HYDROGEOLOGY OF THE ASH CREEK DRAINAGE BASIN, WASHINGTON AND IRON COUNTIES, UTAH

A REPORT FOR WASHINGTON COUNTY WATER CONSERVANCY DISTRICT, 533 EAST WATERWORKS DRIVE, ST. GEORGE, UTAH 84770

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REPORT WCWCD-04

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Photograph looking southeast from the Harmony Mountains at the northern Ash Creek basin and eastern New Harmony basin.
The Hurricane Cliffs and Kolob Terrace are on the left horizon and the Pine Valley Mountains are on the central and right horizon.

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ABSTRACT

Ash Creek drainage basin, about 15 miles wide and 30 miles long, extends along Interstate Highway I-15 down a steep topographic slope from southern Iron County to just east of St. George, in southern Washington County. The basin is south of Cedar basin, which contains Cedar City, and between the Pine Valley Mountains on the west and the Colorado Plateau on the east. The towns of Kanarraville and New Harmony are in the north, Pintura is south of the center of the basin axis, and Anderson Junction and Toquerville are in the south. The basin axis, near I-15, parallels the great north-northeast-trending Hurricane fault on the east, which has uplifted the Colorado Plateau. But the Pine Valley Mountains is a large basin range uplifted by many faults as well, so the basin is a complex graben between two highlands. The southern end of the basin is the Virgin River, into which Ash Creek flows. The present topography has been created mostly in the last 10 million years by basin-range tectonism. Basin-fill sediments and basalt flows were deposited in the basin and are in turn underlain by two thick aquifers, the Miocene Pine Valley laccolith/Pine Valley Latite and the Jurassic Navajo Sandstone. Ash Creek itself is perennial only in its upper part, and it has three perennial tributaries on the west.

The water resources of Ash Creek basin would seem to be limited, based on what remains of the surface water and what is estimated for the groundwater. Ash Creek Reservoir, built in 1960 on a heavily fractured Pleistocene-age basalt flow about 1000 ft west of the Hurricane fault, has received 10.6 cfs (cubic feet per second) average annual stream flow from the perennial upper part of Ash Creek, but this water seeps into the fractures so the reservoir is dry most of the year and Ash Creek is mostly ephemeral below the dam. The three perennial streams, Leap Creek, South Ash Creek, and Wet Sandy, are downstream from the reservoir and together contribute 7.2 cfs average annual flow, after diversions but before all flow seeps into the ground before they join Ash Creek. Two springs on the banks of Ash Creek near Toquerville, named Toquerville Springs and Ash Creek Spring, have an average annual total maximum discharge of 25-30 cfs, nearly all of it now diverted. Therefore, Ash Creek below the springs and continuing to the Virgin River is largely intermittent and unpredictable. Local diversions in the reach below Ash Creek Spring result in low if any flow and many pools of standing water. Regarding groundwater resources, several previous regional groundwater studies provided modest estimates of groundwater volumes. However, with one exception, these studies spoke to the central or entire Virgin

River basin in Utah so have little value to our understanding of resources in the smaller sub-basin of Ash Creek. The exception provides an estimate of about 20 cfs of groundwater (recharge and discharge, steady state) from a digital simulation, but only for the part of the Ash Creek basin upstream of Ash Creek Reservoir. Ash Creek basin groundwater, plus return flows from agriculture north and south of the Virgin River, contribute about 10.7 cfs to the Virgin River.

On more careful analysis of the Ash Creek basin, we find that previous estimates of groundwater volumes are far too conservative. It is likely that significant groundwater crosses into the basin from Cedar basin, most of it from precipitation on the Hurricane Cliffs that moved by surface flow to the Hurricane fault zone at the base of the Cliffs, then by fracture flow southward within the fault zone. Groundwater also must flow in thick Paleozoic aquifers beneath the surface of the Kolob Terrace, then west across the Hurricane fault into the Miocene and Jurassic aquifers that are juxtaposed by the fault. Yet the greatest recharge must come from the lofty Pine Valley Mountains, where precipitation enters a highly faulted, excellent (brittle) Miocene aquifer that forms most of the range, then eastward down gradient to the basin. Finally, the graben of the Ash Creek basin is a complex hash of many faults that cut and brecciate underlying thick aquifers made up of basin-fill sediments, the Miocene aquifer, and the Jurassic aquifer, creating large volumes of permeable rock that are filled by groundwater in storage. The overall result is that the geography of Ash Creek basin is unusually suited for accumulating abundant groundwater resources that likely are several times any previous estimates. Yet our confidence in large amounts of groundwater in the basin comes with a caveat: unlike surface-water resources, groundwater resources cannot be quantified with any accuracy, and any significant level of additional development requires more monitoring of water levels than is done now.

Water-chemistry data indicate that the highest quality groundwater is on the western side of the Ash Creek basin, where recharge is the greatest; and that wells on faults here not only have the highest yields but also higher quality water because fracture flow is rapid. Tritium values indicate that virtually all streams, springs, and shallow wells in the basin have modern water. We echo the findings of two previous studies that recommended drilling and testing "new" (unappropriated) groundwater from Permian to Mississippian aquifers, most of them in the footwall of the Hurricane fault. Discovery of a probable new fault zone cutting Navajo Sandstone on the eastern flank of the Pine Valley Mountains suggests that drill sites on SITLA (Utah School and Institutional Trust Lands Administration) and other lands west of Harrisburg Junction would be productive if water rights could be secured. We agree with the interpretation of a previous worker that water discharged from the Toquerville and Ash Creek Springs is derived largely from the three perennial tributaries, yet deeper fresh groundwater that has been noticed in oil wells that tested the Hurricane fault is probably derived from surface water and groundwater that entered the fault at and upstream from Ash Creek Reservoir. Our study suggests, as did that of a previous worker, that moderately deep fresh groundwater moves south by fracture flow in the Hurricane fault, perhaps all the way to the Grand Canyon. Furthermore, other groundwater in the southern end of the basin is carried by faults and the Navajo Sandstone southward beneath the Virgin River to supply the Sand Hollow well field and other wells, and then continues still farther south along faults and in aquifers that underlie the Navajo Sandstone.

INTRODUCTION

Ash Creek drainage basin extends from north of New Harmony, in Washington County, and Kanarraville, in Iron County, south-southwest to the confluence of Ash Creek with the Virgin River (Figure 1). The basin consists of all streams that are tributary to Ash Creek; as such, the basin does not

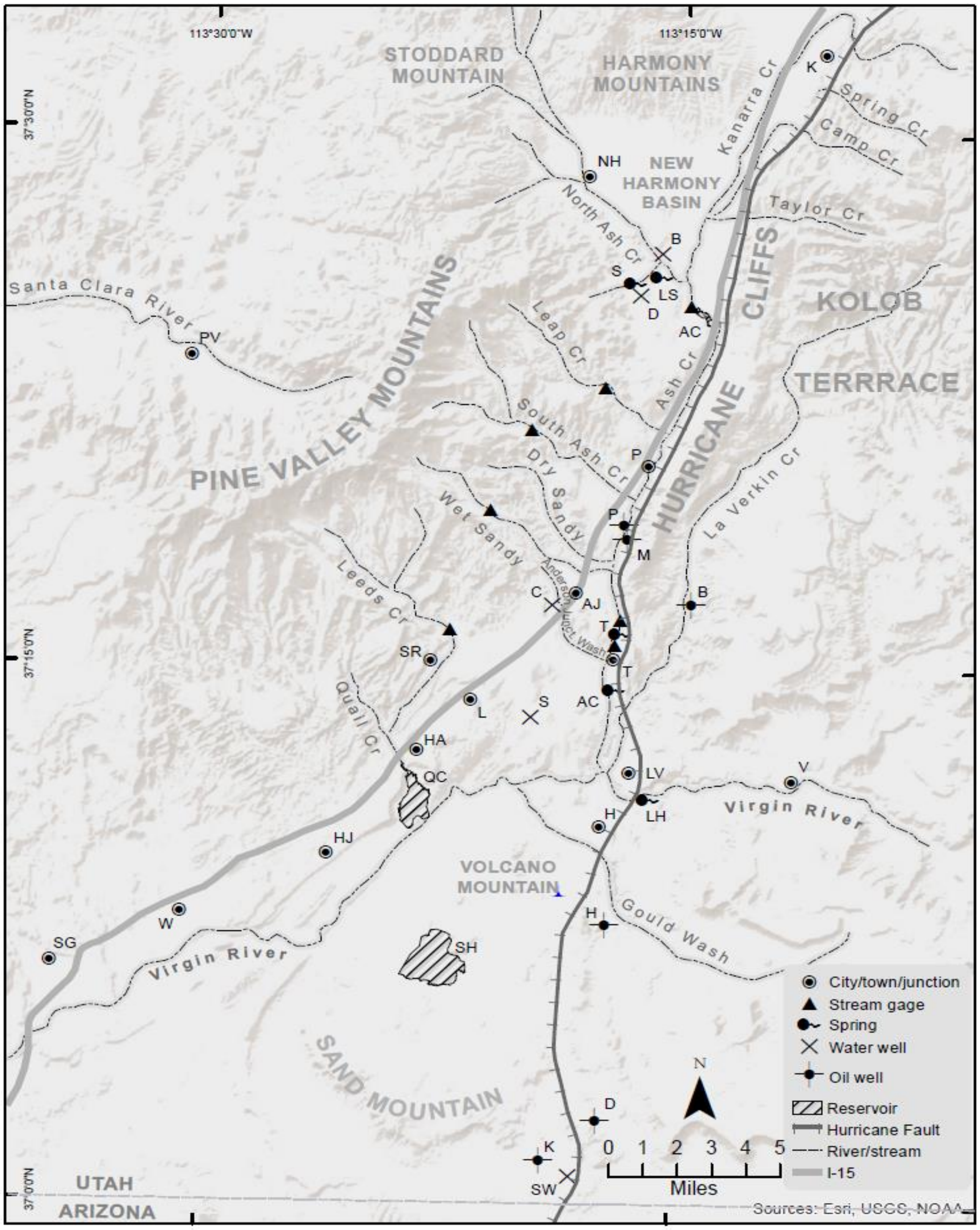

Figure 1. Index map of the Ash Creek drainage basin and adjacent areas, Washington County, Utah, showing geographic features, towns, rivers/streams, springs, water wells, stream gages, and oil wells mentioned in the text. Symbols for cities, towns, and junctions: AJ, Anderson Junction; AV, Apple Valley; H, Hurricane; HA, Harrisburg; HJ, Harrisburg Junction; K, Kanarraville; L, Leeds; LV, LaVerkin; NH, New Harmony; P, Pintura; PV, Pine Valley; SG, St. George; SR, Silver Reef; T, Toquerville; V, Virgin; and W, Washington. Symbols for reservoirs: AC, Ash Creek Reservoir; QC, Quail Creek Reservoir; and SH, Sand Hollow Reservoir. Symbols for springs: AC, Ash Creek Spring; LS, lower Sawyer Spring; S, Sawyer Spring; LH, LaVerkin Hot Springs; and T, Toquerville Springs. Symbols for water wells: B, well B; C, Cottam wells; D, well D; S, Sullivan wells; and SW, a suggested well site on the Hurricane fault near the Arizona border. Symbols for oil wells: B, Buttes 30-B3X; D, Devereaux 1 Federal; H, Hiko Bell 1 Federal; K, Knowles-Skyline; M, McCullough; and P, Pease 1-13 Federal.

include Leeds Creek, Quail Creek, or other streams to the south that drain the Pine Valley Mountains because they join the Virgin River downstream of its confluence with Ash Creek. Aside from not discussing much of these southern streams, some aspects of the surface water, groundwater, and springs in the Leeds and other areas outside this defined basin will be covered where they relate to the basin itself.

As defined, the basin is about 30 miles long, parallel to the course of Ash Creek. When the headwaters of the tributaries are included, the basin is about 15 miles wide. The basin drains the Pine Valley Mountains on the west, the Harmony Mountains on the north, and the Hurricane Cliffs of the Kolob Terrace of the Colorado Plateau on the east. The lip of the drainage divide with the Cedar basin, about 1.5 mi north of Kanarraville (Figure 2), is at an elevation of about 5500 ft, whereas the confluence of Ash Creek with the Virgin River is at about 3000 ft.

Figure 2. Photograph looking east, from the Harmony Mountains toward the Hurricane Cliffs and Kolob Terrace. The town of Kanarraville is at the base of the Hurricane Cliffs just left of center. Cedar basin extends northward from the left edge of the photo.

The axis of the basin trends north-northeast, controlled by basin-range faults so that it is a graben (downthrown structure) between the upfaulted Colorado Plateau and the upfaulted Harmony Mountains and Pine Valley Mountains. The dominant fault is the north-northeast-trending Hurricane fault zone on the east, at the western base of the Hurricane Cliffs. Interstate Highway I-15 runs parallel to the Hurricane fault zone from Cedar City, in Cedar basin on the north, past the small towns of Kanarraville, then Pintura, and Toquerville in the Ash Creek basin. Silver Reef, Leeds, Harrisburg, and Harrisburg Junction are just west of the basin, LaVerkin and Hurricane are just east of the basin, and Washington and

St. George are southwest of the basin. The graben is generally narrow (Figure 2), only 1.5 miles (east-west) at the latitude of Kanarraville, between the Harmony Mountains and Hurricane Cliffs, but widens to at least 5 miles at the latitude of Hurricane. An exception to this shape is a westward bulge formed by the New Harmony basin, south of the Harmony Mountains and almost 10 miles wide, with the small town of New Harmony at its western edge, against the Pine Valley Mountains (Figures 3 and 4). The New Harmony basin is also a graben, containing downthrown, poorly consolidated Miocene-to-Pleistocene-age

Figure 3. Photograph looking south from the Harmony Mountains across the New Harmony basin toward the town of New Harmony (center of the photo) and North Ash Creek. The Pine Valley Mountains are on the far center and right with the high point behind the pine tree. The Hurricane Cliffs and Kolob Terrace make up the far left. Ash Creek Reservoir is near the left edge of the photo.

basin-fill sedimentary rocks and overlying Pleistocene to Holocene surficial sediments (Hurlow, 1998). The southern end of this basin closes to about 2 miles wide near the Ash Creek Reservoir (Figure 5), then continues for about 5 mi to Pintura (Figure 6). Most parts of the main graben are underlain by basin-fill and surficial sediments and by basalt flows.

The topographic basin receives recharge from the surrounding mountains and plateaus. Of these recharge areas, the Pine Valley Mountains contributes by far the most water because this 25-mile-long range reaches elevations of 10,000 feet (Figures 3 and 7) and has precipitation values of as much as 30 inches/year (Heilweil and others, 2000, Figure 2). The southern Markagunt Plateau, east of Cedar basin and north of the Kolob Terrace, has similar elevations and precipitation values as the Pine Valley

Mountains. The relatively small Harmony Mountains, however, rises to only about 8200 ft (Figure 4) and contributes much less recharge to the local groundwater system.

Figure 4. Photograph looking north from the Pine Valley Mountains at the New Harmony basin, New Harmony (in the trees, above the head of the dog on the left), North Ash Creek, and the Harmony Mountains. The bald mountain on the left horizon is Stoddard Mountain underlain by a Miocene laccolith.

Although some reaches of Ash Creek and its tributaries are perennial or were formerly, the amount of surface water seems to be modest. Nor are there any large areas of riparian vegetation. However, we consider that the volume of groundwater beneath the Ash Creek watershed to be larger than previously estimated. The aquifers beneath the basin are large and the basin is cut by many faults, which form aquifers in their own right and provide rapid southward movement of groundwater by fracture flow. Yields on many wells, especially those sited on faults, seem to be large, and water levels are high. Furthermore, it is likely that significant groundwater moves southward from eastern and southern Cedar Valley along fault zones, notably the Hurricane fault zone. Also, more groundwater recharge may be coming from the Kolob Terrace (Figures 2 and 3) than previously considered because the Hurricane fault zone that bounds it may not be the no-flow zone to westward flow as thought in some groundwater models. Finally, few people have recognized that the Pine Valley Mountains is a horst block, its eastern

Figure 5. Photograph looking east, from low hills of Pleistocene basalt flows just east of the Pine Valley Mountains, at Ash Creek Reservoir, with the Hurricane Cliffs beyond. The reservoir is contained by the basalt flows. The spillway is at the left edge of the far end of the reservoir, beyond which is Highway I-15. Picture taken on October 7, 2016, showing the reservoir dry. The mesa on the upper horizon is Black Ridge, made up of the same basalt flow uplifted by the Hurricane fault about 1600 ft relative to the basalt at the reservoir.

side raised by many faults that have provided fracture permeability to the brittle intrusive and volcanic rocks that make up most of the range, and therefore the range supplies greater recharge than previously recognized.

This study was contracted by Washington County Water Conservancy District (WCWCD) so as to learn more about the extent of the water resources and how they might be developed for future public culinary water supplies. WCWCD currently owns two small well fields in the Ash Creek basin, namely Cottam wells and Sullivan wells (Figure 1). South of the basin, WCWCD owns the large well field at Sand Hollow Reservoir (Figure 1). We analyzed the hydrogeologic setting of the Ash Creek basin and its likely total groundwater resources, proposed "new" (unappropriated) groundwater that could be developed, suggested new drill sites, interpreted sources of springs and groundwater, and suggested where the basin groundwater is going. We also looked outside the margins of the basin because in any study of a basin's groundwater, an important part is determining the hydraulic continuity or discontinuity with adjacent basins. In fact, such observations showed significant continuity with basins to the north, east, and south and, partly for this reason, we found that additional water resources in the basin could be developed in the future. Mark Layton of WCWCD did the line-drawing figures in this report.

GEOLOGY

Regional Setting

The Ash Creek drainage basin lies in a transition zone between the Great Basin part of the Basin and Range physiographic province to the west and the Colorado Plateau physiographic province to the east (e.g., Biek and others, 2009). The Great Basin and the transition zone are characterized by alternating,


Figure 6. Photograph looking south, from about a mile south of Ash Creek Reservoir, down the axis of the Ash Creek basin toward Pintura. The Hurricane Cliffs are on the left and the Pine Valley Mountains on the right. Ash Creek itself is just left of I-15.

mostly north-trending basins (valleys) and ranges that formed largely by relative vertical movement along mostly north-trending, high-angle, basin-range normal faults (e.g., Mackin, 1960; Rowley and Dixon, 2001). The Colorado Plateau contains far fewer and smaller faults than those in the Great Basin. The western boundary of the transition zone is the western margin of the Pine Valley Mountains, where the Gunlock fault zone and connecting faults to the north of it have uplifted the western side of the range. The eastern boundary of the transition zone is the down-to-the-west Hurricane fault zone, which defines the eastern side of the Ash Creek basin (Figure 8). The Ash Creek basin is bounded on the west by unnamed fault zones at the eastern base of the Harmony Mountains (Figure 2) and Pine Valley Mountains (Figures 3 and 4). Normal faults such as these have steep dips (average of 60º) in the downthrown direction (i.e., toward the west in the example of the Hurricane fault). The rocks above the dipping fault plane are called the hanging wall (e.g., the western side in the example of the Hurricane fault) whereas those below the fault plane are the footwall (e.g., the eastern side in the example of the Hurricane fault).

