	P	16	23.4	290	16.4	5,990

acre-ft/yr, similar to the 5,610 acre-ft/yr average based on 32 years of measurements at USGS streamflow-gaging station 0940800 (table 11). Average annual discharge, estimated by using equation 2, for South Ash Creek is 5,990 acre-ft/yr. However, when using the smaller drainage basin area (11.0 mi^2) upstream of USGS streamflow-gaging station 09406700, the average annual discharge is 4,900 acre-ft/yr, similar to the 5,000 acre-ft/yr average based on 16 years of streamflow-gaging station measurements (table 11).

The estimated annual recharge from ephemeral streams also is shown in table 13. It is assumed that between 5 and 15 percent of the estimated average annual discharge, or 1,000 to 3,000 acre-ft/yr, is estimated to recharge the Navajo aquifer from ephemeral streams that cross the outcrop. To evaluate the accuracy of this method, the estimated average annual discharge was calculated for the perennial streams by using equation 2. The same percentage of discharge (5 to 15 percent) was compared to values measured during the seepage investigations of perennial streams (not including the Santa Clara River, whose discharge is regulated by dam releases and irrigation diversions). By using method 1, the total estimated recharge from perennial streams would be 1,000 to 3,000 acre-ft/yr, similar to the 900 to 2,800 acre-ft/yr of measured seepage from perennial streams. When compared to another ephemeral stream seepage study, the estimated 5- to 15-percent infiltration of stream discharge for this study brackets the 9 percent of total streamflow estimated to recharge the alluvial aquifer system beneath the ephemeral Rillito Creek in southern Arizona based on microgravity surveying (Parker and others, 1998). The two primary limitations of this method are: (1) no long-term recharge from ephemeral streams in the study area has been measured; and (2) there are no perennial streams southwest of Cottonwood Creek to compare with discharge estimates obtained by using equation 3.

Method 2

This alternative method of estimating ephemeral stream recharge is based on an infiltration experiment done during February and March 1997 along City Creek where it traverses the Navajo Sandstone outcrop (pl. 1, fig. 22). The St. George City Creek Well #2 (Wilkowske and others, 1998, table 1) was pumped at 540 gal/min and discharged into the dry stream channel. Flow measured 4 mi downstream at Dixie-Red Hills Golf Course was 250 gal/min. The test, done in

Table 13. Estimated annual recharge from ephemeral streams to the Navajo aquifer based on estimated annual stream discharge, central Virgin River basin, Utah

Drainage basin	Estimated average annual discharge (acre-feet per year)	Estimated recharge assuming:			Measured seepage, in acre-feet per year (see table 11)
		15 percent infiltration of discharge (acre-feet per year)	10 percent infiltration of discharge (acre-feet per year)	5 percent infiltration of discharge (acre-feet per year)	
Ephemeral streams					
Snow Canyon	2,140	320	210	110	
Halfway Wash	1,080	160	110	50	
City Creek	180	30	20	10	
Middleton Wash	360	50	40	20	
Mill Creek	1,000	150	100	50	
Gould Wash	1,480	220	150	70	
Cottonwood Creek (lower)	2,450	380	250	130	
Grapevine Wash	3,830	570	380	190	
Anderson Junction Wash	3,610	540	360	180	
Dry Sandy Wash	4,050	610	400	200	
Total (rounded)	20,200	3,000	2,000	1,000	
Perennial streams[1]					
Quail Creek	4,490	670	450	220	140
Leeds Creek	5,770	870	580	290	[2]160
Wet Sandy	4,050	610	400	200	270-720
South Ash Creek	5,990	900	600	300	[2]350-1,800
Total (rounded)	20,300	3,000	2,000	1,000	900-2,800

[1] Excludes the perennial reach of Cottonwood Creek because stream discharge is affected by spring diversions.
[2] Based on seepage studies from Cordova (1978, p.17).

early spring when evapotranspiration effects are considered negligible, showed a net seepage loss of 290 gal/min, or 53 percent of the total flow. The loss per mile during this experiment was about 70 gal/min or about 0.31 (acre-ft/d)/mi. When making the simplifying assumption that this infiltration rate is constant for all ephemeral streams crossing the Navajo Sandstone in the study area, the following method was used to calculate total ephemeral stream recharge: (1) this rate was multiplied by the length of each ephemeral stream reach along the outcrop; and (2) this product was then multiplied by the estimated number of days of flow in each ephemeral drainage.

The duration of the flow and length of stream reach along the outcrop in the larger ephemeral stream drainages are shown in table 14. These estimates are based on observations from local residents (Morgan Jensen, oral commun., 1998), as well as on the hydrograph of discharge along Leeds Creek for the past 19 years (fig. 28). Base flow on Leeds Creek, determined from annual discharge hydrographs, is about 2.8 ft^3/s, and is represented by a horizontal dashed line on figure 28. Two distinct types of higher flows can be seen on the hydrograph: (1) narrow spikes representing rainstorms and (2) wider peaks of longer duration representing periods of snowmelt runoff. Factors assumed to affect the duration of flow in ephemeral stream drainages are the estimated number of larger rainstorms, the frequency and length of snowmelt-runoff events, and the presence of springs. On the basis of anecdotal information from local residents, large rainstorms are estimated to occur on average five times per year, causing ephemeral streamflow lasting about 1 day in the larger drainages. Periods of snowmelt are identified on the

Table 14. Estimated recharge from ephemeral streams to the Navajo aquifer based on the City Creek infiltration experiment, February to March 1997, central Virgin River basin, Utah

Factors affecting streamflow: R, rainfall events; SP, spring flow; SN, snowmelt-runoff events.