Two major episodes of structural deformation affected the transition zone, the Sevier orogeny and basin-range extension. Between those two events was an episode of extremely voluminous calc-alkaline magmatism. The Sevier orogeny and calc-alkaline igneous rocks formed during relatively rapid subduction, as Pacific tectonic plates to the west were overridden by west-moving North America (Hamilton, 1995; Schellart and others, 2010). The Sevier deformation affected Paleozoic- to early Cenozoic-age rocks. This compressional event resulted in Late Cretaceous to Paleocene east-directed folds, reverse faults, and thrust faults. These structures, which include the Kanarra and Virgin anticlines, are exposed along the eastern and central part of the Ash Creek basin (Biek and others, 2009).

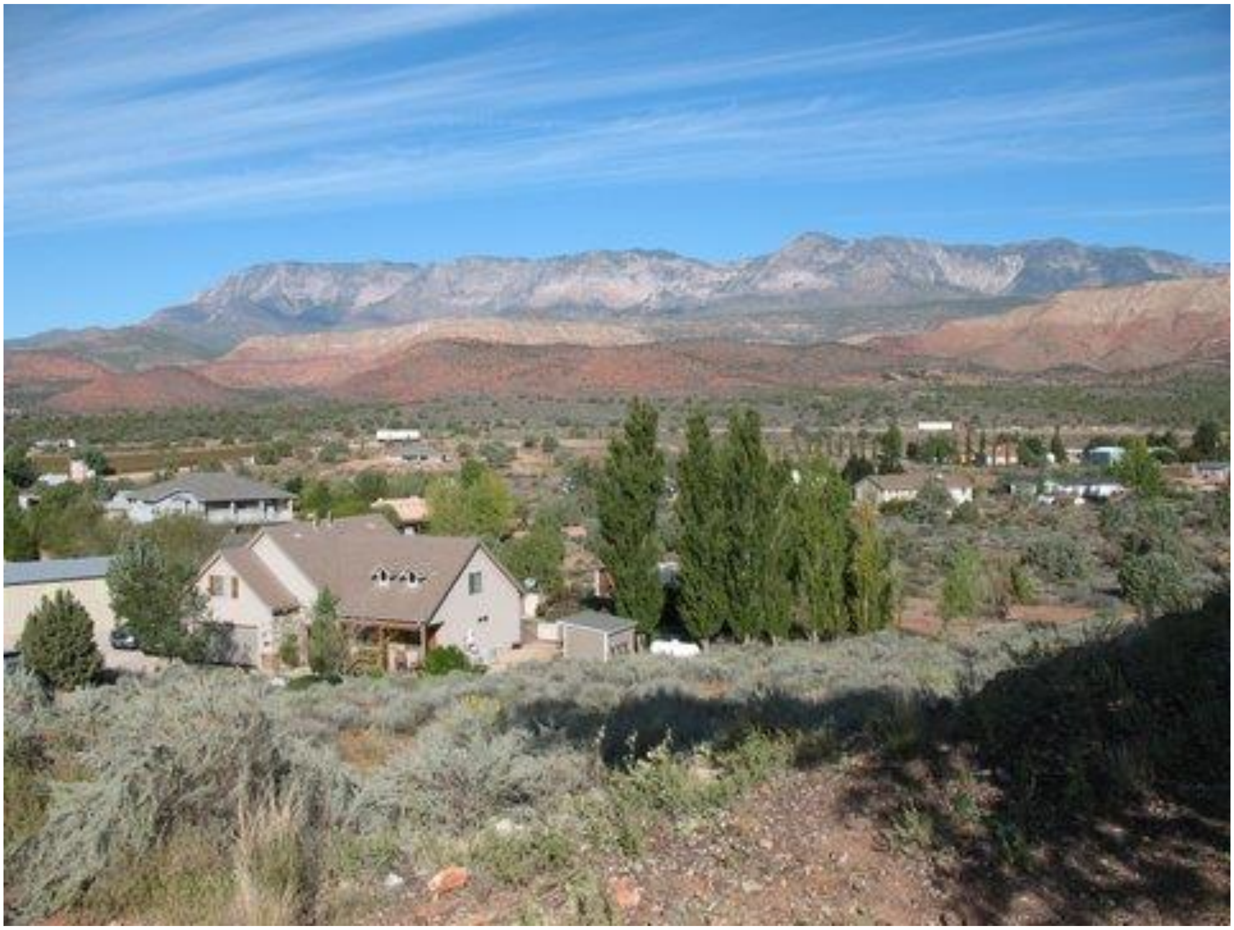

Figure 7. Photograph looking west from a housing development north of Leeds at the southern Pine Valley Mountains. Trucks are on I-15 in the middle ground through the tree tops. The west-dipping dark red beds beyond I-15 are of Triassic and Jurassic confining units, whereas the pink and tan rocks beyond (overlying) them consist of the Jurassic Navajo Sandstone. A single house in a subdivision north of Silver Reef is seen at the left edge of the photo beyond I-15.

Subduction beneath the Great Basin and Colorado Plateau slowed drastically (Schellart and others, 2010) or ended at about 20 Ma, when basin-range deformation began. The basin-range episode resulted from east-west extension (pulling apart), forming the normal faults. Most basin-range deformation, however, took place during the last 10 million years, forming the present topography. The faults define the basins (grabens and half grabens) and ranges (horsts and tilt blocks). As the basins dropped relative to the ranges, they were filled with basin-fill sediments derived from erosion of the ranges; such basin-fill sedimentary deposits are in places many thousands of feet thick.

The calc-alkaline igneous rocks were deposited during the older (Oligocene to Miocene, about 30 to 20 Ma) of two regional Tertiary magmatic episodes. The calc-alkaline volcanic rocks range in composition from andesite to low-silica rhyolite, as elsewhere in the Western U.S. (Lipman and others, 1972). These volcanic rocks consist of extremely voluminous ash-flow tuffs, lava flows, and volcanic mudflow breccia that erupted from large east-trending igneous belts made up of intrusions and eruptive centers (Rowley, 1998; Rowley and Dixon, 2001). Most of the Pine Valley Mountains consist of these rocks.

The younger of the two magmatic episodes (Miocene to present) produced volcanic rocks of bimodal composition, namely basalt and high-silica rhyolite. Bimodal volcanism was prevalent throughout the Great Basin and transition zone but of much smaller volume than the calc-alkaline volcanism (Christiansen and Lipman, 1972). Bimodal volcanism coincided with basin-range deformation. Several basalt lava flows occur in the study area.

Geology and Aquifers of the Ash Creek Drainage

The Ash Creek drainage basin is an internally faulted, downthrown basin (graben) between the Hurricane fault zone and many medium-sized but discontinuous basin-range faults that define the eastern sides of the Harmony Mountains and Pine Valley Mountains. The oldest rocks in the study area are flat-lying and locally folded Permian, Triassic, and Jurassic sedimentary rocks that predate the Jurassic Navajo Sandstone and are either exposed along the western edge of the Hurricane Cliffs or downthrown by the Hurricane fault beneath Ash Creek basin. The folds formed during the Sevier deformation. These sedimentary rocks (Figure 9), exposed mostly east of Highway I-15, are shown on the geologic map (Figure 8) as unit JP (for Jurassic to Permian). Unit JP consists, from oldest to youngest, of the Permian Pakoon Formation, Queantoweap Sandstone, Toroweap Formation, and Kaibab Formation; the Triassic Moenkopi and Chinle Formations; and the Jurassic Moenave Formation and Kayenta Formation (Hurlow, 1998; Rowley and others, 2006; Biek and others, 2009; Inkenbrandt and others, 2013). Of these, the Permian rocks are of carbonate and sandstone lithologies that can be considered aquifers but they are on the Hurricane fault scarp and have not been developed. The Moenkopi and Chinle units are of shale and siltstone lithologies that are confining units (aquitards), except for the thin (5-150 ft) Shinarump Conglomerate Member in the lower part of the Chinle. The Moenave and Kayenta formations are mostly siltstone confining units except for local sandstone beds in them, notably the thin (90-150 ft) Springdale Sandstone Member at the base of the Kayenta that was developed by WCWCD at Sullivan wells (Rowley, 2002b).

The overlying Jn unit east and west of I-15 is the Jurassic Navajo Sandstone, by far the most important aquifer in Washington County (Figures 8 and 9). This unit is a friable, porous sandstone generally about 2000 ft thick that underlies much of the Ash Creek basin and, south of the basin, the Sand Hollow/Sand Mountain area south of the Virgin River (Figure 1). The sandstone has great primary permeability because its sand grains are well rounded as it was being deposited in an eolian (sand dune) environment. The spectacular red and white dune cross beds of the Navajo are one of the tourist attractions in Zion National Park, in and east of the Hurricane Cliffs. When cut by faults, secondary (fracture) permeability will increase the yield in water wells by about an order of magnitude, as suggested by 1:12,000-scale mapping at Sand Hollow Reservoir (Rowley and others, 2004). Therefore, as discussed in detail below, WCWCD developed the faulted Navajo Sandstone as an important source of culinary water at this large reservoir and artificial-recharge well field (Heilweil and others, 2002; Rowley and others, 2004). Within the drainage basin, the Navajo also was developed at Cottam wells, which is west of I-15 (Rowley and Dixon, 2010).

West of I-15 and in the northern part of the Ash Creek drainage, the Harmony Mountains have been uplifted along north-trending faults along the eastern base of the range. The range consists of calc-alkaline volcanic rocks (unit Tv, for Tertiary volcanics), primarily ash-flow tuffs derived from calderas to the west, including beyond the Utah-Nevada border (Rowley and others, 1995). South of the Harmony Mountains is the New Harmony basin, with New Harmony at its western side. Stoddard Mountain, just west of the Harmony Mountains, and the Pine Valley Mountains south of Stoddard Mountain, consist of 22-20-Ma, calc-alkaline laccolithic intrusions that were intruded into the ash-flow tuffs and underlying sedimentary rocks (Hacker and others, 2002). These intrusions form the southern

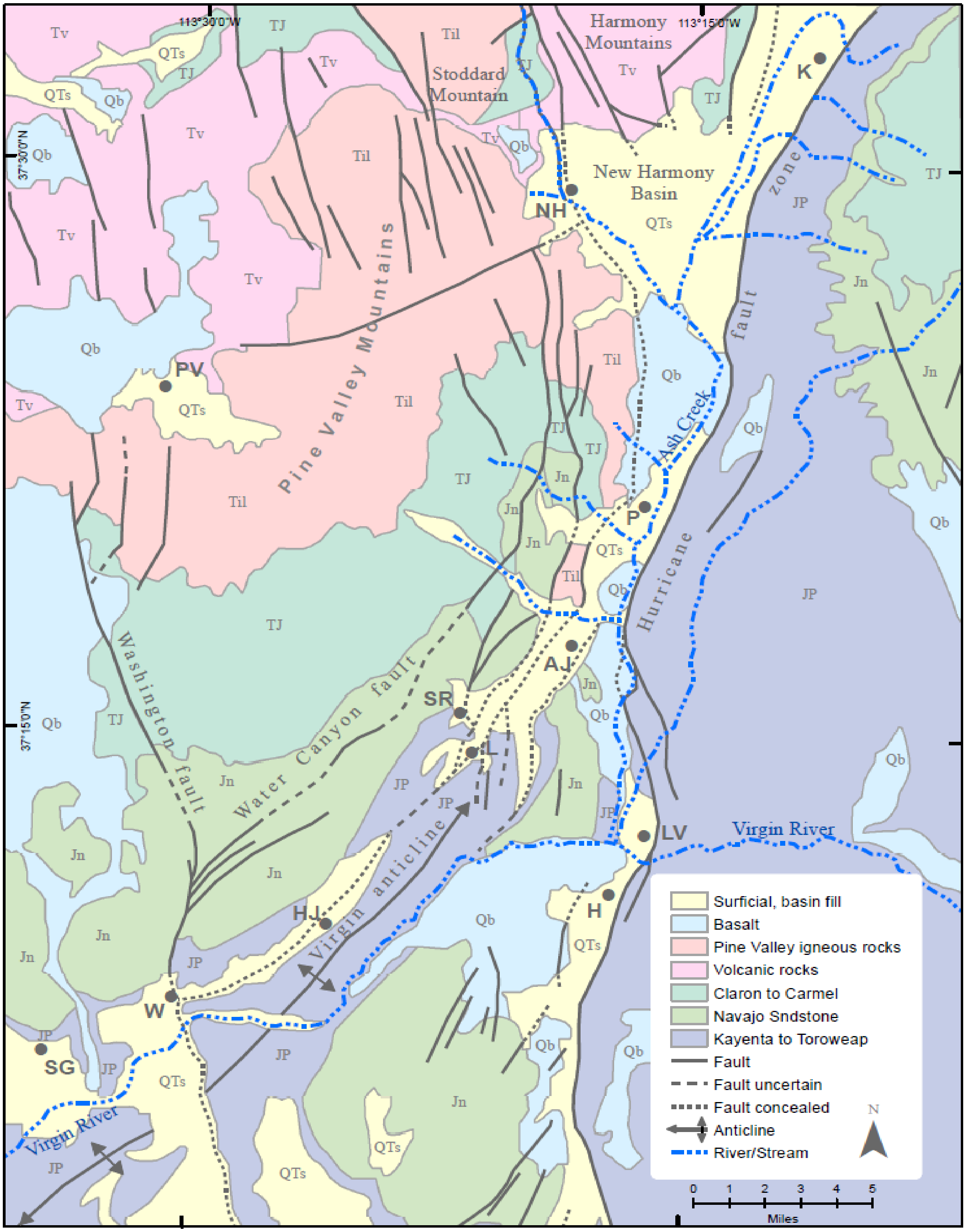

Figure 8. Geologic map of the Ash Creek drainage basin in Washington County, Utah. Symbols for cities, towns, and junctions are as given in Figure 1. Area and scale (about 1:250,000) are virtually the same as those of Figure 1.

(non-mineralized) end of a string of laccoliths of the same age that formed the huge iron deposits of the Iron Springs mining district (Rowley and others, 2006). Most of the Pine Valley Mountains consist of these calc-alkaline concordant intrusive rocks (the Pine Valley laccolith) and lithologically similar lava flows (Pine Valley Latite), shown on Figures 8 and 9 by symbol Til (for Tertiary Pine Valley intrusive rocks and Latite). Of the basin-range faults that uplift the eastern Pine Valley Mountains, one passes south from the eastern side of Stoddard Mountain, through New Harmony, then south past Leeds. Several springs arise along it, including Sawyer Spring (discussed below). Both the laccoliths and volcanics are brittle rocks that form good aquifers where shattered by faults.

The Pine Valley laccolith (Hacker and others, 2002) was concordantly and rapidly intruded along bedding planes in the Claron Formation, a mostly red Paleocene sedimentary unit famous at Bryce Canyon National Park and Cedar Breaks National Monument. Therefore the Claron underlies the laccolith along the southern part of the Pine Valley Mountains (Figure 7). The Claron is in turn underlain by tan shale, siltstone, and sandstone of the Cretaceous Iron Springs Formation. The Iron Springs is underlain by the Jurassic Carmel Formation, which overlies the Navajo Sandstone. The Claron, Iron Springs, and Carmel are mostly confining units shown as unit TJ (for Tertiary to Jurassic rocks).

The other two important aquifers in the Ash Creek drainage basin are made up of relatively young rocks that are exposed in the grabens. Most important of these are upper Tertiary and Quaternary basin-fill sediments and overlying surficial sediments (QTs, for Quaternary and Tertiary sediments), derived from erosion of the uplifted blocks and deposited largely by streams, that filled the New Harmony basin and the main downthrown area on either side of I-15 (Figures 8 and 9). In the New Harmony basin, they reach a thickness of at least 1500 feet, in the valley at Kanarraville they are at least 1000 feet thick, and elsewhere along I-15 they are at least 500 feet thick in most places (Hurlow, 1998). Thin Pleistocene basalt lava flows (Qb, for Quaternary basalt) are interbedded with the basin-fill deposits and exposed along the axis of the Ash Creek graben. The basalt flow (Figure 5) exposed for 6 mi from Ash Creek Reservoir to Pintura is the downthrown equivalent of the flow capping the Hurricane scarp ("Black Ridge") to the east (Biek and others, 2009).

Inkenbrandt and others (2013) noted several other aquifers that are of lesser importance in the Ash Creek basin but might be drilled to tap "new" (unappropriated) groundwater. The oldest of these, the R-aquifer made up mostly of the Mississippian Redwall Limestone (Figure 9), may be as close to the surface as 500 ft in depth if one drills into the hanging wall of the Hurricane fault in an effort to hit the Redwall in the footwall. This aquifer includes several underlying Devonian carbonate units. Another aquifer is the C-aquifer, which is named for the Permian Coconino Sandstone but includes the Toroweap Limestone above it and the Kaibab Limestone above that. In Utah, the name Queantoweap Sandstone is generally used rather than the Coconino. The rock interval of the Kaibab to the lower part of the Toroweap is exposed in Timpoweap Canyon, which was cut by the Virgin River just east of the Hurricane fault between LaVerkin and Hurricane; the Queantoweap is just below the surface in the canyon. Other aquifers are thin ones of Triassic and Jurassic age, namely the Shinarump Conglomerate Member of the Chinle Formation and the Springdale Sandstone Member of the Kayenta Formation, respectively.

Fracture Flow

An important concept in understanding the movement of groundwater in the Basin and Range is known as “fracture flow” or “fracture-dominated flow.” In fracture flow, groundwater moves through rock fractures, most of which in the study area are associated with high-angle faults. The study of fracture flow has increased in the last several decades because of its importance in such topics as isolation of radioactive waste in underground repositories, groundwater transport of radionuclides, cleanup of toxic waste, exploration of petroleum and geothermal reservoirs, and of course in investigations of groundwater resources. The geology of fracture flow was eloquently defined by Caine and others (1996), who proposed that a central "core zone" of a fault contains fine-grained gouge that inhibits flow across it, whereas on either side of the core zone, a "damage zone" consists of fractures parallel to the core zone that provide increased secondary permeability. In other words, groundwater moves along faults and joints oriented parallel to the groundwater gradient (forming "conduits" to flow) but is deflected or obstructed, creating a hydraulic discontinuity, by faults oriented perpendicular to this gradient (forming "barriers" to flow).

Most of the early work on fracture flow resulted from studies funded by the U.S. Department of Energy (DOE) and completed primarily by the U.S. Geological Survey (USGS) and DOE contractors on the Nevada Test Site. The object was to trace movement of groundwater contaminated by hundreds of underground nuclear tests. These studies, which began in the 1950s, resulted in practical—as opposed to academic—research findings; therefore, many reports of these studies are largely unknown to the scientific community because they were published as limited-distribution USGS Open-File Reports and DOE reports. Many summary reports resulted, one of which is that of Rowley and Dixon (2004). In addition to discovering fracture flow, this research led to the recognition of the large Death Valley regional groundwater flow system, where recharge that originated in the high mountains of central Nevada creates hydraulic-head potential that causes groundwater to flow south to terminal discharge areas and springs such as at Ash Meadows, Oasis Valley, and Death Valley. Detailed (1:24,000-scale) and regional (1:100,000 and 1:250,000 scale) geologic mapping gave a first approximation of faults (conduits) and therefore interpreted flow directions.