Drainage basin	Stream reach on outcrop[1] (miles)	Infiltration rate (acre-feet per day per mile)	Factors affecting streamflow	Flow duration (days per year)	Estimated recharge (acre-feet per year)	Measured seepage (acre-feet per year)
			Ephemeral Streams			
Snow Canyon	7.7	0.31	R	5	12	
Halfway Wash	9	.31	R	5	14	
City Creek	5.2	.31	R	5	8	
Middleton Wash	7.7	.31	R	5	12	
Mill Creek	8.9	.31	R	5	14	
Gould Wash	2.8	.31	R+SP	15	13	
Cottonwood Creek (lower)	7.3[2]	.31	R+SN+SP	25	57	
Grapevine Wash	4.2	.31	R+SN+SP	25	33	
Anderson Junction Wash	5.6	.31	R	5	9	
Dry Sandy Wash	3.7	.31	R+SN	15	17	
Total (rounded)					200	
			Perennial streams[3]			
Quail Creek	4.1	.31		365	470	140
Leeds Creek	2.8	.31		365	310	[4]160
Wet Sandy	2.8	.31		365	310	270 -720
South Ash Creek	3.1	.31		365	360	[4]350-1,800
Total (rounded)					1,500	900-2,800

[1] Length of stream reach along either the Navajo Sandstone or Navajo Sandstone and Kayenta Formation outcrop.
[2] Lower Cottonwood Creek (ephemeral part) is about 2/3 of the 11.0-mi stream reach along the Navajo Sandstone and Kayenta Formation.
[3] Excludes the perennial reach of Cottonwood Creek because stream discharge is affected by spring flow diversions.
[4] Based on seepage studies from Cordova (1978, p. 17).

Leeds Creek hydrograph as those multiple-month flows during late winter through early summer with a discharge greater than 10 ft^3/s. On the basis of the Leeds Creek hydrograph, longer periods of snowmelt runoff are estimated to occur on average once every third year. Local residents have observed that these snowmelt-runoff flows last about 30 days (or 10 days per year) for higher altitude ephemeral streams, such as Cottonwood Creek, Grapevine Wash, and Dry Sandy Wash. The presence of springs in an ephemeral wash is assumed to increase the duration of flow by enhancing the discharge. It is estimated that the presence of springs would lengthen rain and snowmelt-runoff flows each by 10 days. Cottonwood Creek, Grapevine Wash, and Gold Wash have springs that discharge into the stream channel (table 14).

The estimated recharge from ephemeral streams to the Navajo aquifer calculated using method 2 is shown in table 14. The total estimated recharge from ephemeral streams is about 200 acre-ft/yr. To verify the accuracy of this method, the same infiltration rates per river mile were applied to the perennial streams and compared to values measured during the seepage investigations (not including the Santa Clara River and Cottonwood Creek, whose discharge is regulated by dam releases, irrigation diversions, and/or spring-flow diversions). With this method, the total estimated recharge from perennial streams would be about 1,500 acre-ft/yr.

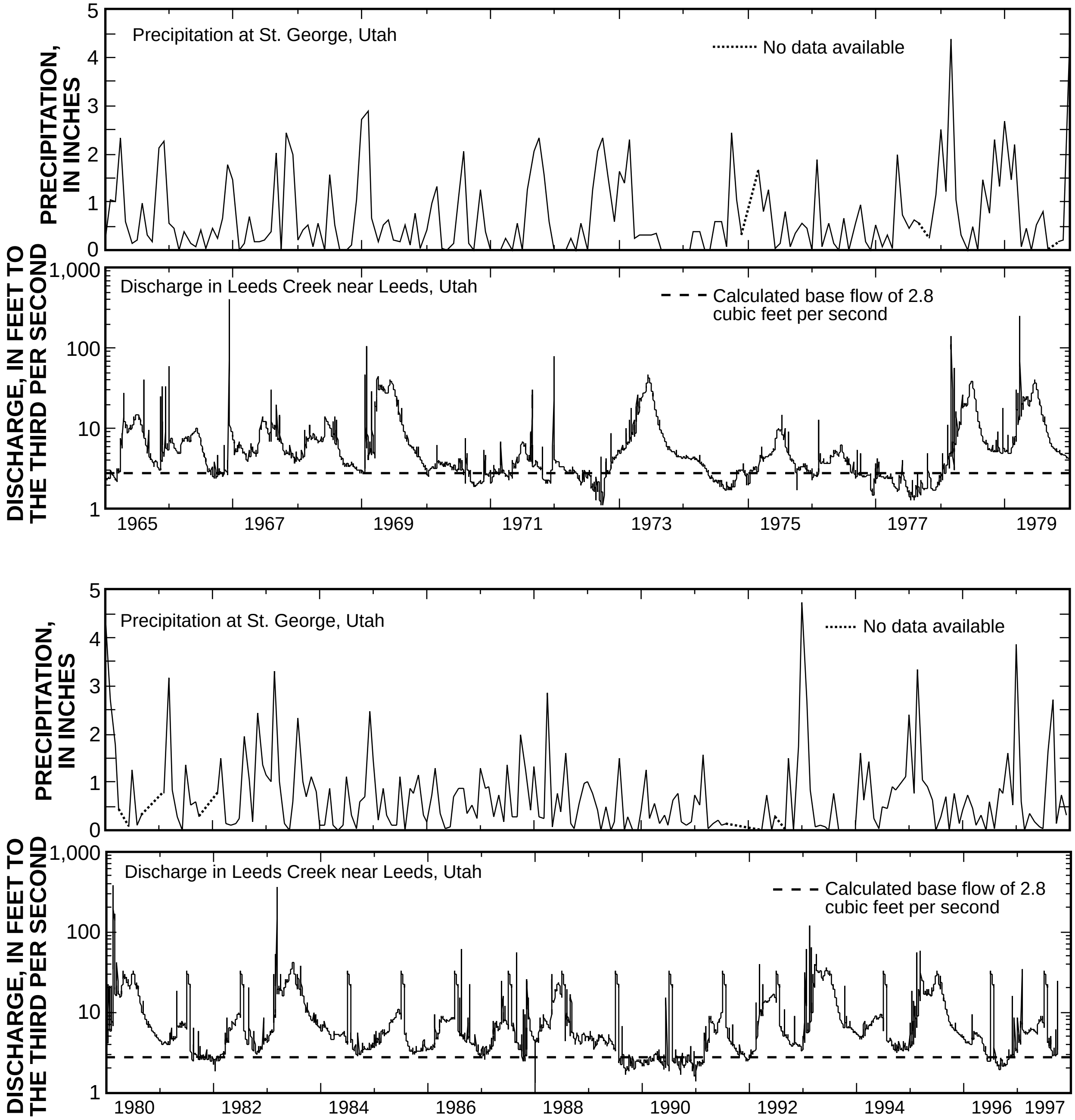

Figure 28. Discharge of Leeds Creek and precipitation at St. George, Utah, from 1965 through 1997.

This value is within the range of 900 to 2,800 acre-ft/yr estimated from base-flow seepage measurements for the same perennial streams. The limitation of this method is the assumption that infiltration occurs at a constant rate, independent of factors such as streambed geometry, total discharge, or evapotranspiration losses during warmer months. It is unlikely that the 0.3 acre-ft/d/mi infiltration rate measured at City Creek would apply for different channel conditions (slope, width, thickness of unconsolidated stream deposits) and different times of year. Also, the City Creek experiment simulated base-flow conditions by adding a constant but small flow to the channel. During an actual flash flood or snowmelt-runoff event, the discharge and corresponding rate of infiltration would be larger. The amount of infiltration from ephemeral streams estimated using method 2 may represent the lower values in the range of possible recharge from ephemeral streams. However, because infiltration values estimated for perennial streams with the experimental infiltration rate are within the measured range of seepage, they may provide a reasonable estimate for recharge from ephemeral streams.

In summary, both methods for estimating recharge from ephemeral streams closely approximate or bracket the measured base-flow seepage to the Navajo aquifer from perennial streams. The amount of ephemeral stream recharge based on the method 1 ranges from 1,000 to 3,000 acre-ft/yr. The amount of ephemeral stream recharge based on method 2 is 200 acre-ft/yr. Therefore, the overall estimated range of ephemeral stream recharge is from 200 to 3,000 acre-ft/yr.

Overlying and Underlying Formations

The Carmel Formation overlies the Navajo Sandstone and consists of limestone, sandstone, shale, and gypsum deposits. Little vertical ground-water movement is likely through these low-permeability sedimentary rocks. However, because of higher precipitation toward the Pine Valley Mountains where the Navajo and Kayenta aquifers are covered by the Carmel Formation, the possible infiltration of small amounts of water downward into the Navajo aquifer cannot be entirely ruled out. Hurlow (1998) suggested that the large thickness and low permeability of overlying formations likely minimizes recharge to the Navajo aquifer. In a study by Cordy, Seiler, and Stolp (1993) of springs in Zion National Park, higher dissolved-solids concentrations were measured in water samples from the Navajo aquifer near where it is covered by the gypsum beds of the Carmel Formation. Lower dissolved-solids concentrations were associated with areas where the Navajo Sandstone outcrop is exposed at land surface. Also, surface water sampled from Bitter Creek (Wilkowske and others, 1998, tables 4, 6) contained high dissolved-solids concentrations in the reach that crosses the Carmel Formation. If large amounts of recharge from the overlying Carmel Formation were moving into the Navajo aquifer, this likely would cause an increase in dissolved-solids concentration in the parts of the aquifer near this contact, compared with parts of the aquifer, such as south of Hurricane, where there is no overlying Carmel Formation. However, the areas of higher dissolved-solids concentration within the study area do not correlate with parts of the Navajo aquifer near the Carmel Formation contact. Therefore, it is assumed that downward infiltration of water through the Carmel Formation is not a substantial source of recharge to the Navajo aquifer.

The Kayenta Formation is underlain by progressively older sedimentary formations including the Moenave Formation, the Chinle Formation, and the Moenkopi Formation (table 2; fig. 5). Although these finer grained formations generally are considered less permeable than the Navajo Sandstone and Kayenta Formation, ground water may migrate upward along fractures into the Navajo and Kayenta aquifers. Two flowing wells in the study area, well (C-41-17)29aba-1 drilled into the Shinarump Conglomerate of the Chinle Formation, and well (C-41-13)16bcd-1 drilled into the Springdale Sandstone of the Moenave Formation (Wilkowske and others, 1998, table 1), each have water levels similar to those of nearby wells in the Navajo aquifer, which indicates that an upward gradient towards the Navajo and Kayenta aquifers may exist at some locations.