The concept of fracture flow has been tested many times in Utah and Nevada by siting production water wells and well fields. A technique developed in the Mesquite basin of Nevada was to geologically map the area at 1:24,000 scale and 1:100,000 scale (Dixon and Katzer, 2002) so as to describe the geometry of north-trending, high-angle, basin-range normal faults that potentially provide conduits for southward groundwater flow from the primary recharge area in the broad Clover Mountains north of the basin. Then Dixon and Katzer (2002) and Johnson and others (2002) sited high-yield production water wells by drilling the downthrown side of the faults so as to intersect the fault below the water table. The same technique was used to evaluate groundwater resources in the Gunlock well field (Rowley, 2002c; Rowley and Dixon, 2004) northwest of St. George, Utah. The well field is supplied by southward fracture flow along the north-trending Gunlock fault zone that passes just east of the well field. The well field, St. George's largest at one time, is in the subhorizontal Jurassic Navajo Sandstone. Good well production is largely due to the secondary permeability provided by the Gunlock fault. High production in several nearby well fields in the Navajo Sandstone, including the Snow Canyon well field just northwest of St. George and the Washington well field northeast of St. George, is similarly due to large adjacent basin-range faults (Rowley, 2007). The Sand Hollow Reservoir well field is another example.

Pumping data to confirm the role of fractures as both conduits and barriers was done as a multiple-well aquifer test study for DOE by Bhark and others (2006) of pervasively faulted and fractured parts of the lower Paleozoic carbonate aquifer beneath the northeastern part of Yucca Flat, Nevada Test Site. Here, a deep water table (about 1500 feet below the surface) made the area favorable for past underground nuclear tests. Groundwater flow is southward along a series of mapped basin-range faults of the same trend. Three wells were drilled in 1993 to 2002 in a north-south line, along the same fault, to depths of about 2100 to 3200 feet. Tracers were placed in two northern holes, located about 600 to 800 feet north of the southern hole, which was pumped at 500 gallons per minute (gpm). The tracers were first detected after 69 hours of pumping, indicating conduit flow. In addition, the pumping affected the water level of a

Ma	System	Series & Stage	Map Unit	Symbol	Thickness (Ft)	Rock Type
	Quaternary		surficial sediments	QTs	200	sand, gravel, clay
	Quaternary		basalt	Tb	200	lava flows
1.8	Tertiary	Pliocene	basin-fill sedimentary rocks	QTs	1500+	sandstone, shale, conglomerate
5.3	Tertiary	Miocene	Pine Valley laccolith Pine Valley Latite	Til	1500	intrusive rocks, lava flows
23	Tertiary	Oligocene	calc-alkaline volcanic rocks	Tv	1000	mostly ash-flow tuffs
34	Tertiary	Eocene	Claron Formation	TJ	1500	shale, mudstone, sandstone, limestone
56	Tertiary	Paleocene	Claron Formation	TJ		
66	Cretaceous	Upper	Iron Springs Formation	TJ	3000	shale, sandstone, siltstone
145	Jurassic	Middle	Carmel Formation	TJ	1000	limestone, gypsum, mudstone, sandstone
	Jurassic	Middle	Temple Cap Formation	TJ	50	sandstone
	Jurassic	Lower	Navajo Sandstone	Jn	2000	sandstone
	Jurassic	Lower	Kayenta Formation – main body	PJ	450+	siltstone, sandstone, mudstone
	Jurassic	Lower	Kayenta Formation – Springdale Sandstone Member	PJ	100	sandstone
	Jurassic	Lower	Moenave Formation	PJ	250	siltstone
201	Triassic	Upper	Chinle Formation – Petrified Forest Member	PJ	400	claystone, mudstone
	Triassic	Upper	Chinle Formation – Shinarump Conglomerate Member	PJ	120	sandstone
	Triassic	Lower	Moenkopi Formation	PJ	1400	mudstone, gypsum, siltstone, limestone
252	Permian	Lower	Kaibab Formation	PJ; C aquifer	400	limestone, gypsum
	Permian	Lower	Toroweap Formation	PJ; C aquifer	450	limestone, gypsum
	Permian	Lower	Queantoweap Sandstone	C aquifer	1700	sandstone
	Permian	Lower	Pakoon Formation	C aquifer	250+	dolomite
299	Pennsylvanian		Callville Limestone		300	limestone
323	Mississippian		Redwall Limestone	R aquifer	1200	limestone
359	Devonian		Devonian and Cambrian rocks, undivided	R aquifer	5000	limestone, dolomite, shale, sandstone
	Cambrian		Devonian and Cambrian rocks, undivided	R aquifer		

Figure 9. Stratigraphic units in the Ash Creek drainage basin in Washington County, Utah.

well 6 miles to the north, along the same fault, yet no effect was noted in water levels in wells to the west-northwest and northeast, each across at least two other basin-range faults (barrier flow). Bhark and others (2006, p. 1-1) concluded that "groundwater flow in this aquifer is primarily in the fractures, and the hydraulic properties are primarily related to fracture frequency and fracture characteristics."

A better example of conduit and barrier flow is at Sawyer Spring (Figure 1), in Sawyer Canyon about 3 mi south-southeast of New Harmony (Rowley and others, 2012). Here a well field supplies irrigation center pivots for alfalfa as well as culinary water. All wells are along faults and in the Tertiary aquifer of the Pine Valley laccolith/Pine Valley Latite, which is downthrown along the east-dipping, down-to-the-east, range-front basin-range fault zone that separates the eastern side of the Pine Valley Mountains from the western side of the New Harmony basin. Groundwater recharge is from the Pine Valley Mountains as precipitation that directly supplies the Tertiary aquifer rocks. Sawyer Spring rises along a small north-striking basin-range normal fault. A second spring, lower Sawyer Spring that is about 0.3 miles east-northeast of Sawyer Spring, rises along another north-striking, basin-range normal fault zone just to the east. Both faults dip west and have displacement that is down to the west. Therefore, they are antithetic to (dip opposite to and have displacement opposite to) the main range-front fault just west of the springs. A high-yield production water well, known as Well D, lies about 500 feet southwest of Sawyer Spring. This well, which supplies culinary water to the Mountain Springs community to the east, taps the fractured Tertiary bedrock aquifer along the range-front fault zone. Two other high-yield production wells (for irrigation), Well B and the East Ash Creek Well, and a monitoring well, Well A, all between 0.5 and 0.8 mi north of lower Sawyer Spring (Figure 1), were drilled into the same fault zone that supplies lower Sawyer Spring. Initial aquifer tests on wells B and D were discussed by Heilweil and others (2000, Appendix A, p. A-25 to A-32) and Montgomery (2000). Following later pumping tests and geologic mapping, Rowley and others (2012) summarized the conduit and barrier groundwater flow along the faults. When pumped, Well D has no effect on any springs or on the big irrigation wells, indicating barrier flow. But when pumped, Well B and the East Ash Creek Well lower the water levels of each other and lessen the discharge at lower Sawyer Spring. This provides proof of conduit flow. However, the pumping has no influence on discharge at Sawyer Spring, the water level in Well D, or wells east of Well B and lower Sawyer Spring.

Conceptually, fracture flow is more in the realm of geology than hydrology and it complicates the task of calculating water budgets. The mathematics of fracture flow are largely unknown, so construction of numerical models of fracture flow have met with only limited success. As a result, most hydrologists use numerical groundwater flow models that are based on porous-media flow as a simplifying assumption for fracture flow.

SURFACE-WATER RESOURCES FROM STREAMS

Data on surface-water resources, as given below, can be confusing and misleading. The Ash Creek drainage basin consists mostly of ephemeral streams, defined in the Glossary of Geology (published by the American Geological Institute) as streams where the water table is beneath the wash and the wash flows only in direct response to precipitation in the immediate vicinity. When these streams or parts of them contain water after storms or spring snowmelt, the tendency is for the water to seep through permeable parts of the channel to the water table. The most permeable parts are the surficial stream sediments that underlie the channel and the basin-fill sediments (also mostly deposited by streams) that the surficial sediments rest on.

Parts of large streams in the drainage basin are referred to as perennial (those that flow continually--but not necessarily always--with their upper stream surface below the water table), although some parts are intermittent (those that flow only at certain times of the year, with continuous flow of at least a month) (Glossary of Geology). In Utah, as elsewhere in the Desert Southwest, all perennial, intermittent, and ephemeral streams may contain large water volumes during large storms.

Most perennial streams in the drainage basin have been developed (partly diverted) for 100 years or more, since the pioneers. Few perennial streams described here resemble a natural stream any more, nor are such streams in our desert environment necessarily perennial for long periods, unlike those in the eastern U.S.A. Values for stream flow given below are mostly individual numbers that pertain to that minute at one small part of the stream or, if we are lucky, are based on stream gages that continuously record stream flow at one point, at least until that gage was discontinued after 5 to 15 years. So, with respect to stream flow, most of our data consists of snapshots of how that developed stream behaves. Gage data provide us with yearly averages, but the problem with such an average is that the monthly or daily variations in flows of perennial streams in the drainage basin are huge. Uncertainty is the key word here in what the numbers mean and in how much we can reliably depend on them in predicting future stream flows. Future climate change provides still greater uncertainty to predictions of volumes of surface water.

Because of the uncertainty and even the meaning of stream flow, groundwater volumes and flows are of much greater importance than surface water. That is because groundwater resources are more reliable and predictable than surface-water resources. Therefore, any Utah rancher would gladly convert his or her surface-water rights to groundwater rights. Yet groundwater is below the surface and therefore volumes are even more difficult to quantify (except when pumped) than those of surface water. Whereas the discussion of groundwater would seem to be particularly speculative, there are multiple approaches and common-sense interpretations available to arrive at predictions of the volume and sustainability of the water resource.

Ash Creek Basin North of Ash Creek Reservoir

Ash Creek itself is shown by USGS 7.5-minute topographic maps to extend from where Sawyer Canyon enters it from the west all the way south to the Virgin River (Figure 1). It is perennial from Sawyer Canyon southward to Ash Creek Reservoir, then ephemeral south to Toquerville Springs. From the springs, it was generally perennial at one time to the Virgin River, although now multiple irrigation diversions have made this lower stretch intermittent to ephemeral, and therefore resources unpredictable. North of its confluence with Sawyer Canyon, to the town of New Harmony, the stream is called North Ash Creek, also perennial (Figures 3 and 4). North of New Harmony, named tributaries - some of which are perennial - drain the western Harmony Mountains, northern Pine Valley Mountains, and Stoddard Mountain. High tritium values determined by Professor Alan L. Mayo of Brigham Young University indicate that the residence times of waters in several places along North Ash Creek are modern.

Single stream-flow measurements from New Harmony to Ash Creek Reservoir were measured on Ash Creek by Wilkowske and others (1998, Table 6) on October 10 and 11, 1995 (see also Heilweil and others, 2000, Tables 7 and 8). These data are not as instructive as stream-gage data because they give only an indication of stream flow during a single instant of time in an entire water year from one place in the entire reach of a stream. Nonetheless, these data are all we have for most streams in the basin. For the reader who wants to get a feel for surface-water resources, we list these almost-meaningless numbers below, with our apologies! From north to south, these flow measurements were (1) 0.553 cfs (cubic feet per second) on North Ash Creek just south of New Harmony; (2) 1.52 cfs on North Ash Creek below where two perennial tributaries enter from the west and above a diversion near the bridge where Harmony Heights Road crosses Ash Creek into the Harmony Heights subdivision; (3) 0.09 cfs just below that diversion (on September 17, 2016, just after the irrigation season and after a long dry stretch, significant flow passed below the bridge); (4) 1.05 cfs about 3000 feet farther south along North Ash Creek; (5)

0.444 cfs about 3500 feet farther south along the creek; (6) 0.238 cfs about 5000 feet farther south on North Ash Creek and just above where Sawyer Canyon enters; (7) 1.56 cfs in Sawyer Canyon (just above its confluence with Ash Creek), which is perennial or intermittent for its last 3000 ft due to discharge from Sawyer Spring; (8) 1.57 cfs on Ash Creek just below where Kanarra Creek enters; and (9) 1.39 cfs just above where Ash Creek enters Ash Creek Reservoir. For a crude sum of the flow from all these streams as they enter Ash Creek Reservoir, Heilweil and others (2000, p. 38) estimated that base flow, that is the flow attributable to groundwater, is about 1 to 4 cfs.

The variations in measurements given above are, except for the single diversion, a reflection of seepage, for the stream is flowing on unconsolidated stream sediments that rest in turn upon largely unconsolidated basin-fill sediments (see similar comments by Heilweil and others, 2000, p. 38-39) . Cordova and others (1972) estimated that this seepage upstream of Ash Creek Reservoir in 1970 was about 3 cfs, whereas Heilweil and others (2000, p. 38) estimated that seepage here was between 0.7 and 1.5 cfs. Most of this seepage, of course, is entering the groundwater system.

To the east, Kanarra Creek is the name for a generally perennial tributary that drains an area as far north as about 2 miles north of the town of Kanarraville, and from there the creek extends south to join Ash Creek just west of Ash Creek Reservoir (Figure 1). As with North Ash Creek and Ash Creek, Kanarra Creek also is flowing on basin-fill sediments of the New Harmony basin, so there is significant seepage of its stream water. The headwaters of Kanarra Creek drain the Hurricane Cliffs and issue to the west at an alluvial fan that overlies the Hurricane fault at the eastern edge of Kanarraville (Figure 2). Based on USGS stream-gage records collected between 1959 and 1968, just upstream of where Kanarra Creek leaves the Hurricane Cliffs at the Hurricane fault on the eastern edge of Kanarraville (gage shown on Figure 1), Cordova and others (1972, Tables 1 and 5) calculated average annual flow in Kanarra Creek at 3.31 cfs, with a base flow of 2.40 cfs. The complete stream gage records (gage #09406300, now discontinued), from 1960 to 1982 and accessed online at http://maps.waterdata.usgs.gov/mapper/, show annual flows that range between 1.98 to 11.3 cfs, with an average annual flow of 4.15 cfs during the 23 years. This is one of a number of USGS stream gages (see below for the others) whose records were kept for relatively short time periods, but the data are valuable so they are given in Table 1 as well as on the USGS website. The annual data represent the arithmetic mean (average) of each daily mean for all days in one month, then all months in the year. On October 12, 1995, Wilkowske and others (1998, Table 6) measured the flow at the fault at 3.38 cfs. These headwaters are perennial, but at the mouth of the creek - at the fault - the creek now is diverted for town culinary and irrigation water and never reaches the main stem of the creek about 1.25 m west of the fault.

The upper part of the main stem of Kanarra Creek receives most of its flow from springs that arise from several basin-range faults, some of which have low fault scarps that had Quaternary displacement. Some of the springs feed small stock ponds. The northern 1.5 miles of the most prominent (clearly seen on stereographic pairs of aerial photos, and on looking east from a car driving on I-15) of the fault scarps (about 15 ft high) is just east of I-15 and trends north-northeast. Southward, it passes beneath the freeway and continues south-southwestward for about 2 miles. This fault is downthrown on its western side, so it could be considered the western fault of the Hurricane fault zone, even though the main fault is a mile to the east. Yields on some wells drilled in that mile-wide zone are high, suggesting that other faults of the fault zone are concealed by, but underlie, alluvial fans. Kanarraville is sitting on a lot of groundwater due to the Hurricane fault zone and due to a lot of recharge from the west, north, and east.

Farther south along the Hurricane Cliffs, two other tributaries to Kanarra Creek, named Spring Creek and Camp Creek (Figure 1), are also perennial until they pass west over the main Hurricane fault into the valley, where they are diverted for irrigation or seep into fans at their mouths; their flows rarely, if ever, now reach Kanarra Creek. Cordova and others (1972, Table 1) estimated average annual flow of these two streams at 0.22 and 0.29 cfs, respectively. The flows in these creeks measured at the Hurricane fault on October 13, 1995 are 0.063 and 0.057 cfs, respectively (Wilkowske and others, 1998, Table 6). Still farther south, just north of a National Park Service center at the northern entrance to Zion National Park, perennial Taylor Creek crosses the Hurricane fault and passes west beneath I-15 to join Kanarra Creek. Tritium values determined by Professor Alan L. Mayo of Brigham Young University indicate that the waters in Kanarra and Taylor Creeks are modern. Cordova and others (1972, Table 1) estimated the average annual flow in Taylor Creek at 0.25 cfs. Wilkowske and others (1998, Table 6) measured the flow in Taylor Creek on October 12, 1995, at a waterfall 1000 ft east of the fault at 0.280 cfs, then the flow of water decreases through seepage at and west of the fault to 0.170 cfs just west of I-15, then 0.013 cfs about 2000 ft upstream from the confluence with Kanarra Creek. Just above its confluence with Ash Creek, the flow in Kanarra Creek was measured on October 11, 1995, at 0.280 cfs. Heilweil and others (2000, p. 38) suggested that seepage in the last third of a mile to Ash Creek was about 0.08 cfs.

Ash Creek Reservoir

Ash Creek Reservoir (Figure 5) is unable to hold significant amounts of surface water for more than a few months (on September 17, 2016, it was dry even though the irrigation season has ended). Ash Creek Reservoir backs up behind (west of) an earthen dam that lies beneath the highway base of I-15. Although there were many misgivings from engineers and other experts that it would hold water, the dam was built in 1960 (Board of Water Resources, 1975; note: the Board of Water Resources later was named the Utah Division of Water Resources). At first the reservoir was conceived as a flood-control structure but as water filled it, it became an irrigation reservoir (Utah Division of Water Rights, 1979). The first time it filled to capacity, with some spilling over the spillway, was in the spring of 1969. That first high water caused the crest of the dam, and therefore I-15, to settle, resulting in depression holes and cracks (Board of Water Resources, 1975). Following an inspection report (Utah Division of Water Rights, 1979), several problems were recommended to be fixed but the overall structure was considered safe. According to Corey Cram (WCWCD, oral communication) the only other times surface water went down the spillway was during floods in 2005 and 2010.

The report by the Board of Water Resources (1975) included conclusions from a 1973 geologic report by Bryce Montgomery, then a staff geologist with the Utah Division of Water Resources. He found that both abutments of the dam and much of the floor of the reservoir are on a basalt lava flow that lies well above the water table. This flow, the Pintura lava flow that is about 0.85 million years old (Pleistocene; Biek, 2007), is unable to hold water because it is heavily fractured. Basalt flows are typically well fractured because the rock type is brittle, but this problem is compounded by the Hurricane fault zone, which is shown by Biek (2007) to be 1000 ft east of the dam (Figure 5). Airfall cinders from later eruptions of the lava flow overlie the flow in I-15 roadcuts just south of the dam. The lava flow here has been downthrown about 1600 ft along the Hurricane fault zone, for the same flow caps Black Ridge about 1.5 mi east-southeast of the dam.

Surface-water flow from Ash Creek into the Ash Creek Reservoir was recorded from 1939 to 1947 by a USGS stream gage (#09406500), now discontinued, located about 500 ft northwest of the dam (location shown on Figure 1 and the USGS Kolob Arch 7.5-minute quadrangle). The eight years of annual data from the Ash Creek Reservoir gage range between 1.9 and 23.1 cfs, with an average of 10.6 cfs (Table 1). No flow was seen entering the reservoir on September 17 or October 7, 2016.

Stream-flow data from limited and past years of record can be brought up to date by correlating the old gage records with other gages in the general area whose records were maintained for much longer periods. This was done by the Riverware simulation model of McGettigan (2014, Tables 2 and 9, appendices), which used gages on Leeds Creek and the North Fork of the Virgin River. The model simulated monthly and annual flows for each discontinued gage from 1965 to 2011, then produced an overall average of all annual flows. This estimation of overall mean annual flows at the Ash Creek Reservoir gage and the other gages given below provides flow numbers that can be applied now and in the future. For the Ash Creek Reservoir gage, the result is a mean annual flow of 10.52 cfs (McGettigan, 2014, Tables 2 and 9). These annual and monthly readings were adjusted by Gardner (2014) to result in his Figure 2 and Appendix C, which shows an annual flow past this gage point of 10.20 cfs. This number is similar to the average from the 8 years recorded by the stream gage near the dam.

Ash Creek Basin South of Ash Creek Reservoir

Downstream from Ash Creek Reservoir, ephemeral Ash Creek continues south for several miles in a shallow canyon cut in the same fractured basalt flow as at the reservoir. Then it continues mostly in surficial sediments and underlying, mostly unconsolidated basin-fill deposits in the graben. Seepage to the underlying water table removes surface water. Anecdotal information indicates that this reach has been dry even prior to pioneer settlements except during periods of high snow melt or summer thunderstorms. Many short ephemeral tributaries flow into Ash Creek from off the Hurricane Cliffs. The northern of these is Deadman Hollow, which joins Ash Creek just east of the dam of the Ash Creek Reservoir, and has some phreatophytes (cottonwood trees) that may be observed from I-15 that are fed by one or more small springs that rise from the Hurricane fault zone.

Three long perennial tributaries, as well as several long ephemeral tributaries, drain the Pine Valley Mountains and join Ash Creek, all of them upstream from Toquerville Springs. From north to south, the three tributaries, which are perennial to intermittent most of their reaches to Ash Creek, are Leap Creek, South Ash Creek, and Wet Sandy. Discontinued USGS stream gages operated on each stream, as shown on Figure 1, and these and other available stream-flow data are given below. The streams are considered perennial above their gages, and perennial to intermittent below them. Doug Wilson (WCWCD, oral communication, October 2016), who has visited the three tributary streams many times, reported that in the last several years the only time that much surface water passed below the diversions is in during the springtime in high-water years and that no water has reached the confluence with Ash Creek during this time. Wilberg and others (2001) published seepage studies on the three streams that included more flow data. Tritium values determined by Professor Alan L. Mayo of Brigham Young University indicate that the waters in Leap Creek, South Ash Creek, Wet Sandy, and LaVerkin Creek are modern.

Leap Creek had a stream gage (#09406640) that recorded stream flow between 1995 and 2001 (Table 1). The gage, just below where ephemeral Maple Hollow joins Leap Creek, is about 2.8 mi above the confluence of Leap Creek with Ash Creek (Figure 1). The average annual stream flow at the gage during the 7 years of record ranged between 0.649 and 5.09 cfs, with an average of 2.03 cfs. In comparison, McGettigan (2014, Tables 2 and 9) used his Riverware simulation model to arrive at an overall average annual stream-flow number at the same gage of 2.39 cfs. Gardner (2014, Figure 2, Appendix C) adjusted these data to calculate 2.41 cfs at the gage. McGettigan and Gardner also calculated simulated monthly flow data from 1965 to 2011. Leap Creek had formerly been diverted for irrigation, with an intake pipe just below the former stream gage, and the diversion has periodically been used to irrigate WCWCD-owned land.

Wilberg and others (2001) reported on three seepage studies along Leap Creek, in late May, mid-October, and late October of 1998. The entire tributary is underlain by bedrock, which was mapped by Hurlow (1998). Some of the stream-flow data that Wilberg and others (2001, Table 1) collected is given below to provide the reader with a feeling for flow along the entire creek rather than just at the stream gage. The readings from the three studies that were collected from the highest station, about 4500 ft upstream from

Water Year	MEAN ANNUAL FLOW (IN CFS) RECORDED BY USGS STREAM GAGES						
	Kanarra Creek at Kanarraville #09406300	Ash Creek at Ash Creek Reservoir #09406500	Ash Creek above Toquerville Springs #09407000	Ash Creek below Toquerville Springs #09407200	South Ash Creek #09406700	Leap Creek #09406640	Wet Sandy #094069000
1940		3.32					
1941		23.1					
1942		10.9					
1943		7.28					
1944		13.7					
1945		10.3					
1946		1.9					
1947		14.4					
1960	1.98						
1961	2.75						
1962	3.86						
1963	2.25						
1964	2.80						
1965	3.93						
1966	3.53						
1967	3.78				6.31		
1968	4.73				4.95		
1969	7.86				16.0		
1970	2.75				3.07		
1971	2.90				2.69		
1972	2.25				2.93		
1973	11.3				15.7		
1974	3.18			18.9	2.95		
1975	3.67			11.9	3.98		
1976	2.87			10.6	3.39		
1977	2.06			7.79	1.26		
1978	5.32			31.7	13.3		
1979	7.24			46.6	14.0		
1980	7.52			46.2	12.9		
1981	3.41			20.4	3.22		
1982	3.51			6.22	3.81		
1987			3.77				
1988			3.94				
1989			0.350				
1990			0.050				
1991			0.610				
1995						5.09	3.84
1996						0.649	0.804
1997						1.10	0.969
1998						3.97	2.98
1999						0.806	0.999
2000						1.54	0.725
2001						1.07	1.24

Table 1 -- Stream-flow volumes in cubic feet per second from all available, but now discontinued, USGS stream-gages in the Ash Creek drainage basin.

gage and diversion intake, were 6.63 (in May), 0.79 (mid-October), and 1.24 (late October) cfs, respectively. At the gaging station, the readings were 6.02, 0.68, and 1.18 cfs, respectively. Inasmuch as these readings were less than those 4500 ft upstream and the stream is flowing largely on the Navajo Sandstone, this is a good example of stream seepage into the Navajo. About 1200 feet downstream from the diversion, stream flows were 5.96, 0.72, and 0 cfs, respectively. About 4000 ft farther downstream, near a waterfall called Peters Leap, the readings were 7.12, 0.59, and 1.06 cfs, respectively. From Peters Leap to just above the confluence of Leap Creek with Ash Creek, the stream flowed on the same fractured Quaternary basalt as at the Ash Creek Reservoir. Just above this confluence, the readings were 5.79, 0.46, and 0.90 cfs, respectively, all of lower volume than that at Peters Leap, so here Wilberg and others (2001) concluded that the stream experienced significant seepage into the basalt.

South Ash Creek had a stream gage (#09406700, shown on the USGS 7.5-minute Pintura quadrangle), that recorded stream flow between 1967 and 1982 (Table 1). The gage, just below where perennial Mill Creek joins perennial Harmon Creek to become South Ash Creek, is almost 5 mi above the confluence of South Ash Creek with Ash Creek (Figure 1). The average annual stream flow at the gage during the 16 years of record ranged between 1.26 and 16 cfs, with an average of 6.9 cfs (Table 1). In comparison, McGettigan (2014, Tables 2 and 9) used his Riverware model to get an overall average annual flow of 7.00 cfs at the gage, extremely close to the 16 year actual average. Gardner (2014, Figure 2, Appendix C) adjusted McGettigan's data to derive a number of 6.94 cfs at the gage. McGettigan and Gardner also calculated simulated monthly flow data for the years 1965 to 2011. In comparison, Heilweil and others (2000, Table 12) calculated an annual mean discharge for South Ash Creek at its mouth of 8.27 cfs based on a formula that included drainage-basin size and precipitation averages. South Ash Creek had been diverted for irrigation by a lined open ditch whose intake is a distance of a little more than 5000 ft above the confluence of South Ash Creek with Ash Creek.

Wilberg and others (2001) reported on four seepage studies along South Ash Creek, in mid-May, late August, early October, and late October of 1998. The lower 8500 ft of the creek flows on surficial and basin-fill sediments, but the rest of the creek flows over bedrock. Not all the stream-flow data are given here. The readings from the four studies collected by Wilberg and others (2001, Table 3) from the stream gage were 33.4, 7.29, 4.91, and 4.65 cfs, respectively (Wilkowske and others, 1998), Table 6, reported a reading of 3.58 cfs collected from the same place on October 9, 1995). For about the next 15,000 ft the creek flows on the Navajo Sandstone, and at the downstream stratigraphic contact the readings were 30.2, 3.74, 3.08, and 3.52 cfs, respectively (Wilkowske and others, 1998, Table 6, reported a reading of 2.20 cfs collected from the same place on October 9, 1995); these readings, which are lower than those at the stream gage at the same respective date, demonstrate seepage of surface water into the Navajo. About 2000 ft farther, just below the stream diversion, the readings were 20.5, 0.19, 0.02, and 0.02 cfs, respectively. About 2000 ft farther, the readings were 26.9, 3.26, 1.68, and 1.77 cfs, respectively. After the last 6500 ft reach of the stream, just above its confluence with Ash Creek, the readings were 25.7, 1.55, 0.50, and 1.00 cfs, respectively, and clearly reflect seepage into the surficial and basin-fill sediments.

Wet Sandy had a stream gage (#09406900) that recorded stream flow between 1995 and 2001. The gage is about 4.5 mi above the confluence of Wet Sandy with Ash Creek (Figure 1). The average annual stream flow at the gage during the 7 years of record ranged between 0.725 and 3.84 cfs, with an average of 1.65 cfs (Table 1). In comparison, McGettigan (2014, Tables 2 and 9) used his Riverware model to get an overall average annual flow of 1.73 cfs, close to the 7-year average. Gardner (2014, Figure 2, Appendix C) adjusted McGettigan's data to derive a number of 1.79 cfs at the gage. McGettigan and Gardner also calculated simulated monthly flow data for years 1965 to 2011. In comparison, Heilweil and others (2000, Table 12) calculated an annual mean discharge for Wet Sandy at its mouth of

5.59 cfs based on a formula that included drainage-basin size and precipitation averages. Wet Sandy had for years been diverted for irrigation by a canal whose intake is just downstream from the stream gage; this canal was upgraded in 2010 by WCWCD to a pipe.

Wilberg and others (2001) reported on three seepage studies along Wet Sandy, in early June, mid-October, and early November of 1998. The lower 8500 ft of the creek flows on surficial and basin-fill sediments, but the rest of the creek flows over bedrock. Not all the stream-flow data are given here. The readings from the three studies collected by Wilberg and others (2001, Table 5) from the highest station, about 8000 ft upstream from the stream gage and diversion intake, were 4.28, 1.16, and 1.02 afy, respectively. The readings at the stream gage were 5.30, 1.88, and 1.71 cfs, respectively. The amounts of stream water diverted just downstream of the gage on the three dates were 2.28 cfs, all the water, and no water (the irrigation season had ended), respectively. Because of these diversions, the readings from 3000 ft downstream, at the contact with the Navajo Sandstone, were 2.98, 0, and 1.51 cfs, respectively (Wilkowske and others, 1998), Table 6, reported a reading of 1.0 cfs collected from the same place on October 6, 1995). About 15,500 ft farther downstream and 1000 ft past the contact between the Navajo and surficial and basin-fill sediments, the readings were 2.41, 1.40, and 1.25 cfs, respectively (Wilkowske and others, 1998, Table 6, reported a reading of 0.63 cfs collected from the Navajo/surficial contact on October 6, 1995); the data from the early June and early November studies indicate creek seepage to the Navajo, but the diversion of all water in mid-October prevents us from making the same conclusion for that study. After the last 7000 ft reach of the stream, just above its confluence with Ash Creek, the readings were 1.30, 0.93, and 0.88 cfs, respectively, providing clear evidence of seepage into the surficial and basin-fill sediments.

As part of his study of recharge to the Navajo aquifer, and using a formula based in part on the size and precipitation values of a stream's drainage basin, Heilweil and others (2000, Table 12) calculated an annual mean discharge for two ephemeral streams draining the Pine Valley Mountains and joining Ash Creek. Dry Sandy, whose confluence with Ash Creek is about 500 feet north of where Wet Sandy joins Ash Creek (Figure 1), was calculated to have a mean annual discharge at this confluence of 5.59 cfs. Anderson Junction Wash, a name proposed by Heilweil and others (2000) for a long wash just south of Wet Sandy that joins Ash Creek just west of Toquerville (Figure 1), was calculated to have a mean annual discharge at this confluence of 4.98 cfs.

The confluence of Wet Sandy with Ash Creek is about 1 mi northeast of Anderson Junction, where Utah Highway 17 joins I-15 (Figures 1and 2). Highway 17 goes southeast from this junction to Toquerville, about 2 mi away. From the confluence with Wet Sandy, Ash Creek continues south for nearly 2 mi to Toquerville Springs (shown on the Pintura 7.5-minute quadrangle). Although this stretch is generally ephemeral, a USGS stream gage (Figure 1) just above the springs recorded flow stream between 1987 and 1991. The annual average flows ranged between 0.05 and 3.94 cfs, with an average of the 5 years of 1.74 cfs (Table 1).

Toquerville Springs (discussed below) issue from the eastern bank of Ash Creek about 0.75 mi upstream from where it passes beneath State Highway 17, on the northern edge of Toquerville (Figure 1). Anecdotal information (Doug Wilson and Corey Cram, WCWCD) suggests that, since the days of the pioneers, diversions for agricultural and municipal use just downstream of Toquerville Springs are such that the creek routinely goes dry and currently provides little benefit to the Virgin River. Another spring, Ash Creek Spring (discussed below), issues about 2.5 mi downstream Ash Creek from Toquerville Springs (Figure 1). Although it seems likely that at one-time Ash Creek was perennial from Toquerville Springs all the way to the Virgin River, past and current diversions--some of them illegal--leave the creek at times and places dry or with non-flowing pools for nearly the entire reach (Corey Cram and Doug Wilson, WCWCD, oral communication, 7/27/2016). Presumably some of the water that is present in this reach of the creek represents return flow from agricultural fields. A check of streamflow on Ash Creek on September 17, 2016, after a late-summer dry stretch, showed (1) significant flow just below Toquerville Springs; (2) significant flow 0.7 mi south of Toquerville Springs at the Utah Highway 17 bridge on the northern edge of Toquerville; (3) pooled water with no apparent flow at a bridge 0.25 mi west of the southern edge of Toquerville (1.3 mi downstream from Ash Creek Spring); and (4) significant flow at a bridge in a housing development on Ash Creek 0.9 mi above its confluence with the Virgin River.

LaVerkin Creek enters the Virgin River about 500 ft upstream of the confluence of Ash Creek with the Virgin River. Therefore, it is outside the Ash Creek drainage basin. However, after LaVerkin Creek debouches from the Hurricane Cliffs about a mile south of Toquerville, the two creeks flow for more than two miles parallel to each other and within a half mile of each other. Therefore, LaVerkin Creek contributes recharge to the groundwater of the basin from seepage of its water into surficial and basin-fill sediments and into fractures in bedrock caused by the Hurricane fault on which this lower part of LaVerkin Creek flows (Biek, 2003a). Cordova and others (1972, Table 1) estimated the annual average flow of LaVerkin Creek to be 4.28 cfs. On September 17, 2016, significant flow was observed at the Utah Highway 17 bridge 0.6 mi north of the intersection of this highway with Utah Highway 9 (to Zion National Park) in LaVerkin.

Although also outside the Ash Creek basin, we include information on perennial Leeds Creek, from an active (1965-2016) stream gage (#9408000, shown on the Pintura 7.5-minute quadrangle and on Figure 1). The 51 years of annual stream-flow records range from 2.20 to 26.5 cfs, with an average annual stream flow of 7.24 cfs. Leeds Creek flows into perennial but smaller Quail Creek near the community of Harrisburg. Both streams doubtless contribute seepage recharge to the Leeds and Harrisburg areas. On September 17, 2016, Quail Creek had minor flow extending from the Red Cliffs Campground to where it passes beneath I-15, but it was dry upstream of the campground.

SURFACE-WATER RESOURCES FROM SPRINGS

Relatively few springs in the Ash Creek basin are mentioned here. Three from the basin are discussed below because they are large and bear on the hydrogeology of the area. They are listed by their location from north to south and are shown on Figure 1. We also discuss LaVerkin Hot Springs (Figure 1), even though it is outside the basin, because it is owned by WCWCD and bears on some conclusions given below on fracture flow along the Hurricane fault zone.

Sawyer Spring

Sawyer Spring (geology discussed above) is in Sawyer Canyon about 0.5 mi west of its confluence with Ash Creek (Figure 1). Heilweil and others (2000, p. 43) noted a discharge of 1.51 cfs in October 1995. Lower Sawyer Spring, an informal name given by Rowley and others (2012) to a spring 0.3 mi east-northeast of Sawyer Spring, had an apparent discharge of 2.15 cfs according to Player (2009). The importance of both springs is that their water levels rise and fall independently of each other (barrier flow) but that large nearby irrigation wells to the north interfere with (that is, lower the water level in) lower Sawyer Spring (but not Sawyer Spring) because lower Sawyer Spring and these wells are in the same fault and experience conduit flow. Tritium values determined by Professor Alan L. Mayo of Brigham Young University indicate that the residence times of waters in lower Sawyer Spring, the big irrigation wells, and Ash Creek are modern (Montgomery, 2000; Rowley and others, 2012, Table 1). Tritium values from Sawyer Spring are mostly modern, suggesting slightly greater residence time in its fault. Tritium values from Well D suggests that its water has a residence time of 50 to 400 years, suggesting greater residence time to get to the well intake along the range-front fault.

Toquerville Springs

Toquerville Springs, Utah's largest, issue from the eastern bank of Ash Creek along fractures caused by the Hurricane fault zone, which underlies the springs. Cordova and others (1972) and Clyde (1987) discussed two Toquerville springs, an upper and a lower, but the coordinates given by Cordova and others (1972, Table 16) make it clear that the upper spring is the one shown as Toquerville Springs (for added confusion, two spring symbols are shown) on the USGS Pintura 7.5-minute quadrangle and the lower spring is along Ash Creek 1 mi south of both Toquerville and the confluence of Anderson Junction Wash with Ash Creek. Heilweil and others (2000, Table 4) called this Ash Creek Spring. We will continue the name of Heilweil and others, as discussed below. Toquerville Springs issue from basalt of the Pintura lava flow, the same unit as at Ash Creek Reservoir (Hurlow and Biek, 2003). The creek is cut into the basalt here. Unlike at and downstream from the Ash Creek Reservoir, the water is under artesian pressure so water issues from, rather than seeps into, the basalt flow. The spring water is of high water quality (TDS about 460 mg/l according to Clyde, 1987), yet the current primary use of the water is irrigation.