Solute mass balances were developed to quantify recharge to the Navajo and Kayenta aquifers in the areas north of St. George and west of Hurricane (fig. 9). The mass balances were developed on the basis of 4 assumptions: (1) That the principal source of dissolved solids in the aquifer originate from underlying formations, (2) that other sources of dissolved solids were not considered, (3) that there is no change in storage in the aquifer, and (4) that the dissolved-solids concentration does not change with time. The water- and solute-mass balance equations used are:

$$Q_1 + Q_2 = Q_3 \quad (4)$$

and

$$Q_1C_1 + Q_2C_2 = Q_3C_3 \quad (5)$$

where

Q_1 is recharge (ft^3/s) from surface infiltration;

Q_2 is recharge (ft^3/s) from underlying formations;

Q_3 is discharge (ft^3/s) from the high dissolved-solids concentration parts of the Navajo and Kayenta aquifers;

C_1 is average dissolved-solids concentration (mg/L) of ground-water samples from the low dissolved-solids concentration parts of the Navajo and Kayenta aquifers, which represents water recharged predominantly from surface infiltration that interacts with the aquifer solids;

C_2 is average dissolved-solids concentration (mg/L) of ground-water samples from the underlying Triassic and Permian Formations; and

C_3 is average dissolved-solids concentration (mg/L) of water that discharges from the high dissolved-solids concentration parts of the Navajo and Kayenta aquifers.

Equation 4 is the water-budget mass balance. Equation 5 is a solute mass balance that describes the mixing of two water sources with different dissolved-solids concentrations while retaining conservation of mass. The amount of discharge, Q_3, from the aquifer in the area north of St. George is estimated to be about 8.2 ft^3/s, equal to the average annual well pumpage and spring discharge for that area. The amount of discharge, Q_3, west of Hurricane is estimated to be about 4.5 ft^3/s, equal to the average annual well pumpage and seepage to the Virgin River. Assuming steady-state conditions, equation 4 indicates that these amounts of discharge are equal to the two sources of recharge, Q_1 (infiltration of surface water) and Q_2 (recharge from underlying formations). Equation 5 indicates that the amount of each source of recharge, multiplied by the average dissolved-solids concentration of that recharge, will equal the amount of discharge, multiplied by the average dissolved-solids concentration of the discharge. The two unknown parameters, Q_1 and Q_2, can be determined by simultaneous solution of equations 4 and 5. C_1, C_2, and C_3 are estimated to be about 300 mg/L, 2,500 mg/L, and 1,020 mg/L, respectively for both areas of dissolved-solids concentration.

The results indicate that in the area of high dissolved-solids concentration north of St. George, as much as 2.7 ft^3/s enters the Navajo aquifer from underlying formations and 5.5 ft^3/s or more enters the aquifer from infiltration of surface water. West of Hurricane, as much as1.5 ft^3/s enters the aquifer from underlying formations and 3.0 ft^3/s or more enters the aquifer from infiltration of surface water. These estimated amounts of recharge from underlying formations should be considered a maximum because it is assumed that the only source of water with a dissolved-solids concentration greater than 300 mg/L is the underlying formations. It is possible that another source is seepage from streams traversing the Navajo Sandstone outcrop after dissolution of higher-solubility minerals as the streams cross overlying layers such as the Carmel Formation.

On the basis of these calculations, the estimated recharge to the Navajo and Kayenta aquifers from underlying formations in the higher dissolved-solids concentration parts of the aquifer north of St. George and west of Hurricane, is as much as 4.2 ft^3/s.

Irrigation

Irrigation of alfalfa occurs along a small part of the Navajo Sandstone outcrop west and southwest of Hurricane, Utah. Most of the alfalfa (2,100 acres) is flood irrigated in townships/ranges C-41-13 and C-42-13 (fig. 22). These alfalfa fields are located along thick alluvial deposits associated with Gould Wash and Frog Hollow Wash (pl. 1). A drillers' log for well (C-42-13)15bad-1 at the mouth of Frog Hollow Wash shows alternating layers of clay, sand, and gravel to a depth of 400 ft. A much smaller area of about 200 acres directly on the Navajo Sandstone outcrop in section 12 of Township 42 S., Range 14 W. (fig. 22) is sprinkler irrigated. A study of recharge beneath sprinkler- and flood-irrigated fields near Milford, Utah, indicated that there was no recharge beneath the sprinkler-irrigated field, whereas about 30 in. of recharge occurred beneath the flood-irrigated field (Susong, 1995). On the basis of this study, no recharge is assumed to occur beneath the sprinkler-irrigated fields on the Navajo Sandstone outcrop within the study area. The amount of recharge from unconsumed irrigation water on the flood-irrigated fields cannot be accurately measured because no information is available regarding the amount of water applied annually to the fields. The consumptive use of water by alfalfa at Milford (altitude 5,000 ft) is about 34 in/yr, whereas the consumptive use near Hurricane (altitude 2,900 ft) is about 43 in/yr, because of higher mean annual temperatures and lower relative humidity (Hill, 1994). Therefore, it is assumed that the amount of recharge from unconsumed irrigation water near Hurricane is less than the infiltration measured at Milford. Assuming an infiltration rate of 0 to 20 in/yr beneath the flood-irrigated fields near Hurricane, estimated recharge is from 0 to 5 ft^3/s (4,400 acre-ft/yr). But without information concerning the amount of water applied yearly to the flood-irrigated fields, this estimated range is poorly constrained.