Cordova and others (1972, Table 8) listed 19 discharge measurements from upper Toquerville Springs done by the USGS or a consulting engineer: (1) 5 measurements from late April to late August, 1961, of 5.04 to 4.77 cfs; (2) 2 measurements in early and late June, 1962, of 7.35 and 6.20 cfs, respectively; (3) one measurement in late May, 1963, of 8.97 cfs; (4) one measurement in late July, 1967, of 10.92 cfs; (5) 3 measurements in mid September, early November, and early December, 1968, of 10.53 to 8.02 cfs; (6) 2 measurements in September and early October, 1969, of 16.13 and 21.68 cfs, respectively; (7) 4 measurements in mid-February to mid-November, 1970, of 21.61 to 14.98 cfs; and (8) one measurement in late April, 1971, of 10.95 cfs. Clyde (1987) noted that the discharge from upper Toquerville Spring has been measured at more than 21.7 cfs and, when the discharge from the lower spring (Ash Creek Spring) is added, the overall flow has exceeded 30 cfs at times. Wilkowske and others (1998, Table 3) measured discharge from upper Toquerville Spings on April 12, 1996, at 21.79 cfs. Corey Cram (written communication, October 2016) summarized his impression of recent flow from Toquerville Springs as having a "reliable discharge of about 10 cfs and much lower in many years."

A USGS stream gage, in Ash Creek downstream from the Toquerville Springs, collected stream-flow data (presumably all or most of it from the springs) between 1974 and 1982. The coordinates for this gage indicate that the gage is about 1000 ft downstream of the springs (Figure 1), yet a stream gage is shown on the Pintura 7.5-minute quadrangle that is about 2000 ft downstream of the springs. As with the other measurements, the data from the gage show significant variation in flow, between 6.22 and 46.6 cfs, with an average during the 9 years of 22.26 cfs (Table 1).

The large variations in flow from Toquerville Springs indicate that the source of the spring discharge is local and shallow, so that water volume parallels wet versus dry years. One small test of this conclusion is by comparison of the gage records with those of the only other local gage whose years of data collection partly coincided with the Toquerville Springs gage, namely that of the South Ash Creek gage, discussed above. Table 1 shows that the three years of highest annual discharge (31.7, 46.6, and 46.2 cfs) from the springs (1978-1980) coincides with the same three years of highest South Ash Creek flow (13.3, 14, and 12.9 cfs, respectively) in the same 9 years. In that same 9-year span, Kanarra Creek had its highest annual flows (5.32, 7.24, and 7.52 cfs, respectively) during the same three years (Table 1), as did Leeds Creek (11.9, 14.5, and 18.1 cfs, respectively). This immediate response of Toquerville Springs to local storms is in marked contrast to the steady flow from LaVerkin Hot Springs (mentioned below), whose water has had a long groundwater residence time before emerging as spring flow. The source of the water discharged from Toquerville Springs is discussed below.

Ash Creek Spring

Ash Creek Spring, as named by Heilweil and others (2000, Table 4), was called lower Toquerville spring by Cordova and others (1972) and Clyde (1987). Both Ash Creek Spring and Toquerville Springs issue from the same basalt unit, the Pintura flow (Biek, 2003a) and both issue from the sides of Ash Creek, yet they are more than two miles apart (Figure 1). Cordova and others (1972, p. 18) measured discharge in 1968 at 5.85 cfs and in 1970 at 6.92 cfs. Wilkowske and others (1998, Table 3) measured discharge on April 12, 1996, at 6.55 cfs.

LaVerkin Hot Springs

LaVerkin Hot Springs, also known as Pah Tempe Hot Springs or Dixie Hot Springs, is a spring complex of dozens of orifices that issue from both banks and beneath the Virgin River in Timpoweap Canyon (Biek, 2003a). This canyon is cut in the Hurricane Cliffs just east of the communities of LaVerkin and Hurricane and nearly 4 mi upstream from the confluence of Ash Creek with the Virgin River. The springs issue from fractures in the nearly horizontal Toroweap Formation, in the footwall of the Hurricane fault (Figure 10).

The springs, the largest of which are beneath or at river level, are distributed over about 2000 feet extending east of the main trace of the fault. For 60 years, repeated measurements have shown that discharge has been at a nearly constant rate of about 11 cfs, a constant temperature of 100º to 110ºF (40ºC), and a nearly constant TDS of about 9,500 mg/l. Isotope studies, including Tritium, indicate that the springs are from old groundwater derived from high elevations in the Markagunt Plateau, then theorized to have made its way to Timpoweap Canyon by fracture flow in the footwall of the Hurricane fault, mostly in the gypsiferous C aquifer (Nelson and others, 2016). Two small springs, the grotto springs, on the southern side of the river, issue by artesian flow from the limestone bedrock at a height of 12 feet above the river. The U.S. Bureau of Reclamation (1973) did an exhaustive study of the springs because the high TDS (highest for a spring in Utah) of the discharge naturally pollutes the Virgin River, and these salts are carried down to the Colorado River, then down it to Mexico, where the U.S. is required by treaty with Mexico to maintain acceptable drinking-water standards. Such high TDS requires that the intake for the water-supply pipeline to Quail Creek Reservoir is upstream of the springs. The springs have been studied by many workers (e.g., Everett and Einert, 1994; Biek, 2003a; Rowley 2002a, 2005; Dutson, 2005; Nelson and others, 2009; Rowley and Dixon, 2014).

GROUNDWATER OF ASH CREEK DRAINAGE BASIN

Quantification of groundwater resources in any area is a tricky job because the error bars in any estimate of groundwater volumes are likely to be much greater than the estimate itself. Groundwater, of course, is beneath the surface so you cannot see it or measure its volume directly, as in a stream. For the Ash Creek drainage basin, quantification is especially problematic because its southern boundary is the west-flowing Virgin River instead of bedrock, as in most basins. And the eastern bedrock rim of the Ash Creek drainage is the large Hurricane fault, with a high west-facing scarp and a damage zone (zone of likely fracture flow) that continues south to beyond the Grand Canyon. Does all the excess groundwater in the Ash Creek basin end up in the Virgin River? Evidence discussed below indicates that significant groundwater continues south beneath the river.

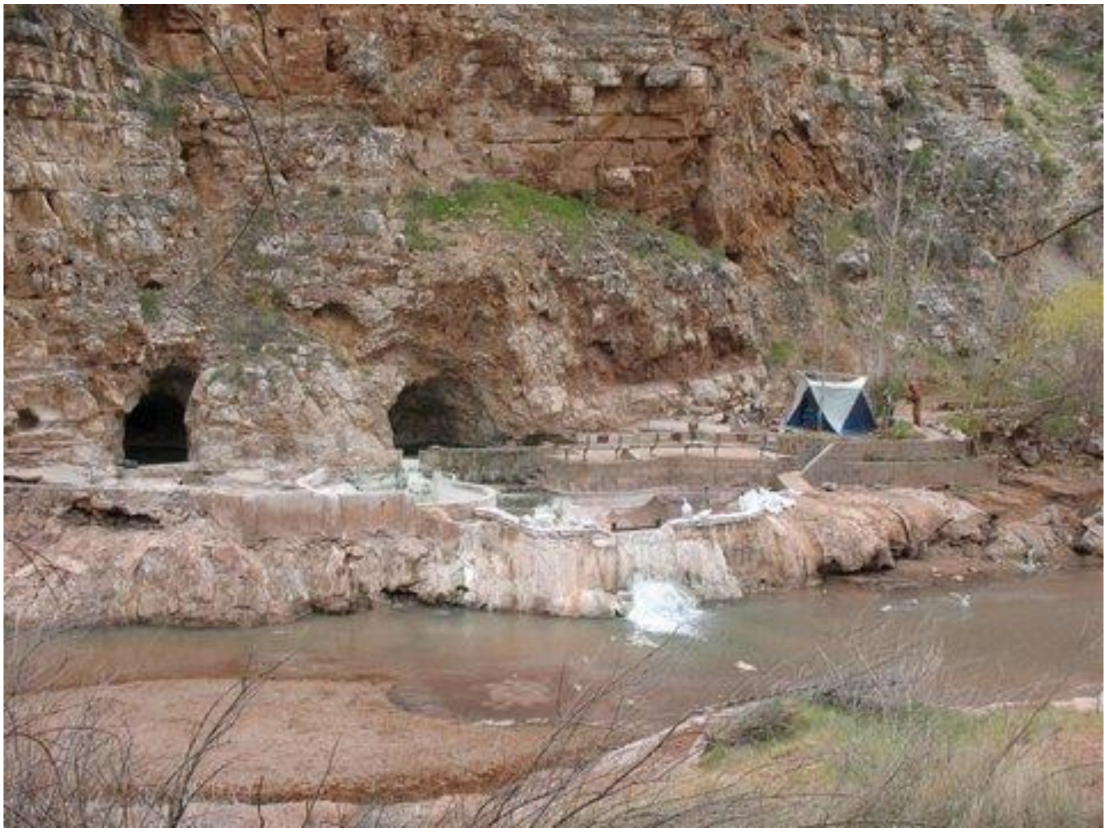

Figure 10. Photograph looking south, across the Virgin River, of bath pools at the grotto springs of LaVerkin Hot Springs, in Timpoweap Canyon. The entire cliff in the view is made up of highly faulted and fractured rocks of the Permian Toroweap Formation, yet these faults are more than 1500 feet east of the main trace of the Hurricane fault. The largest springs are at and beneath the river, which here is at a low stage typical for this time of year, on November 19, 2013. The intake for the WCWCD pipe that takes water from the river and transports it to Quail Creek Reservoir is about two miles upstream (to the left).

Resource Estimates

The first significant study of the groundwater conditions in the central Virgin River basin, which is the area west of the Hurricane fault and therefore includes the Ash Creek basin, was that of Cordova and others (1972), following a request by the Utah State Engineer because of "water-rights problems" in the area. Their primary conclusions concerned calculation of a groundwater budget. They estimated that the long-term average recharge to the aquifers of the central Virgin River basin at that time was 138 cfs (100,000 afy) after adding up the parts of recharge, namely infiltration of precipitation, stream flow from adjacent areas, and subsurface inflow. Discharge was calculated at 110 cfs (80,000 afy) based on adding up its parts, namely seepage into streams, springs and drains, evapotranspiration, wells, and subsurface outflow. Cordova and others (1972) assembled some hydrographs of water levels in wells, which at that time gave no indication of long-term declines in water levels. In their calculation of recharge, they noted that Thomas and Taylor (1946) and Sandberg (1966) suggested that some southerly subsurface inflow into the Kanarraville area came from southern Cedar basin. But when Cordova and others (1972, Figure 4) compiled water levels from wells from across the topographic divide between the two basins, they concluded that by then no groundwater entered the Virgin River basin from Cedar Valley.

In a later analysis of groundwater in the entire (upper and central) Virgin River basin (not including the Beaver Dam Wash along the Utah-Nevada border), Clyde (1987, Table 3) calculated that the recoverable water in storage is 7.2 million acre feet, of which 6 million is in the Navajo Sandstone. He split out the New Harmony basin alone to have 1.05 million acre feet available for recovery from wells. But such a calculation is based on rock volume beneath the water table multiplied by its percentage of porosity, a figure that will not change as years go by, if one assumes steady state. Yet calculating the thickness of the Navajo Sandstone below the water table is problematical because the internal stratigraphy of the 2000-ft-thick Navajo Sandstone has never been determined, so it is uncertain how far below the surface one can project the unit. Furthermore, steady state cannot be assumed for most of the basins he studied because most of them have been developed since the time of the pioneers. In fact, as one might expect, some of his well hydrographs (outside the Ash Creek basin) by then showed long-term falling water levels. Of the basins that Clyde studied, however, we consider it likely--as elaborated below--that the Ash Creek basin is in steady state, even today. Next Clyde (1987) presented a groundwater budget, calculating recharge to groundwater (precipitation, stream flow infiltration, subsurface inflow) in the entire Virgin River basin of 214 cfs (155,000 afy) and discharge of groundwater (seepage to streams, flow from springs/drains, withdrawal by wells, evapotranspiration, subsurface outflow) of 181 cfs (131,300 afy). The Ash Creek basin was not broken out in the calculations. The results of Clyde's study are general in scope, providing little guidance for determining water resources of the Ash Creek basin.

By far the most detailed attempt to determine the volume of the groundwater resource in the Ash Creek drainage basin is that of Heilweil and others (2000). They applied a conceptual model (Table 9), then a numerical simulation model (Table 17) to determine groundwater budgets for the entire central Virgin River basin. Unfortunately, they dealt differently with parts of their overall area. One part is what they called the upper Ash Creek drainage basin groundwater flow system, that is the area at and upstream from Ash Creek Reservoir (Heilweil and others, 2000, Table 9). The rest of the central Virgin basin, including the area south of Ash Creek Reservoir, was treated by calculating groundwater budgets for the outcrop belt of the Navajo aquifer (upper parts of the Kayenta were also included), not only in the Ash Creek drainage basin but extending westward into the drainage basin of the Santa Clara River and west of Gunlock, as well as south to the Arizona border. They started their analysis by providing precipitation contours for the entire area (their Figure 2).

For the conceptual model of the upper Ash Creek drainage basin, Heilweil and others (2000, Table 9) summed up the amounts contributed by precipitation, seepage contributions from ephemeral and perennial streams, and infiltration on unconsumed irrigation water. They came up with an estimate by several methods for total recharge at between 8.4 and 25.9 cfs (6100-18,800 afy). This did not include inflow from adjacent areas, including Cedar basin, surrounding mountains to the west, or east of a Hurricane fault "no-flow" zone. Total discharge in the conceptual model of the upper Ash Creek basin, itemized from well withdrawal, evapotranspiration, spring discharge, and subsurface outflow through the basalt at Ash Creek Reservoir, was calculated at between 4.2 and 38.8 cfs (3000-28,000 afy). The huge disparity in budget estimates (an order of magnitude for discharge!) illustrates the problems inherent in quantifying groundwater resources. But can we do any better? Unfortunately, we cannot!

The simulation model for the upper Ash Creek basin determined the total recharge and total discharge to be both 19.8 cfs (14,320 afy) (Heilweil and others, 2000, Table 17). Another simulation model, allowing inflow from east of the Hurricane fault, determined total recharge and total discharge to be both 21.1 cfs (15,260 afy) (Heilweil and others, 2000, Table 18). Heilweil and others (2000) made no case for fracture flow in any part of the entire study area, and the groundwater flow model applied here is for porous-media flow. Presumably an attempt to apply some kind of model that incorporates even some fracture flow would give larger budget numbers.

To determine the conceptual model of the groundwater budget for the saturated part of the entire Navajo aquifer, Heilweil and others (2000, Table 15; 2002) broke the Navajo outcrop belt into a "main part" and a "Gunlock part." Both parts were simplified as an unfaulted entity, except for two assumed no-flow boundaries, the Gunlock and Hurricane faults. The part of the Ash Creek basin south of Ash Creek Reservoir was lumped into the main part, with no individual data to break it out. Recharge for both parts was calculated by adding up infiltration from precipitation on the outcrop, seepage from streams crossing the outcrop, seepage from overlying and underlying rocks, infiltration from unconsumed irrigation, and seepage from reservoirs. The total recharge in the conceptual model for the main part of the aquifer was estimated to range from 12 to 49 cfs (8700-36,100 afy). This did not include inflow from the Pine Valley Mountains or east of the Hurricane fault no-flow zone. Discharge in the conceptual model was calculated by itemizing well discharge, spring discharge, groundwater seepage to streams, evapotranspiration, and seepage to underlying rocks. The total discharge in the conceptual model for the main part of the aquifer was estimated to range from 23 to 30 cfs (17,000-28,000 afy). The simulation model for the main part of the Navajo outcrop belt determined the total recharge and total discharge to be 35.3 cfs (25,600 afy) and 35.6 cfs (25,800 afy), respectively (Heilweil and others, 2000, Table 22); several other alternatives were simulated (Table 23) that produced small changes from these numbers. As with the upper Ash Creek basin, the numbers that result from both conceptual and simulation models must be considered minimal.

Modern hydrogeologic studies that were followed by numerical groundwater flow models were done by Southern Nevada Water Authority and the Utah Geological Survey for large areas that centered on Spring Valley in Nevada and Snake Valley in Utah and Nevada, as summarized by Rowley and others, 2009, 2016, in press) and Hurlow (2014), respectively. Both involved preparing a 3-dimensional geologic and hydrogeologic framework based on geologic maps and cross sections at 1:250,000 scale and on regional and detailed geophysics. Both studies took many years. Are the resource estimates that resulted from the groundwater flow models any better than the estimates of Heilweil and others (2000)? We do not know. Trying to come up with numbers may be satisfying but may be unrealistic.

The most recent detailed summary of the groundwater in the central and upper Virgin River basin is the study of Inkenbrandt and others (2013). However, it does not deal with groundwater budgets or volumes of groundwater. They did, however, propose drilling for "new" water for WCWCD.

New Water Supplies and the McCulloch Oil Company #1 Government Wolf Well

Among several oil wells that were drilled in the area, the McCulloch Oil Company #1 Government Wolf well (API #4305310704, total depth 7315 ft) bears especially on the water resources of the area, as summarized by Inkenbrandt and others (2013). Drilled in 1964, it was spudded in flood plain and colluvium deposits several hundred feet east of Ash Creek (Figure 1), about 700 feet north of its confluence with Wet Sandy and somewhat more than 3 mi north of Toquerville (Hurlow and Biek, 2003). It is about 600 ft west of the main trace of the Hurricane fault, on the downthrown side (hanging wall), so drill logs indicate that it penetrated at least two faults of the west-dipping fault zone, at 375 ft and 3375 ft depth (Hurlow and Biek, 2003, Table 3). Of these, at 375 ft the well hole passed through the main trace of the fault and into the footwall of the fault, encountering the top of the Mississippian Redwall Limestone at 792 ft and the top of Devonian strata at 1742 ft; the hole bottomed in Cambrian strata (http://oilgas.ogm.utah.gov/data_center/livedata_search/scan_data_lookup.cfn).

The significance of the well is that the driller noted fresh water at 400 to 1600 ft depth (579 TDS at 1440 ft depth) in Callville Limestone and/or Redwall Limestone, with a flow of 400 to 500 gallons per hour; and "salty" water at 4960 to 5002 ft in Devonian rocks (Inkenbrandt and others, 2013). During the drilling, the USGS measured the depth to the water level in the well at 765 ft. Inkenbrandt and others (2013) noted that the driller suggested that the water issued through fractured carbonates, most likely the Callville Limestone and/or Redwall Limestone. Inkenbrandt and others (2013) reported that a letter written by consulting geologist S. Bryce Montgomery on February 26, 1992, to the mayor of Toquerville, however, suggested that the most water was at a depth below the surface of 1200 to 1750 ft, in the Pakoon

Formation, and that the probable recharge area for this groundwater was the Pakoon in the Kolob Terrace and Markagunt Plateau to the east.

In a deposition for a civil trial, after he had more years to think about the McCulloch well, Montgomery (1999) had three brainstorms. This deposition is a remarkable document because it allowed an excellent hydrogeologist, with considerable experience in the Ash Creek drainage basin, to give opinions. The format is unusual, in which he gave testimony on various topics asked by one or more attorneys, so it is not a traditional scientific report where data to back up opinions are laid out. Another report by Montgomery (2000), which is also unpublished, provides some of the data behind the opinions of Montgomery (1999). So it will be up to our report to see if there is any additional support for Montgomery's three opinions. In his first brainstorm, Montgomery (1999, p. 55-56) noted that the fresh groundwater in the McCulloch well was at least 400 ft lower than the groundwater that issues from Toquerville Springs and Ash Creek Spring. More significantly, " it's not being utilized by anybody in Utah" (Montgomery, 1999, p. 56). In other words, the importance of deep, confined water in the groundwater system is that it might not be controlled by groundwater or surface water rights (Montgomery, 1999, p. 62-64). He made recommendations to the towns of Hurricane and Toquerville to drill and develop this deep groundwater. There is no evidence that this advice was followed.

Inkenbrandt and others (2013, p. 24, 39) also urged that WCWCD develop such unappropriated ("new") water supplies. They suggested targeting the C or R aquifers by testing three areas by use of small-diameter (8-inch) wells, then (1) secure water samples to use water chemistry to see if the water had a source different from that in the Navajo Sandstone (from where most water rights take water), and (2) do aquifer pumping tests to determine the volume of the new water and characterize the aquifer. We agree with their methodology and all three priorities. Their first choice was to drill into the footwall of the Hurricane fault "near Pintura" to intercept the new water source in the McCulloch well, which they thought is coming from the C aquifer (Permian rocks, defined above and in Figure 9) or R aquifer (Redwall Limestone and older rocks) and could be pumped at 500 gallons per hour. We would be more specific in the drill location by recommending that the well be spudded close to that of the McCulloch well. The only drawback they found is that the electric power to pull this new water to the surface from 400 ft or greater depth might be a prohibitive expense. We suggest that the problem might be solved by using solar power.

The second-priority drill site of Inkenbrandt and others (2013) was the footwall of the Hurricane fault near the Arizona border. This would serve to verify that the new water is moving southward along the fracture-flow "pipeline" in the hanging wall or footwall of the Hurricane fault. We, however, propose an actual drill site, which Rowley (in preparation) has already suggested as part of a report to site several dozen shallow, low-volume wells to supply water for construction of the Lake Powell Pipeline (Rowley and others, 2005). Specifically, this well would be along the right-of-way of the Lake Powell Pipeline just west of where it climbs east up the Hurricane fault scarp (shown on Figure 1). The third-priority drill site proposed by Inkenbrandt and others (2013) was to spud the hole on the axis of the Virgin anticline, where the C and R aquifers are closest to the surface in the Ash Creek basin. This option should be done only if the other two were successful. If so, we could site the well at that time.

New Well Fields

There are many places in the Ash Creek basin where wells could be sited that would yield large volumes of groundwater. Of course, few of these could be considered "new" (unappropriated) water as discussed in the preceding subchapter. Any development, therefore, would require securing or purchasing water rights before drilling. The best sites would be located on faults in the Navajo Sandstone on the western side of the basin. Most of these faults have been mapped and are shown on detailed geologic maps. Most faults on the western side of the basin are on Forest Service or BLM land, including the Cottonwood Forest Wilderness (USFS) and the Cottonwood Canyon (BLM) and the Red Cliffs National Conservation Area (BLM), but some private, State, and BLM land east of these areas could be selected.

In the course of preparing the geologic map (Figure 8), we found a new northwest-trending fault zone that had not been mapped before. It is significant because it primarily cuts the Navajo Sandstone. The new fault extends southwest from several large faults mapped west of Anderson Junction (Hurlow and Biek, 2003; Biek and others, 2009) and joins the Washington fault north of Washington (Willis and Higgins, 1995). At the north-northwest-trending Washington fault, Biek and others (2009) showed several north-northeast-trending fault splays off the Washington fault. One of these splays passes beneath, and controlled the eruption of, a Pleistocene basalt cinder cone on the edge of Grapevine Wash. Their fault ends at the cinder cone. Yet BLM 1:24,000-scale, color, stereoscopic aerial photos (flight lines 1-13 and 1-14), taken in 2000, show that this fault continues and swings to the northeast, then passes along the flank of the Pine Valley Mountains, all within the outcrop belt of the Navajo Sandstone (Figure 7). In fact, the northwest-dipping Navajo outcrop belt is unusually wide (about 5 miles) in this area, for parts of the Navajo section must have been repeated by being extended (pulled apart) northwest and southeast along many down-to-the-southeast basin-range normal faults, the same ones that uplifted the Pine Valley Mountains. Biek (2003b) mapped this area in detail and showed on his map many northeast-trending lineaments, which he called "prominent joints." Many of these joints fall on what I interpret to be parts of the fault zone, so the authors of the 2009 map (I am one of them!) found pieces of the fault zone but had no evidence to tie them all into a major fault zone. Mapping faults in the Navajo Sandstone is difficult because the dipping beds you see are eolian dune traces, rather than dips on a geologic formation; such dune traces can get to more than 30 degrees in active dunes moving along a horizontal surface. Furthermore, there are no marker beds in the 2000-thick Navajo, so any offset along faults cannot be measured. Also, the sandstone is friable even when not faulted and ground up and weathered away when faulted, so outcrops showing faults may be sparse. Nonetheless, prominent fault scarps resulting when the Navajo was pulled apart in a NW-SE direction are clear on the shaded relief map that Biek and others (2009) used as the base for their geologic map. To draw attention to the fault zone, we call it the Water Canyon fault zone after the canyon of this name along Quail Creek, as the stream cut through the Navajo here. Some faults were seen on September 17, 2016, in lower (upstream from the BLM Red Cliffs Campground) Water Canyon, but the main fault zone is interpreted to cross the canyon about 0.8 mi up the canyon from the campground, and technical rock-climbing skills prevented us from getting to it from the campground. Most of the fault zone is in wilderness land so cannot be drilled, including in Water Canyon, but north of Washington City, much of the land is state-owned SITLA (Utah School and Institutional Trust Lands Administration) land. Washington has a well field north of town along the Washington fault, but not east of the fault.

Examination of a land-use map compared with a geologic map show other places where other faults along the flank of the Pine Valley Mountains could be drilled. The main range-front fault on which Well D is sited passes southward, to Pintura, into Forest Service land, but some parts may be on BLM land. SITLA land west and southwest of Pintura is cut by faults, as is BLM land northeast of Anderson Junction. Other faults cut private and BLM land north of I-15 between Anderson Junction and Leeds. The rocks below the water table in all these areas are aquifers of Navajo Sandstone, the Tertiary igneous aquifer, and basin-fill sedimentary rocks.

Groundwater Flow

The first attempt to construct a potentiometric surface (water level map, using contours) in and just south of the Ash Creek area was by Cordova and others (1972), who provided contours in the New Harmony basin and in the Warner Valley to St. George area. They showed that flow in the New

Harmony basin was southeast and that flow in the Warner Valley to St George area (both north and south of the Virgin River) was toward this part of the Virgin River. Clyde (1987) compiled these data as well as unpublished 1980 data from Bryce Montgomery on the Colorado Plateau that also indicated flow toward the Virgin River from both north and south of the river. Cordova (1981, p. 30), in his study of more eastern parts of the Virgin River basin, concluded that groundwater flow from the Colorado Plateau was east to west across the Hurricane fault zone, with his best documented contours in Gould Wash (headwaters in Apple Valley; see Figure 1). Heilweil and others (2000), on the other hand, disagreed for purposes of his conceptual and digital simulation models when they assumed that the Hurricane fault is a no-flow eastern boundary because of gouge (a barrier) in the fault zone. Hurlow (1998) and Inkenbrandt and others (2013, p. 23), however, agreed with Cordova (1978, 1981) that groundwater flow passes west across the Hurricane fault. For the C aquifer, Inkenbrandt and others (2013, Figure 14) showed southward flow just east of the Hurricane fault.

For the Ash Creek drainage basin north of Ash Creek Reservoir, the conceptual groundwater model of Heilweil and others (2000, Figure 18) provided detailed potentiometric contours that showed, as expected, nearly the same southeastward flow shown by Cordova and others (1972). No significant long-term declines in the water table were found, so for the purposes of their groundwater model, the groundwater was considered steady state (Heilweil and others, 2000, p. 72). The simulation model showed potentiometric contours that were similar to those of the conceptual model (Heilweil and others (2000, Figure 38), with slight changes (Figure 39) in the contours when inflow across the Hurricane fault was simulated. Inkenbrandt and others (2013, Figure 12) provided the most detailed potentiometric surface of the Ash Creek basin from north of Kanarraville to just south of Anderson Junction; it showed a steep and shallow, south-sloping water table, with its axis along I-15.

South of Ash Creek Reservoir, in the main part of the Navajo Sandstone and Kayenta Formation west of the Hurricane fault, the conceptual model of Heilweil and others (2000, Plate 2) provided potentiometric contours that indicate flow toward the Virgin River, from both the northern and southern sides of the river. The southern part of the outcrop belt (Sand Mountain to the Arizona border) was not shown, however. For the simulation model of the main part of the outcrop belt, potentiometric contours were generally similar (Heilweil and others, 2000, Figure 52) to those of the conceptual model, including several alternatives in the simulation model (Figures 54, 55, 56). Water levels in the Sand Hollow Reservoir area, north of Sand Mountain, indicate flow from the reservoir north to the Virgin River and flow from the reservoir south to Sand Mountain, but these reflect the groundwater dome provided by seepage from the reservoir (Marston and Heilweil, 2013, Figure 6).

South of the Virgin River and the Ash Creek drainage basin and west of the Hurricane fault, a more regional portrayal of the potentiometric surface by Cordova (1978, Plate 3) suggested that as one gets farther south of the river, the surface is sloping south into Arizona. In their study that was more recent but still based on sparse water-level data from Arizona wells, Inkenbrandt and others (2013, Figure 9) found that a roughly east-trending groundwater divide exists more than half the way from the Arizona border to the Grand Canyon, north of which flow is northward and south of which flow is southward into the Grand Canyon. In detail, for different aquifers, they provided (Figures 12, 13, 14, 15) some evidence for the east-trending groundwater divide, but the scarcity of the wells leaves a confused picture.

Farther east on the Colorado Plateau, and immediately east of the Virgin River basin, the potentiometric surface clearly slopes south into Arizona (Cordova, 1981, Plate 2). This is confirmed by Inkenbrandt and others (2013, Figure 13; note, however, that their flow-direction arrow is pointing northwest when it should be pointing southeast), at least for Triassic aquifers. The potentiometric surface for the C-aquifer in this area (Cordova, 1981, Figure 14) is more confused and was interpreted to show the same type of east-trending groundwater divide seen farther west in Arizona.

Source of Water Discharging from Toquerville Springs

The most enduring mystery in the Ash Creek drainage basin is the source of the discharge at Toquerville Springs. Cordova and others (1972, p. 18) noted that "An increase in the rate of discharge of the springs reportedly began soon after the construction of the [Ash Creek] reservoir in 1961." But discharge measurements of the springs before 1961 "are not available" and only began to be collected in 1961, showing a general increase in volume between then and 1971 (Cordova and others, 1972, Table 8). In an attempt to determine the source of spring discharge, Cordova and others (1972) tried to compare records of discharge at Toquerville Springs with general records of precipitation at New Harmony by installing a continuous water-stage recorder in October 1969 at (upper) Toquerville Springs. Although precipitation results seem to correlate with stream discharge and with water levels in a well just south of Kanarraville, the results were of short duration, before they prepared their report (Cordova and others, 1972, Figure 5). Nonetheless, they concluded that New Harmony basin seems to be the source of the water discharging at Toquerville Springs because of the correlation between wet years in the New Harmony basin and greater discharge at Toquerville Springs. However, wet years affect the entire Ash Creek drainage basin, not just the Kanarraville or New Harmony part of it. This is shown by the far better correlation between the same 9 years of stream-gage data for Toquerville Springs and several streams, including South Ash Creek, noted in the subchapter on Toquerville Springs above. Therefore, the data indicate that increased discharge at Toquerville Springs is due to wet years in the drainage basin, and decreased spring discharge is due to dry years. Clearly these springs are extremely responsive to weather patterns, and the groundwater being discharged must be shallow and have a large component of stream water.

Another method used to test the path taken by water seepage from Ash Creek Reservoir began in July 1970, when Cordova and others (1972) injected fluorescent dye into Ash Creek Reservoir. Although it was assumed that the dye would be detected at Toquerville Springs, no dye was found there or the Pintura public-supply well between that date and June 1971. A series of additional dye tests followed, as reported by Mower (1982): two by t he Utah Division of Water Resources in 1973 and 1975; one by Hurricane City in 1977; then one by the Utah Division of Water Resources in 1980 that was described by Mower (1982). The two in 1973 and 1975 by the Division of Water Resources were done by Bryce Montgomery when he was the staff geologist there; he described them in his expert-witness deposition (Montgomery, 1999). Nonetheless, all 5 dye tests proved negative. Despite these results, Mower (1982) concluded that seepage from Ash Creek Reservoir found its way to Toquerville Springs within six months (he suggested that he just missed seeing it), a conclusion with which Montgomery (1999) and we disagree.

Heilweil and others (2000, Fig. 14) tried to gain insight into the origin of the water at Toquerville and Ash Creek springs by plotting water chemistry. Unfortunately, their only conclusion was that the spring water came from a mixture of waters from Ash Creek Reservoir seepage, Sawyer Spring area, and the three perennial tributaries from the Pine Valley Mountains.

The second brainstorm in the deposition of Montgomery (1999) is the answer to the question on the origin of the discharge at Toquerville Springs. To answer this question, Montgomery (1999, p. 53-64) started by providing the reasons why water from and upstream of Ash Creek Reservoir could not be the source of Toquerville Springs, as others had suggested. To do this, he emphasized a geographic fact that others have missed, namely that much of perennial Ash Creek between New Harmony and the Ash Creek Reservoir flows south and south-southeast along the eastern edge of the Pine Valley Mountains. Then, just below the confluence with Sawyer Canyon, the creek swings southeast and east-southeast and continues for three miles to the eastern side of the New Harmony basin, at the dam of Ash Creek

Reservoir. There its water disappears into fractures in the reservoir, which is virtually on top of the Hurricane fault zone, the largest fault in southern Utah. But it is not just surface water that is being dumped into the fault zone, for the contours of the potentiometric surface trend northeast, so of course the groundwater is also flowing southeast into the fault zone. Montgomery (1999, p. 53-56) pointed out that the fault zone acts like "a large drain" to groundwater. In fact, the fault carries that water by fracture flow south beneath Toquerville Springs.

Montgomery (1999, p. 55) next developed evidence from the McCulloch Oil Test well (discussed above), which was drilled into the Hurricane fault zone. This groundwater level here is much deeper, with a depth of 765 ft, and he speculated that this is the water from the New Harmony basin, eastern Cedar basin, Kanarraville area, and Ash Creek Reservoir, which then moved south along the Hurricane fault by fracture flow.

Therefore, Montgomery (1999, p. 61) reasoned, the water at Toquerville Springs is shallow so must be mostly local stream water. As to which stream, Montgomery (1999) proposed that his favored option would be the nearest local source, namely Wet Sandy, which empties into Ash Creek about 2 miles upstream from Toquerville Springs. For that two miles, Ash Creek is ephemeral and the wash is in the Pintura basalt flow, so it is reasonable to assume that the groundwater is in the basalt and the underlying basin-fill sediments, where it was locally confined by, and thus developed a head due to, the overlying lava flow so that it exhibits artesian flow to the surface. Montgomery (1999, p. 58-62) did not rule out some other sources for Toquerville Springs, including Leap Creek, South Ash Creek, and Dry Sandy to the west and Paleozoic rocks east of the Hurricane fault. This shallow groundwater is generally unconfined, and it recharges the Navajo Sandstone and other shallow aquifers (Montgomery, 1999, p. 65). If one compares water chemistry of Toquerville and Ash Creek Springs with water from the perennial tributaries draining the Pine Valley Mountains, using Figure 14 of Heilweil and others (2000), we can see that the only water that is virtually the same as that of the two springs is the Pintura town well, located south of Pintura and just north of South Ash Creek; perhaps the source of that water is South Ash Creek. Mayo (2002) found, on the basis of Tritium values and water chemistry, that the water issuing from Toquerville Springs is modern, yet it differs in chemistry from modern waters collected in various places in the New Harmony basin, including the Sawyer Spring area (see the chapter on Water Quality for this evidence).

WATER QUALITY

A determination of water quality for surface water and groundwater depends mostly upon four things: the hydrochemical facies (water chemistry, in mg/l) of the water, TDS (total dissolved solids, generally given in mg/l), arsenic or other heavy-metal values, and nitrates. We will not cover arsenic, other heavy metals, or nitrates in this report. Data to determine the other two are given primarily in tables by Cordova and others (1972) and Wilkowske and others (1998), and given in figures by Heilweil and others (2000) using data primarily from Wilkowske and others (1998). The best general way to depict hydrochemical facies is by a piper diagram, also called a trilinear diagram. Heilweil and others (2000, Figures 10, 11, 14) gives three of them for our area, with little discussion. Inkenbrandt and others (2013) did a more detailed analysis of the entire Virgin River basin, including use of cluster analysis of the chemistry regardless of the stratigraphic unit from which the sample was collected. This study resulted in four groups (A, B, C, and D) classified from low (A) to high (D) TDS and "maturity" (that is, down-gradient flow and residence time). The characteristics of these four groups were not much different from a stratigraphic classification except that high-TDS samples from the Navajo (Heilweil and others, 2000, Figure 10) were placed with pre-Navajo stratigraphic units (D).

We summarize some of the plots from Heilweil and others (2000) on our Figure 11 and add some data points of our own, taken from Wilkowske and others (1998, Table 4). The interpretation of piper diagrams requires a person more gifted in chemistry than we are. Our discussion will be limited in extent and perhaps overly simplistic. Some of our understanding derives from Hurlow (2013), who analyzed piper diagrams from samples collected down the groundwater flow paths in Snake Valley, Utah and Nevada.

Water chemical analyses gather only the most important cations and anions dissolved in water, and a piper diagram has the ability to display these visually. Interpreting a piper diagram, however, is hardly intuitive. The three cations (the left triangle) and three anions (the right triangle) that form the corners of the triangles are given in relative percentages (the numbers on the sides of the triangles) instead of actual amounts of those cations and anions, so a water sample containing large amounts of some cation and anion (for example, a high-TDS water) does not necessarily show up as one would expect because the percentage of this amount relative to the others is what counts. For each water sample, a point is given on both the cation triangle and the anion triangle, then each is projected up onto the diamond along lines parallel to the left side of the cation triangle and the right side of the anion triangle, respectively. The projected lines cross each other to provide a third point that attempts to show combined cations and anions.

The corners of the diamond give the names of the facies, which depend partly upon the author of the analysis. Generally, the left corner is called calcium bicarbonate water, and it is closest to meteoric water (i.e., rainwater) and to spring water, stream water, or groundwater that is adjacent to a high-precipitation part of a range that produces the recharge. It is typically the highest quality water, including being low in TDS. It can generally be considered the starting point for a groundwater flow system in a basin. If the sample is of groundwater, those falling in this part of the diamond would come from a shallow well, whether in a basin-fill or bedrock aquifer, and it would have low residence time (that is, "modern" water). With greater residence time, there is greater water-rock interaction, and plots of these water samples would radiate in all directions to the right of this corner on the diamond, depending mostly upon the rock type of the aquifer it is passing through. TDS generally, but not always, increases in these radiating lines, even though it cannot be shown on any triangle or the diamond. On the triangles, high-TDS and low-TDS analyses can be intermixed, except in the left corners and left bases, where the waters are low-TDS.