Gunlock Reservoir

Recharge to the Navajo aquifer most likely is occurring beneath the southern half of the Gunlock Reservoir, which overlies about 125 acres (5,450,000 ft^2) of the Navajo Sandstone outcrop (fig. 24). It is assumed that about 20 ft of silt has been deposited at the base of the reservoir since it was constructed. The water level in the reservoir generally is about 3,580 ft. It is assumed that a mound has developed beneath the reservoir so that the water in the reservoir is in hydraulic connection with the water table of the Navajo aquifer.

Assuming that the water table in the Navajo aquifer at the base of the reservoir is at about 3,470 ft and the vertical conductivity is about 0.01 ft/d for silts (Freeze and Cherry, 1979), Darcy's law calculations indicate that up to 3 ft^3/s (2,200 acre-ft/yr) may seep into the Navajo aquifer. However, this estimate is based on many unknown parameters such as the actual thickness and hydraulic conductivity of the silt layer at the base of the reservoir.

Ground-Water Movement

Ground water moves from areas of high hydraulic head to areas of low hydraulic head. In an unconfined aquifer, this is generally from higher elevation areas to lower elevation areas. Based on water levels measured in wells during February and March of 1996 and 1997 (Wilkowske and others, 1998) ground water in the Navajo and Kayenta aquifers generally moves from the base of Pine Valley Mountains southward towards the Santa Clara and Virgin Rivers (pl. 2, fig. 26). The exception to this is the part of the aquifers southwest of Hurricane, where ground water moves northwestward toward the Virgin River. The potentiometric surface within the Navajo Sandstone and Kayenta Formation outcrop (unconfined) part of the aquifers is similar to the topography; ground water moves perpendicular to the potentiometric contours, generally from higher-altitude areas of the outcrop toward lower-altitude areas. There are three areas of the outcrop with very sparse water-level data: the eastern part of the outcrop west of Hurricane Fault, the area between Leeds Creek and Grapevine Pass Wash, and the area northwest of the St. George municipal well field in the Gunlock part of the Navajo aquifer (pl. 1). In these areas, the direction of ground-water movement can only be inferred from distant water-level measurement sites. Also, many of the water levels on plate 1 and in figure 26 are from production wells, many of which are pumped for most of the year. Although water levels were measured near the end of the winter when pumping is minimal, water levels may still be recovering from earlier pumping and may not be representative of the regional potentiometric surface.

Vertical movement of ground water between the Navajo and Kayenta aquifers likely occurs, as indicated by small vertical gradients inferred from nearby pairs of wells finished in the two formations. Small downward vertical gradients likely exist near the Navajo Sandstone/Kayenta Formation contact southwest of Hurricane, northwest of Toquerville, and north of Washington. The vertical gradients estimated in these areas generally are less than 0.10 and were determined by dividing the difference in water-level altitude (generally less than 50 ft) by the vertical distance between the perforated intervals of the well pairs (generally about 500 ft). There are no nested pairs of wells finished in the Navajo and Kayenta aquifers for direct measurement of vertical gradient. Smaller vertical gradients are consistent with the assumption that water moves easily between the two aquifers.

In the high dissolved-solids concentration parts of the aquifers, upward vertical gradients likely exist between the Kayenta Formation and underlying formations as a result of hydrothermal circulation. The evidence of this, as discussed above, includes a strong correlation between elevated dissolved-solids concentration and elevated ground-water temperature. Also, flowing well (C-41-17)29aba-1 in the Shinarump Member of the Chinle Formation had a reported water level similar to that in the nearby Navajo aquifer, indicating the possible upward vertical gradient.

Discharge

The principal sources of discharge from the Navajo and Kayenta aquifers are well discharge, spring discharge, and seepage to streams. Additional possibilities for discharge include seepage to underlying formations and evapotranspiration. Measured and estimated sources of discharge from the Navajo and Kayenta aquifers are shown in figure 29. The total amount of discharge is estimated to range from 23 to 39 ft^3/s (17,000 to 28,000 acre-ft/yr) and from 5 to 8 ft^3/s (3,800 to 5,900 acre-ft/yr), respectively, for the main and Gunlock parts of the Navajo aquifer. These ranges of discharge values are much narrower than the range of recharge reported above. This is because the larger discharge components, including well discharge, spring discharge, and stream seepage, can be more accurately measured than many of the recharge components, especially infiltration of precipitation.

Wells

Well pumpage is the largest source of discharge from both the main and Gunlock parts of the Navajo and Kayenta aquifers. Except for an irrigation-well area southwest of Hurricane, most well discharge is for potable use. Historical well-pumpage records are incomplete for some municipalities and for many private potable and irrigation wells. The best source of data is St. George, where accurate discharge measure-

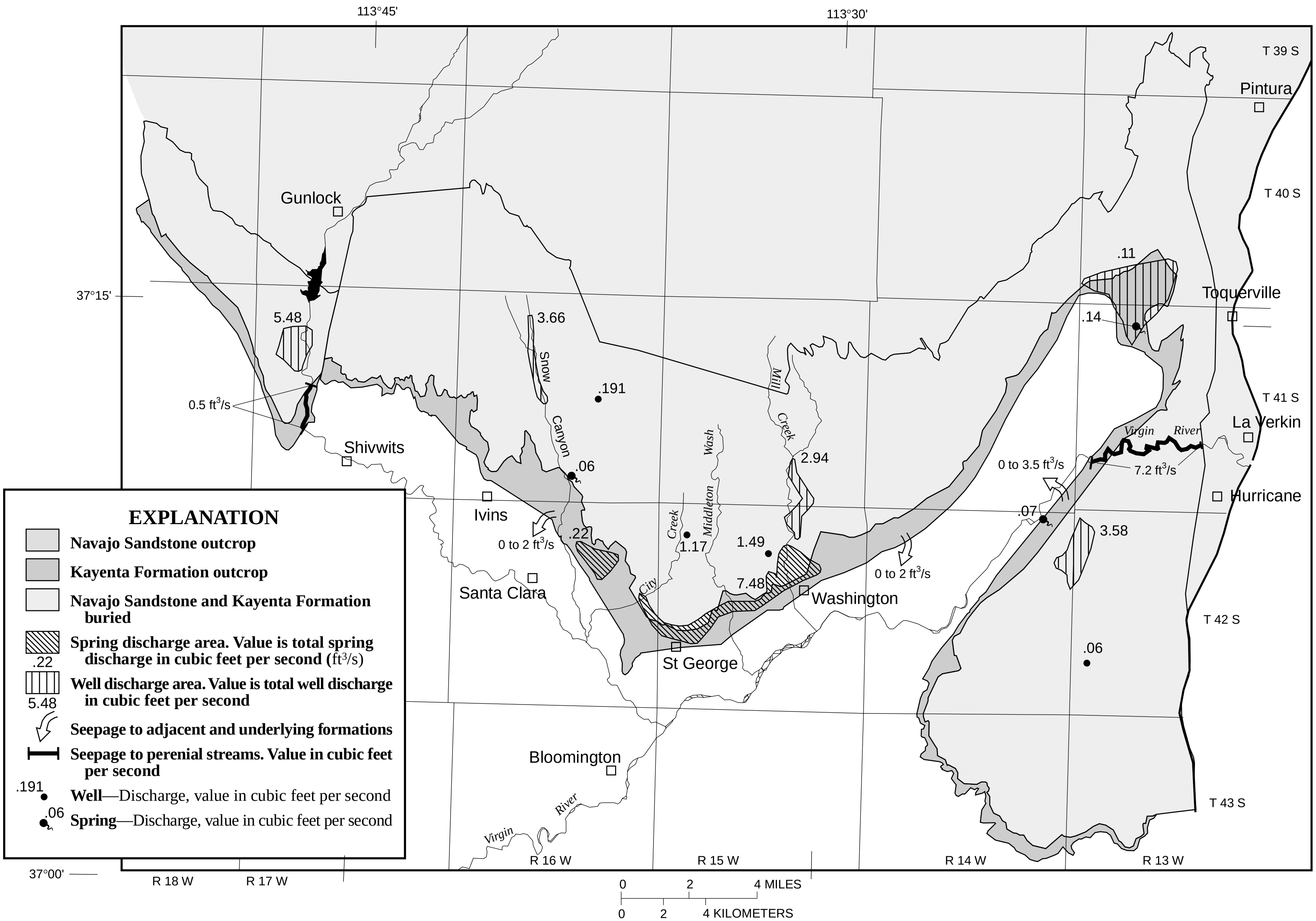

Figure 29. Measured and estimated sources of discharge from the Navajo and Kayenta aquifers in the central Virgin River basin study area, Utah.

ments have been kept since the late 1980s (Phillip Solomon, City of St. George, oral commun., 1995). Well discharge from St. George municipal wells in the main and Gunlock parts of the Navajo and Kayenta aquifers from 1987 through 1996 is shown in figure 30. Average well discharge from 1987 through 1996 for the Gunlock part of the aquifers was 5.5 ft^3/s (4,200 acre-ft/yr), and varied from 4.7 to 7.6 ft^3/s (3,400 and 5,500 acre-ft/yr). Average St. George well discharge in the main part of the aquifers for this period was 4.4 ft^3/s (3,200 acre-ft/yr), and varied from 3.6 to 5.4 ft^3/s (2,600 to 3,900 acre-ft/yr) (Jerry Olds, Utah Division of Water Rights, written commun., 1998). Except for 1995 data, total pumpage for the main part is not known because irrigation-well discharge and some potable-well discharge from subdivisions and municipalities is not regularly reported to the Utah Division of Water Rights.

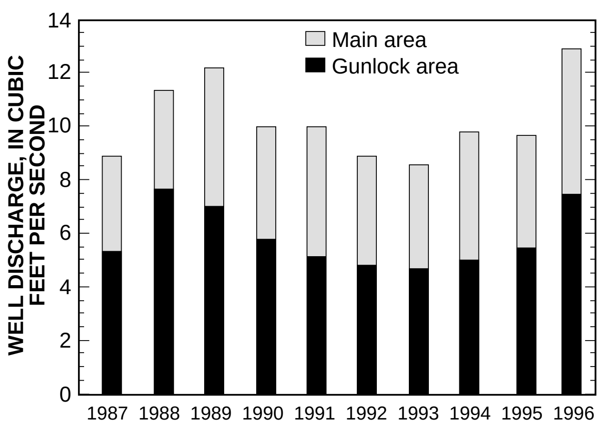

Figure 30. Well discharge from St. George municipal wells in the main and Gunlock parts of the Navajo and Kayenta aquifers from 1987 through 1996.