The facies near the upper corner of the diamond is calcium sulfate water. A sample plotted in that corner would be from an aquifer of gypsum or would be mine drainage. The facies near the right corner is sodium chloride water, which would be marine water or water with deep flow and ancient residence times. The facies near the lower corner is sodium bicarbonate water, and a sample plotted in the corner itself would consist also of deep and ancient groundwater. In any series of samples from a particular aquifer or spring, the plot of the one that is farthest in one of the radiating lines from the left corner would be considered a chemical end point, whereas samples in between this end point and the left corner of the diamond would be made up of a mixture of both. The end-point sample farthest to the right (or upper right or lower right) would likely be the oldest or deepest water or at the discharge end (farthest down-gradient) of a groundwater flow system, all of which have experienced the most water-rock interaction and influence from evaporation.

On Figure 11, near the extreme left corner of the combined diamond, is a field of samples circled in dark gray that includes plots of water chemistry, from Heilweil and others (2000, Figure 14), collected from Sawyer Spring, Well B northeast of Sawyer Spring, Cottam wells (pumping from the Navajo aquifer), South Ash Creek, and the Newell Matheson well (a half mile north-northeast of Anderson Junction, from basin-fill). In this field, we also plotted (data in Wilkowske and others, 1998, Table 4; names from Table 1) Well D south of Sawyer Spring, monitoring Well A near Well B, a well of H. Ludwig (1 mi northeast of Leeds, from Navajo), and a well of L. Sullivan (southern edge of Leeds, from basin-fill). Most of these samples would constitute group A of Inkenbrandt and others (2013). On the triangle, the field also plots tightly, near the 60-percent calcium part (relative to magnesium) on the left side of the cation triangle and near the bicarbonate corner on the anion triangle. In the field, all samples have low TDS (less than 273) except the wells of Newell Matheson (370 TDS), Ludwig (325 TDS), and Sullivan (497 TDS), which plot farther from the left corner. Some of these waters have Tritium values from A.L. Mayo: South Ash Creek at the gaging station, Well B, and Sawyer Spring have modern water, whereas Well D and Cottam wells have low Tritium so their waters are considered greater than 50 years and less than 400 years old. All samples in this field (Figure 11) occur on the western side of Ash Creek basin, near the main recharge area. Two are shallow wells, pumping from basin-fill deposits (Sullivan) and Navajo Sandstone (Ludwig) at 98 and 100 ft respectively. Probably a north-northeast-trending fault passes close to these wells and through the western side of Leeds itself, providing rapid fracture flow (Figure 8). The bottom of the casing in the Newell Matheson well is at 180 ft, so it draws from relatively shallow groundwater, and north-northeast-trending faults pass close to it. Cottam wells are cased to 500 ft (we do not know where it is drawing its water from) but mapping showed that it clearly is drilled on a large basin-range fault (Figure 8; see also Rowley and Dixon, 2010).

We show another tight field (in green) with only slightly poorer water quality (farther up and to the right from the field outlined in dark gray) on the diamond and triangles because in large part of increased sulfate (Figure 11). These are the four remaining wells (except for Sullivan flowing wells and two mentioned in the next paragraph) in the Ash Creek basin that contain water analyses (Wilkowske and others, 1998, Table 4), all shallow and pumped from the Navajo Sandstone. These four wells are (1) the Leeds domestic well 1 mi north of Silver Reef, with the bottom of their casing at 69 ft and with 356 TDS; (2 and 3) two Goddard/Savage wells about 1 mi east of Silver Reef, with the bottom of their casings at 31 to 40 ft and with 361 and 443 TDS; and (4) a well owned by Lorin Lee 2 mi east-northeast of Leeds at 100 ft depth and with 425 TDS. The field for these wells is not far from the field marked by the dark gray line probably because all sample sites are near the Pine Valley Mountains recharge area.

An interesting field (in blue) not far away on the piper diagram is made up of five points (Figure 11). Two points, plotted on top of each other by Heilweil and others (2000, Figure 14), are of samples from Toquerville Springs and Ash Creek Spring, containing 480 and 522 TDS, respectively. Most of this field would be the same as field B of Inkenbrandt and others (2013). Toquerville Springs has high Tritium so its water is modern. Two more points are the Pintura town well, just north of the confluence of Ash Creek with South Ash Creek (Heilweil and others, 2000, Figure 13), and the Anderson Ranch well, at Anderson Junction (Heilweil and others, 2000, Figure 14), the former drilled to 345 ft in basin fill and with 406 TDS, and the latter drilled to 300 ft in basin fill and with 430 TDS. The fifth point in the field is from a sample collected in 1964 from the McCulloch oil-test well and reported by Wilkowske and others (1998, Table 4). Its water chemistry is surprisingly similar to that of the two springs except for higher SO_4 and calcium and with a TDS of 633. It is not recorded where the sample came from in the well, but it is similar to the sample noted above (subchapter on New Water and the McCulloch well) of 579 TDS at 1440 ft depth. The McCulloch sample has higher TDS than the two spring samples, suggesting that it was collected from depth, but an even more interesting question is why the two spring samples have such a high TDS for modern, near-surface water. Inasmuch as these spring samples discharge along Hurricane-generated fractures, it would seem that the answer is that there is some mixing here with deeper water in the fault zone. The overall field plots tightly about halfway between the left and top corners of the diamond and on the left side of the cation triangle. On the anion triangle, only the sample from Anderson Ranch is outside a tight field halfway between the HCO_3 and SO_4 corners on the left side of the triangle but, because of high Cl, the Anderson Ranch point is closer to the Cl corner.

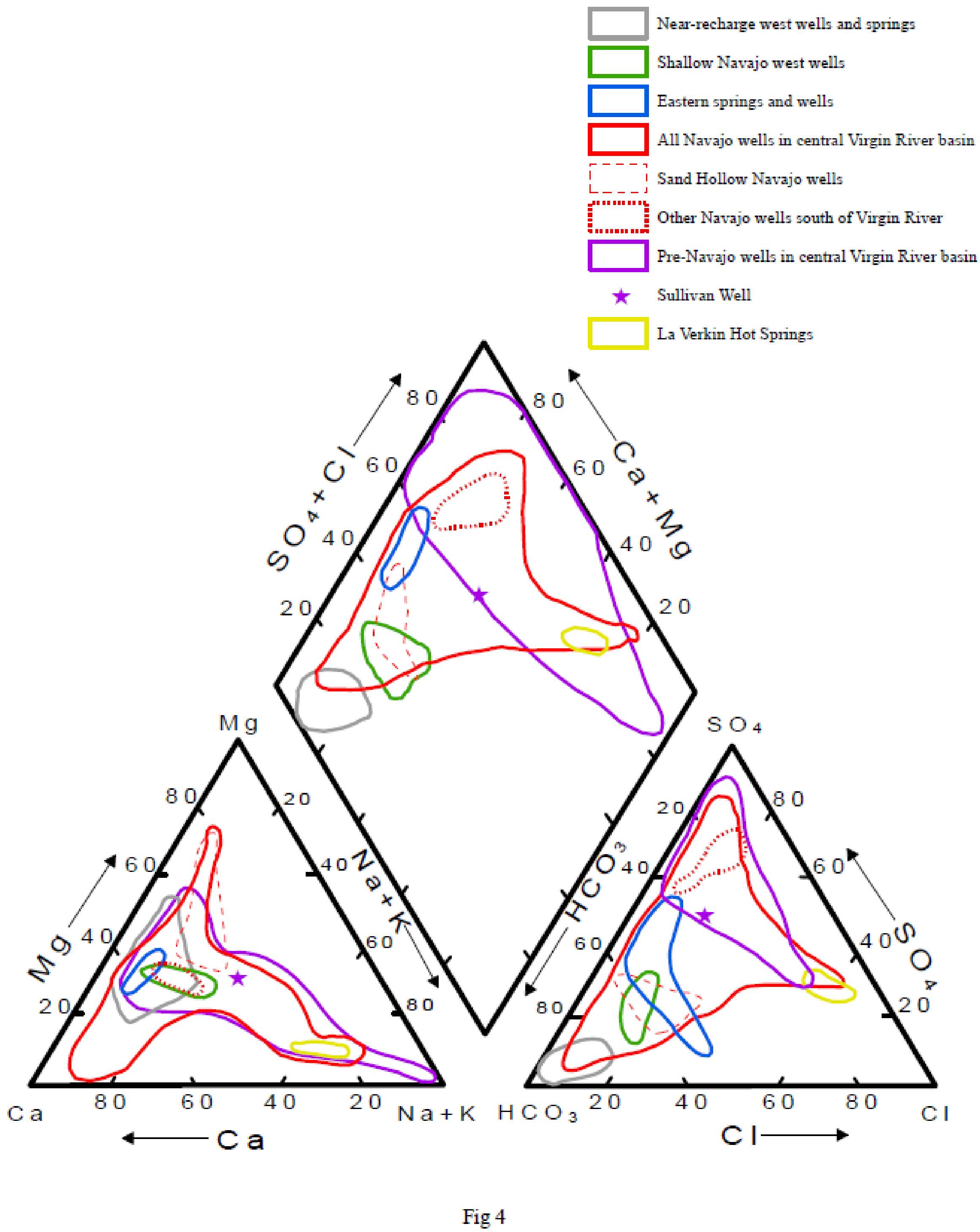

Figure 11. Piper diagram showing water chemistry of groundwater and surface water in wells, streams, and springs in and adjacent to the Ash Creek drainage basin.

Heilweil and others (2000, Figure 10) plotted points for 73 wells (Wilkowske and others, 1998) drilled in the Navajo aquifer from the entire central Virgin River basin. Inkenbrandt and others (2013, Figure 30) plotted Navajo samples from the central and eastern Virgin River basin, taken from the chemical analyses in Wilkowske and others (1990, Table 4) and the USGS website. In red on Figure 11, we show the boundary of the field of Heilweil and others (2000). They separated out waters with less than 500 TDS from those with more than 500 TDS, and they and we included both in the field. In general, the high TDS samples plot in the upper and right part of the diamond, in the central part and lower right corner (Na + K) of the cation (left) triangle, and the upper part (SO_4) and central to right part of the anion (right) triangle. Except for the high-TDS samples, these samples make up group C of Inkenbrandt and others (2013); our tight field shown in green would also be included in their group C.

Heilweil and others (2000, Figure 11) plotted water samples from wells drilled in rock units that overlie and underlie the Navajo Sandstone. The field of those (basin-fill, basalt, Pine Valley laccolith/Latite) that overlie the Navajo is nearly identical to a combination of the dark gray and green fields on our Figure 11, largely because it consists of nearly the same data points given by Wilkowske and others (1998, Table 4). However, the field of those units (Moenave, Chinle, Moenkopi, and Permian) that underlie the Navajo is shown by a purple line because it is instructive, even though it includes samples (Wilkowske and others, 1998, Table 4) from the entire central Virgin River basin. It plots in the upper and right corners of the diamond, in the central to lower right corner of the cation triangle, and the central to upper corner of the anion triangle (Figure 11). This is what one would expect from aquifers containing deeper and higher-residence-time waters or waters from aquifers high in salts. Inkenbrandt and others (2013, Figure 30) also showed similar fields for his pre-Navajo samples.

One of the data points in the field of pre-Navajo aquifers is emphasized by a purple star (Figure 11), from Sullivan (flowing) wells, because it is owned by WCWCD. Its aquifer is the thin (100 ft) Springdale Sandstone Member, formerly the uppermost member of the Moenave Formation (e.g., Heilweil and others, 2000) but currently classified as the lowermost member of the Kayenta Formation (Biek and others, 2009). The data point is from a water sample collected in 1970 that had 998 TDS from a well drilled in 1969 to more than 1000 ft (Wilkowske and others, 1998, Table 4). WCWCD re-drilled the well in 2002 to a depth of about 700 ft, with a pump test yielding 2000 gpm and TDS of about 500 mg/L (Rowley, 2002b). The well was drilled into the eastern flank of the Virgin anticline. The Springdale Sandstone Member is a brittle rock bed that was made more permeable by fracturing like a glass plate when the rocks were folded. This bed is confined by siltstones and shales above and below it, resulting in artesian flow because recharge to it comes from a higher topographic source. This recharge reaches the confined bed through many basin-range faults that make up the axis of the Ash Creek corridor.

In an attempt to identify the source of groundwater south of the Virgin River, we plotted 6 water samples (from Wilkowske and others, 1998, Table 4) in two fields that are representative of several other wells drilled in the Navajo Sandstone there. One field of samples (from the Royal Garden, WCWCD Sky Ranch, and northern Wayne Wilson wells) is from or adjacent to the Sand Hollow well field and all of low TDS (193-220); the field is indicated by a red dashed line (Figure 11). The field is not much different from the Navajo field in green, suggesting that the source of water in the Sand Hollow well field is from north of the river. The other field consists of three other samples in Navajo, also representative of several others, from south of the Virgin River (from the Judd, Hurricane domestic well, and Windy River #1 wells). These wells have higher TDS (558-1310) and occupy a field surrounded by a red dotted line (Figure 11). They make up a higher sulfate part of the overall Navajo field (red solid line). We consider it likely that the three samples from the Sand Hollow well field have lower TDS than the other three south of the river because they are on basin-range faults (Rowley and others, 2004), where recharge can travel faster by fracture flow so residence time is less than in the other wells in Navajo. All are likely recharged by Ash Creek basin groundwater that passes beneath the Virgin River.

Even though outside the Ash Creek drainage basin, we plotted a field for samples from LaVerkin Hot Springs (Figure 10) by a yellow line. It includes one sample from Wilkowske and others (1998, Table 4) that was collected in 1986 and had a TDS value of 7388 mg/l, and some of many dozens of samples collected by the U.S. Bureau of Reclamation (1973, Tables A-5, A-6, and others) where TDS values were about 9,500 to 9,800 mg/l. The plots on the piper diagram (Figure 11) form a remarkably tight grouping.

EVENTUAL DESTINATION OF GROUNDWATER
The Virgin River and Sand Hollow Area

Where does the south-flowing groundwater from Ash Creek drainage basin go? At least some of the shallow groundwater in the basin would seem to flow into the Virgin River. In November 1994, Herbert (1995) did the field work for a seepage study of the Virgin River. He started at a stream gage just downstream from the confluence of Ash Creek with the river (1 mi west of the town of LaVerkin) and ended 14 mi downriver where the St. George and Washington Canal diverted water from the river, about 4 mi east of Washington. Overall, the Virgin River gained 10.7 cfs, with much of the gain (7.2 cfs) in the upper part of the reach, from just downstream of Ash Creek to about 1.5 mi upstream from the confluence of the river with Quail Creek. However, some of the gain likely represents return flows from agriculture north and south of the river.

A volume of 10.7 cfs does not seem much for the eventual outcome of most of the groundwater in the Ash Creek drainage basin. Although limited potentiometric-surface data south of the Virgin River suggests that groundwater flow is toward the river (Cordova and others, 1972), this outcome does not seem reasonable. The story at Sand Hollow Reservoir, before it was filled, suggests another alternative. Sand Hollow Reservoir, developed by WCWCD as a large artificial-recharge reservoir, sits in a saucer-shaped, shallow, north-tilted, shallow syncline of thick Navajo Sandstone (Figures 1and 8). The reservoir, whose water line is at about 3100 ft elevation, overlies the Navajo. The south and southeast sides of the saucer form a gentle northerly-dipping cuesta of Navajo whose crest reaches an elevation of a little more than 4000 ft, called Sand Mountain and about 5 mi south of the reservoir. Sand Mountain has an abrupt south-facing cliff that forms the rim of the saucer, and the base of the Navajo Sandstone is exposed at the southern base of that cliff. Another prominence of the same elevation that overlooks the reservoir is Volcano Mountain (also called Sullivan Knoll), a basalt cinder-cone volcano about 3 mi northeast of the north reservoir dam at Sand Hollow (Figure 1). The north-trending Hurricane fault scarp rises to 4600 ft about 2.5 mi east of Volcano Mountain on the eastern edge of the town of Hurricane. None of these high points can be expected to produce much precipitation to recharge the Navajo, nor does ephemeral Gould Wash, which has headwaters in the Apple Valley community east of the fault scarp, then drains northwestward across the fault scarp, then through the southern outskirts of Hurricane and northeast of Volcano Mountain before emptying into the Virgin River. A potentiometric-surface survey of the entire course of Gould Wash showed groundwater flow parallel to the flow of the wash (Clyde, 1987, Figure 6).

Before the Sand Hollow Reservoir was filled, wells that had been sited by WCWCD had been pump tested with various results, including about 2000 gpm for the southern Wayne Wilson well (1 mi south of the northern Wayne Wilson, for which water chemistry was discussed in the previous subchapter) about 0.75 mi north-northeast of the north dam. This well is about 3 mi south-southeast of the Virgin River. During geologic mapping of the reservoir area, and before siting additional production wells, Rowley and others (2004) found that the southern Wilson well had been sited on one of a series of relatively small-displacement (100 ft or so), north-trending basin-range faults that cut the "saucer." Other nearby WCWCD wells near the north dam, with pump tests in excess of 1000 gpm before filling the reservoir, were farther from faults. A new well sited on a basin-range fault just east of the reservoir by Rowley and others (2004) was tested at 2500 gpm before the reservoir was filled (Corey Cram, oral commun., 2006).

The northern end of the Navajo saucer dips northward beneath the Virgin River, so that almost the entire thickness of the faulted Navajo is beneath the water table and the river. Probably the Navajo gets some of its recharge from the Virgin River. But that cannot explain the high yields of some of the wells in the Sand Hollow well field. We suggest that the southward flow for deeper groundwater in the Ash Creek basin continued beneath the Virgin River and supplied wells that were pumped south of the river before the reservoir was filled. This groundwater moved by fracture flow southward along faults beneath the river. The similarity in chemistry between water in Navajo Sandstone both north and south of the river (Figure 11) supports this suggestion.

Groundwater flow likely continues south of Sand Mountain but, if so, it would have to be in aquifers that predate the Navajo Sandstone, including the C and R aquifers. Groundwater would access these deep aquifers by the small faults and the fractures west of the Hurricane fault, if not the fractured hanging wall of the Hurricane fault itself.

To the Grand Canyon?