The total 1995 well discharge for the main part of the Navajo and Kayenta aquifers is estimated to be 12.7 ft^3/s (9,200 acre-ft/yr) based predominantly on St. George City Water and Power Department (Phillip Solomon, written commun., 1996) and Utah Division of Water Rights (Jerry Olds, written commun., 1996) reported usage. About 70 percent, or 9.1 ft^3/s (6,600 acre-ft/yr), of well discharge is for potable use by municipalities and subdivisions. The 1995 well pumpage also includes about 3.6 ft^3/s (2,600 acre-ft/yr) from private potable and irrigation wells southwest of Hurricane. This amount was determined with discharge measurements from each well taken with either a sonic velocity device or bucket and stopwatch. The discharge measurements are then combined with power-meter readings to determine average annual pumpage for each well (calculated by multiplying the ratio of discharge rate to power consumption by the total power consumption for the year).

Because 1995 discharge from the St. George wells is similar to the 1987-96 average St. George pumpage, it is assumed that the 1995 total discharge of 12.7 ft^3/s (9,200 acre-ft/yr) from the main part of the Navajo and Kayenta aquifers is close to the 10-year average. Assuming that the 20 percent variation in St. George well discharge between 1987 and 1996 is similar to variations in well discharge for the entire main part of the aquifers, well discharge is estimated to range from about 10 to 15 ft^3/s (7,200 to 10,900 acre-ft/yr).

The trend in St. George well discharge from 1987 through 1996 (fig. 30) is generally related to the amount of precipitation, which determines the availability of surface water. However, to keep up with population growth there have been numerous wells drilled since 1995, including the St. George municipal wells downstream from Gunlock Reservoir and in Mill Creek, a Washington City well in Grapevine Pass, and a WCWCD well at Anderson Junction. In addition, there have been recent acquisitions of private wells and water rights south and west of Hurricane by the cities of Hurricane and St. George, and the WCWCD. As these new and redeveloped wells become fully operational and if the population of the region continues to grow, it is likely that a general trend of increased well discharge will occur and be magnified during periods of less-than-normal precipitation.

In the main part of the Navajo and Kayenta aquifers, about 80 percent of the well discharge is estimated to be from the Navajo aquifer and 20 percent from the Kayenta aquifer. Most of the Navajo aquifer discharge occurs along Snow Canyon, City Creek, in the Mill Creek area, and southwest of Hurricane (fig. 29). Most of the Kayenta aquifer discharge occurs from wells along Snow Canyon, Mill Creek, and near Leeds that are drilled into the Navajo Sandstone but also perforated in the upper part of the Kayenta Formation. In the Gunlock part, all of the well discharge is from the Navajo aquifer.

Because drawdown associated with pumping rapidly decreases with distance away from production wells in an unconfined to partly confined aquifer there likely is not much drawdown in areas at large distances (generally more than a mile) from a production well in the Navajo and Kayenta aquifers. However, in areas such as Millcreek, Snow Canyon, and downstream from Gunlock Reservoir, where many large production wells are located in close proximity, the drawdown effects are additive and farther reaching. Although only a few feet of drawdown likely occurs regionally along the perimeter of these wells fields, such change could be large enough to (1) reverse the direction of flow between ground water and surface water, as seen by the change in the Santa Clara River near the St. George municipal well field from gaining reach to losing reach during the past few decades; or (2) capture naturally occurring discharge that, prior to ground-water development, emanated at springs and gaining stream reaches. It is possible that additional ground-water development in areas upgradient of naturally occurring discharge (springs or gaining streams) may eventually capture some of this water. Anderson Junction is one such location where additional pumping may divert some of the ground water from seeping into the Virgin River.

Springs

Springs are the second-largest source of discharge from the main part of the Navajo and Kayenta aquifers. There is no known spring discharge from the Gunlock part of the aquifers. Total spring discharge for the main part is estimated to be about 7.7 ft^3/s plus or minus 10 percent, or 6.9 to 8.5 ft^3/s (5,000 to 6,200 acre-ft/yr) (fig. 29), based on two spring inventories done in December 1995 and April 1996 (Wilkowske and others, 1998, table 3). All of the larger springs discharge from the lower Navajo Sandstone and upper Kayenta Formation between Snow Canyon and Mill Creek (fig. 29). It is estimated that there is little seasonal variation in spring discharge from the Navajo and Kayenta aquifers. Six springs measured during both the 1995 and 1996 surveys had less than 10-percent variation in discharge, within the error of the measurement methods. Similarly, a total spring discharge of 2,655 gal/min was measured at seven springs (Snow, Mill Creek, Warm, Huntington, Cox, East City, and West City Springs) during November 1974 (Cordova, 1978, table 2). Total discharge from the same springs measured during 1995 and 1996 was 2,635 gal/min, a variation of less than 1 percent from the earlier study. Finally, discharge at Sheep Springs showed little variation (1.9 to 2.1 gal/min) during 12 monthly measurements from November 1990 through October 1991 (Jensen and others, 1997, table 14).

The location of springs within the Navajo and Kayenta aquifers may be related to permeable fractures. Jensen and others (1997) noted that Beecham, Gray, and Sheep Springs are located along a fracture identifiable on areal photographs. These springs trend on a line that extends northwestward along the axis of the inferred Snow Canyon Fault. Similarly, Warm Spring, north of Washington, may be associated with hydrothermal circulation along the nearby Washington Fault (Budding and Sommer, 1986).

Streams

A seepage study done during November 1994 along the Virgin River documented about 7.2 ft^3/s (5,200 acre-ft/yr) streamflow gain across the Navajo Sandstone outcrop west of La Verkin (Herbert, 1995). Assuming a temporal variation in discharge of 10 percent, the estimated discharge from the Navajo is 6.5 to 7.9 ft^3/s (4,700 to 5,700 acre-ft/yr). The Virgin River cuts deeply into the Navajo Sandstone, and it is assumed that the source of this gain in streamflow is discharge from the Navajo aquifer (fig. 29). Because the study was done in late fall, it is assumed that evapotranspiration losses were minimal.

A larger gain of 13.8 ft^3/s (10,000 acre-ft/yr) in the Virgin River was determined during a seepage study done in 1974 by Cordova (1978). The decrease in aquifer discharge since the 1970s may be caused by increased well discharge from the Navajo aquifer in the residential area northeast of Leeds and in the agricultural area southwest of Hurricane.

As part of this study, two seepage studies were done along the Santa Clara River (Wilkowske and others, 1998, table 6). On the basis of these discharge measurements, an estimated average streamflow gain of about 0.5 ft^3/s (400 acre-ft/yr) was calculated in the Santa Clara River as it crossed the Kayenta Formation outcrop.

Adjacent and Underlying Formations

The November 1994 seepage study along the Virgin River showed additional streamflow gains of about 3.5 ft^3/s along the Kayenta Formation outcrop and downstream Quaternary sediments (Qs) in contact with underlying formations (fig. 29, pl. 1) (Herbert, 1995). The part of this discharge coming from the Kayenta Formation could not be determined because no measurement was taken at the contact between the Kayenta Formation and the Quaternary sediments. However, it is assumed that most of this water originates in the Navajo Sandstone and Kayenta Formation, is discharged into the Quaternary and Tertiary basalt (Qtb), infiltrates into the Quaternary sediments, and finally seeps into the

Virgin River. On the basis of discharge measurements along the Santa Clara River (Herbert and others, 1997) and observations by local residents (R. Levitt, oral commun., 1998), an estimated streamflow gain of from 0 to 2 ft^3/s (1,400 acre-ft/yr) between Ivins and St. George originates from the Navajo and Kayenta aquifers (fig. 29). This water may seep into the Santa Clara River from Quaternary sediments and basalt in contact with the Navajo Sandstone and Kayenta Formation near Snow Canyon, or through fractures in the underlying Moenave and Chinle Formations (pl. 1). Likewise, there are numerous seeps and small springs along the Moenave and Chinle Formation outcrop between St. George and Leeds (pl. 1). From 0 to 2 ft^3/s (1,400 acre-ft/yr) of discharge is estimated to migrate from the Navajo Sandstone and Kayenta Formation through fractures into these underlying formations before seeping to the surface (fig. 29). A total estimated discharge of from 0 to 7.5 ft^3/s (0 to 5,400 acre-ft/yr) moves from the main part of the Navajo and Kayenta aquifers into adjacent unconsolidated or consolidated formations, eventually discharging as seepage to springs or streams.

Evapotranspiration

Transpiration occurs from phreatophytes growing along perennial stream reaches that cross the Navajo Sandstone and Kayenta Formation outcrops. Except for the Virgin River, phreatophyte growth along the perennial reaches is generally sparse because of the steep canyon topography along the streams. Except for the Virgin River, all the perennial streams lose water to the aquifer. Thus, only the net amount of water recharging the aquifer (after removal by transpiration) is estimated and was based on seepage studies conducted during the autumn when transpiration is minimal. While transpiration losses are larger during the spring and summer, flow is also generally higher. Therefore, it is likely that the increased transpiration losses during the warmer months is offset by higher stream flow.

For the Virgin River, seepage studies were also conducted in the late autumn (Herbert, 1995) when transpiration losses were minimal and total discharge from the aquifer to the river could be accurately estimated Therefore, transpiration did not need to be considered for the ground-water budget.

Ground-water budget

The estimated ground-water budgets for the main and Gunlock parts of the Navajo and Kayenta aquifers are shown in tables 15 and 16.

NUMERICAL SIMULATION OF GROUND-WATER FLOW

Computer models were developed to simulate various concepts of how ground water moves through the upper Ash Creek aquifer system and the Navajo and Kayenta aquifers. Computer models are able to test the viability of conceptual models and to determine the sensitivity of simulation results to uncertainty in data and interpretations based on those data. A model should reasonably represent most aspects of ground-water recharge, movement, and discharge, and results of simulations should reasonably match measured ground-water budget components and measured water levels in wells. The differences between simulation results and the measured aquifer flows and water levels should be “acceptable” for the intended use of the model.

Another equally important purpose for developing a ground-water flow model is to guide the collection of additional data. Data-collection priority can be set for parameters that are not well known by determining the sensitivity of simulation results to different types of data. Data to which the simulation results are sensitive should be given a high priority in future data-collection efforts. Only then can a model be successfully improved and updated in the future.

The purpose for developing the three models described in this report was to (1) evaluate the practicality of the conceptual models described, (2) evaluate alternative conceptual models, and (3) determine the sensitivity of simulation results to uncertainty in properties and flows to help prioritize future data collection.

The ground-water flow models were constructed with the latest version of the MODFLOW finite-difference simulation code (McDonald and Harbaugh, 1988). The updated version (Harbaugh and McDonald, 1996), known as MODFLOW-96, adds double precision to budget calculations and new input and output capability but retains the same programming structure for solving the ground-water flow equation.

The mathematical boundaries used to represent hydrologic boundaries of the aquifers include no-flow boundaries, specified-flux boundaries, and head-dependent flux boundaries. A no-flow boundary does not allow water to move through it. A specified-flux bound-