But what about still deeper groundwater, including that in large basin-range fault zones? The possible answer to this makes up the third brainstorm of Montgomery (1999, p. 53-64), that the Hurricane fault carries large amounts of fresh groundwater southward, confined and isolated and therefore flowing largely beneath locally-derived groundwater. His wording (p. 56) was "and so, in my mind, there is a large flow, an appreciable amount of groundwater that's moving along the Hurricane fault like a big pipeline, a conduit, and moving out of the State of Utah into the Grand Canyon." He based this opinion largely on his knowledge of the McCulloch oil well that demonstrated that large amounts of fresh water are being carried by the Hurricane fault zone. This opinion also explains why fluorescent dye from multiple tests, put into the water at Ash Creek Reservoir, was never detected at Toquerville Springs and several shallow wells. Therefore, he reasoned that the fresh water in the McCulloch well had a different source than the water issuing from Toquerville and Ash Creek springs. Montgomery (1999, p. 56) thus suggested that the source of the deep water in the McCulloch well is the New Harmony basin, including the Kanarraville area, and that the surface water and groundwater was largely poured into the Hurricane fault zone above and near Ash Creek Reservoir ("so that's where the groundwater is going in my mind out of New Harmony basin"). Most of the surface water in the Kanarraville area, in fact, had already been dumped into the fault zone, for the perennial and ephemeral tributaries that drain the Hurricane Cliffs terminate at fans they created at the west base of the Hurricane Cliffs, where the fault zone is. In addition, the same could be said of tributaries from the Hurricane Cliffs, including Coal Canyon, that debouch at the base of the Hurricane Cliffs in central to southern Cedar Valley.

We and Montgomery propose that the deep fresh groundwater in the Hurricane fault zone continues south beneath Toquerville Springs and passes out of the Ash Creek basin by flowing beneath the Virgin River. The eventual destination for the deep fresh groundwater would seem to be the Grand Canyon (Montgomery, 1999), where it discharges as springs that form travertine spring mounds. Strangely enough, we came to this idea of fracture flow of Utah groundwater along the Hurricane fault to the Grand Canyon when we prepared reports on the geology of Anderson Junction and LaVerkin Hot Springs (Rowley and Dixon, 2010, 2014), before we saw Montgomery's (1999) deposition.

Inkenbrandt and others (2013, p. 23) reviewed the arguments for and against Utah water moving along Hurricane fault fractures to the Grand Canyon and concluded that there is "no evidence that the Virgin River basin provides intrabasinal groundwater flow to the Grand Canyon." Inkenbrandt and others (2013) based their conclusion largely on the large distance (80 mi) of travel and the geologic terrain in which it would travel, as well as the potentiometric surfaces they constructed for northern Arizona. These surfaces (Inkenbrandt and others, 2013, Figures 9, 12, 13, 14, 15) show northward groundwater flow in northernmost Arizona for the Triassic and C aquifers, if not the R aquifer. The few wells that they show in these figures, however, are many miles east and west of the trace of the Hurricane fault.

Inkenbrandt and others (2013, p. 16-18) also compiled other relevant oil wells that tested the Hurricane fault in the area, in addition to the McCulloch oil well discussed above. The overall data are provided by http://oilgas.ogm.utah.gov/data_center/livedata_search/scan_data_lookup.cfm. Oil wells are helpful because they provide information on groundwater at greater depth than that from production water wells. Here we analyze what these wells mean, in conjunction with the McCulloch well and LaVerkin Hot Springs. Locations of all except the Shurtz Creek well are shown on Figure 1. The northern of these oil wells is the Shurtz Creek well (API #4302130002, total depth 5996 ft), spudded in the footwall (east side) of the Hurricane fault several miles south of Cedar City. At 5100 ft depth, in the Redwall Limestone, the drillers encountered water with a TDS of 4500 mg/l. Farther south, at the base of the Hurricane Cliffs south of Pintura (Figure 1), the Pease Oil and Gas Company No. 1-13 Federal well (API #4305330007, total depth 3171 ft; see geologic map of Hurlow and Biek, 2003) was spudded in the hanging wall (west side), then penetrated the fault and sampled "slightly brackish" water at 523 to 612 ft, in the Callville Limestone. Farther south, along LaVerkin Creek, the Buttes Federal 30-B3X well (API #4305330001, total depth 7060 ft) was spudded in the footwall and found water between 3000 and 10,000 TDS at a depth of 1000 to 3000 ft in the C aquifer, with still higher TDS water below that. Inkenbrandt and others (2013), however, cautioned that this water could have been contaminated by drilling fluid. About 2 mi south of Hurricane, the Toledo Minng Co. Hiko Bell No. 1 Federal well (API #4305330005, total depth 6927 ft; see geologic map of Biek, 2003a) was spudded in the hanging wall, then it passed through the fault into the footwall, to encounter fresh water at 1240 to 2300 ft depth in the Queantoweap Sandstone and at 3510 ft depth in Mississippian rocks. About 9 mi south of Hurricane, on top of the Hurricane Cliffs, the Devereaux Company No. 1 Federal well (API #4305320044, total depth 6000 ft) was spudded in the footwall (Hayden, 2004), sampled "relatively fresh" water at 1700 ft in apparently the Queantoweap Sandstone, found "some relatively fresh" water at 2736 to 2754 depth in the Pakoon Formation, and reported "a lot of relatively fresh water" at 3292 to 3325 ft depth in the Redwall Limestone. To the west of the Devereaux well, the Intex 5 Penn USL Knowles-Skyline No. 1 well (API #4305310602, total depth 3006 ft) was spudded in the Moenkopi Formation about 1.5 mi west of the Hurricane fault (Hayden, 2004) and found water at between 270 to 295 ft depth in apparently the Virgin Limestone Member of the Moenkopi Formation and at three other intervals from 975 to 2940 ft in the C aquifer, although no information was given on water quality.

When we combine the limited and incomplete information from these oil wells with what we know about the McCulloch oil well, Toquerville Springs, and LaVerkin Hot Springs, what can we conclude about fracture flow along the Hurricane fault? Let us cautiously suggest the following: (1) in the hanging wall at the surface/shallow depth near Toquerville, significant groundwater of high quality issues as springs from basalt (Toquerville and Ash Creek Springs); (2) near the hanging wall at shallow to great depth near the Arizona border, significant water of unknown quality is present at depths of 270 to 2940 ft (Knowles-Skyline well); (3) in the footwall at moderate to great depth in the Pintura/Hurricane area to the Arizona border, significant groundwater of high quality is present at 400 to 1600 ft (McCulloch well), of "slightly brackish" quality at 523 to 612 ft (Pease No. 1-13 Federal well), of high quality at 1240 to 3000 ft and of "relatively" high quality at 2736 to 2754 ft (Toledo Hiko Bell well), and of "relatively" high quality at 1700 to 3325 ft (Devereaux well); (4) in the footwall at shallow depth, significant groundwater of low quality (high TDS) discharges at one place near Hurricane (LaVerkin Hot Springs); (5) in the footwall at moderate to great depth from south of Cedar City to the Pintura/LaVerkin area and likely much farther south, groundwater of low quality (moderate to high TDS) is found at 5100 ft (Shurtz Creek well), at 4960 to 5002 ft (McCulloch well), and at 1000 to 3000 ft and deeper (Buttes Federal well). The Knowles-Skyline well, 1.5 miles west of the Hurricane fault and only about 3 miles north of the Utah-Arizona state line, offers the additional information that groundwater--even though of unknown quality--is present in pre-Navajo rocks south of Sand Mountain and west of the Hurricane fault.

Of the various types of waters, LaVerkin Hot Springs (Figure 10) seems to be unique in that the geothermal gradient has heated high TDS water and moved it quickly from great depth to the surface by fracture flow in the footwall, as part of a convection cell where cooler water must move to depth to replace the rising hot water. Perhaps the groundwater was blocked from westward flow here rather than elsewhere in the footwall by confining units (Moenkopi Formation) in the hanging wall. Elsewhere along the fault, fresh water of unknown to high volume must be moving with the gradient southward by fracture flow in the footwall, and perhaps the hanging wall, of the fault at moderate to significant depths. Below this fresh water, extending to great depths, is moderate to high TDS water--perhaps like that discharging at LaVerkin Hot Springs but not brought to the surface by the geothermal gradient--that does not seem to mix much with the fresh water above it. The deep fresh water must be considered "new" water that can be developed, and how far this aquifer and its southward flow continues into Arizona is only speculation. Nonetheless, we still think it is getting to the Grand Canyon, even though this point is significantly down gradient.

Other Utah Fault Zones That Cross the Grand Canyon

Four large-displacement, north-trending, down-to-the-west, basin-range fault zones that define ranges in Utah continue south of the Arizona border and cross the Grand Canyon. One of these, the Hurricane fault, is of greatest interest because it forms the eastern side of the Ash Creek basin. Yet some water from the basin could find its way south down the next big fault zone to the west, the Grand Wash fault zone about 25 mi west of the Hurricane fault. The Grand Wash fault zone forms the large fault scarp that defines the western end of the Grand Canyon and the eastern edge of Lake Mead (Billingsley and Wellmeyer, 2003). If one traces the Grand Wash fault north from Lake Mead, it defines the eastern side of the Beaver Dam Mountains and crosses the Virgin River just east of where it and Highway I-15 cut through the range in a canyon that includes The Narrows at its western end, west of which is Littlefield and the Mesquite basin (Billingsley and Workman, 2000). From the river, the fault zone continues north and becomes the Gunlock fault zone, which defines the western side of the Pine Valley Mountains (Biek and others, 2009). Surface water from the Virgin River probably seeps into the fault zone and into fault splays in the canyon just to the west, where it combines with groundwater that probably moves south by fracture flow in the fault zone. Travertine deposits are abundant along the northern side of the Grand Canyon, emerging from springs in the footwall of the fault.

The Sevier fault is nearly 40 mi east of the Hurricane fault and 10 mi west of Kanab, just east of the headwaters of the Virgin River (Sable and Hereford, 2004). This fault defines the western sides of the Sevier and Paunsaugunt Plateaus in Utah. As it continues south into Arizona, it swings west and becomes the Toroweap fault zone, which crosses the Grand Canyon at Vulcan's Throne (Billingsley and Wellmeyer, 2003). About 25 mi east of the Sevier fault is the Paunsaugunt fault, which defines the eastern side of the Paunsaugunt Plateau (the erosional scarp at Bryce Canyon National Park faces east, but the fault at the base of the scarp is actually down on the west). By the time this fault reaches the Grand Canyon, it is called the Muav fault, and it crosses the canyon among a maze of other faults that create springs and travertine deposits (Billingsley, 2000). In the canyon, the Muav fault intersects the northeast-trending Bright Angel fault, which passes southwest to the South Rim and through the Visitors' Center there.

In the area between the Sevier and Paunsaugunt faults, the potentiometric surface slopes south into Arizona (Cordova, 1981, Plate 2). In addition to these two faults that bound this block of south-sloping water levels, Kanab Creek and Johnson Creek, in between them, also trend north-south and are also controlled by basin-range faults (Sable and Hereford, 2004). Fracture flow is suggested by all these faults, which drain areas in Utah of high elevation and precipitation amounts. Logic therefore suggests that these fault zones are highly charged with groundwater that may get as far as the Grand Canyon. But water chemistry or other evidence seems to be unclear.

The Study of Crossey and Others

In a series of studies of travertine deposits and springs in the Grand Canyon, Crossey and others (2006, 2009) and Crossey and Karlstrom (2013) found two types of groundwater that produced the travertine deposits and spring waters. On the basis of water chemistry that they plotted on piper diagrams, as well as samples of gases and isotopes, they proposed two types of waters, epigenic and endogenic. Epigenic waters are those derived from surface recharge, some of which may take many thousands of years of residence time to reach their point of spring discharge. These waters are cool (13-17ºC), have a small compositional range, and contain a neutral to slightly alkaline pH (>8), low TDS (total dissolved solids at <350 mg/L), and low CO_2 gas. This water occupies a tight field (end member) consisting of simple Ca-Mg-HCO_3 fresh water that is close in chemistry and water quality to meteoric waters. Most springs with this water type have high discharge, which occurs generally on the northern side of the canyon at the contact of the base of the R aquifer (Redwall and Muav Limestones) with the underlying confining unit, the Bright Angel Shale. Epigenic water type, therefore, is exactly that plotted on the left side of our piper-diagram diamond and the same parts of the triangles as our Ash-Creek-basin field shown in dark gray on Figure 11.

Of greater interest to us are endogenic waters, which are generally warmer (22-31ºC) and of lower discharge, and contain neutral to slightly acid pH (6-7.5), high TDS (>350 mg.L), and high CO_2 (Crossey and others, 2006, 2009, 2016; Crossey and Karlstrom, 2013). Degassing of CO_2 means that travertine buildup is much greater than with epigenic waters, despite their lower discharge. A key to this water type is that it contains the noble gas He, which the authors demonstrate is derived from the mantle. Most of these waters emerge from faults, including the Hurricane fault, that cut the canyon and penetrate the basement. These faults have had a long mixed structural heritage that includes an older history of Sevier-age reverse faulting or of forming monoclines that was reactivated by basin-range tectonism, including some Pleistocene and Recent displacement and seismicity. Therefore, the authors concluded that the groundwater in these faults has had deep crustal circulation and longer residence time that included some mantle input of chemicals and isotopes, including the He and CO_2. We would add, although Crossey and colleagues did not stress it, that the circulation must be driven by the geothermal gradient and that the flow is fracture flow in convection cells. Their piper diagrams indicate that these waters mixed with the epigenic end-member water.

Colman and others (2014) took the study beyond the Grand Canyon to look at 28 artesian endogenic warm springs in Colorado, Arizona, and New Mexico to focus on unusual microbial communities, primarily bacteria, in the spring water. They found a wide assortment of such "bugs" that they grew in waters attributed to deep crustal groundwater sources, the same that the CO_2 and He came from. The finding is comparable to the discovery of a large assemblage of microscopic and macroscopic plants and animals deep in the ocean basins where hot springs ("black smokers") vent from rocks containing underlying magma bodies (Crossey and others, 2016). On a piper diagram (Colman and others, 2014, Figure 2), the water from the springs containing the largest contribution from depth (highest CO_2) plot in the right and lower corners of the diamond, in the Na+K (right) corner of the cation (left) triangle and in both (HCO_3 and Cl) lower corners of the anion (right) triangle.

Plots of the endogenic waters on the piper diagram of Crossey and her colleagues (2006) reveal considerable chemical complexity that may be grouped into different fields from different faults. Their fields radiate to the right, upper right, and lower right on the diamond. End members representing the springs that discharge from different faults are farthest to the right, although the derivation of their different chemistry is unclear for most of them. Crossey and others (2006), however, found that, in the eastern Grand Canyon, most of the big endogenic (fault-related) travertine mounds and springs are on the southern and eastern side of the Grand Canyon. Furthermore, the groundwater flow to the southern and eastern sides of this part of the river was from the south and southeast, largely off the mountains of the San Francisco volcanic field (Crossey and others, 2009, Figures 2 and 4). Therefore, the groundwater that discharged to create these mounds and springs is from the south, not from Utah. However, a few springs and travertine mounds are on the northern and western sides of the river, where groundwater flow is southward (Inkenbrandt and others, 2013); presumably the discharge to create these springs is from the north, even where flow is along the same fault, but Crossey and colleagues did not state this one way or the other, let alone isolate chemistries on the northern side.

In contrast to the eastern Grand Canyon, big endogenic travertine mounds and springs in the western Grand Canyon are both north and south of the river (Crossey and others, 2006). Here also, groundwater flow paths on the southern side of the river are northward (Crossey and others, 2009), and flow paths on the northern side of the Grand Canyon are southward (Inkenbrandt and others, 2013). Southward flow occurs as one travels northward from the canyon, to about halfway to the Utah-Arizona border, when flow seems to cross a groundwater divide and reverse to northward flow (Inkenbrandt and others, 2013, Figure 9). Despite this suggested northward flow, which seems to be poorly documented, it seems possible that the endogenic-water springs and mounds on the northern side of the river, controlled by the Grand Wash/Gunlock, Hurricane, and Sevier/Toroweap faults, if not the Paunsaugunt/Muav fault, may be derived from groundwater from Utah.

To test the possibility of groundwater from Utah moving south along the Hurricane fault or others, we compared our water chemistry (Figure 11) with that of Crossey and others (2006, Figure 2) and Crossey and Karlstrom (2013, Figure 5). Unfortunately, no correlations are clear. This may be largely because Crossey and others (2006) did not distinguish between samples from the Hurricane and Sevier/Toroweap fault zones--the most likely faults that can carry water from the Ash Creek basin (Hurricane) or eastern Virgin River basin (Sevier/Toroweap)--that came from north of the river (southward flow) versus those from south of the river (northward flow). Their field for the Hurricane and Toroweap faults is in the lower half of the piper diamond, where almost none of the samples on our Figure 11 plot, but most of their samples might have been from south of the river, derived from the San Francisco volcanic field.

Other correlations might be made, from Utah groundwater traveling southward along the Gunlock/Grand Wash or Paunsaugunt/Muav faults, but we have little water chemistry from samples near these faults in Utah. Having said that, both of their fields in the Grand Canyon - for the Travertine Slot spring mounds that discharge from the Grand Wash fault, and the Black Tail Creek spring that discharges from the Muav fault (Crossey and others, 2006) - lie along the upper left side of their diamond and the left parts of both their triangles, which is where most of our samples plot, except for samples of Utah pre-Navajo Sandstone waters in Figure 11. Furthermore, the correlation for the Grand Wash waters with Utah waters is probably reasonable because samples collected from the western part of the central Virgin River basin (Heilweil and others, 2000; Inkenbrandt and others, 2013) plot in the same place as the Travertine

Slot samples of Crossey and others (2006). The correlation of Utah waters with Black Tail Creek waters require the assumption that Utah waters west of Kanab are the same as in the upper Virgin River basin, for no such analyses exist. Yet the assumption is not unreasonable because the Navajo Sandstone dominates in this area, as it does in the entire Virgin River basin.

It is worth noting here that LaVerkin Hot Springs (Figures 1 and 10) is made up of endogenic water, for it clearly shows deep circulation to get its heat from the geothermal gradient. It also is high in CO_2, for bubbles from orifices in the Virgin River are nearly pure CO_2 (Dutson, 2005). Also, the noble gas He has apparently been detected from the springs (Crossey and others, 2016, Figure 1). The LaVerkin field plots on a piper diagram (Figure 11) in the same fields for high-TDS Navajo samples and pre-Navajo samples from the central Virgin River basin (Heilweil and others, 2000, Figures 10 and 11) and in Group D of Inkenbrandt and others (2013). The LaVerkin field also plots in the same places as the endogenic springs of Colman and others (2014, Figure 2). But it does not plot in any of the Grand Canyon fields of Crossey and others (2006) and Crossey and Karlstrom (2013). It is also worth noting that endogenic waters are slightly acid, so fractures in the C aquifer can be expected to become larger, and therefore permeability greater, than would be expected from standard carbolic (rain water) acid. Therefore, fracture flow perhaps is much greater in this part of the Hurricane fault footwall than elsewhere in the footwall, so that here is the only place where hot springs discharge.

DISCUSSION: THE CASE FOR GREATER GROUNDWATER IN ASH CREEK BASIN

The case is strong for more groundwater in the Ash Creek drainage basin than has been modeled for. However, as with the modeled volumes of groundwater, there is little if any proof in calculating water volumes. The modeled amounts, of course, are more conservative than any case made here for additional volumes of groundwater not previously accounted for. Yet neither volume estimate can be quantified. Under this reality, if WCWCD expects to develop additional groundwater resources, whether based on the more conservative published modeled amounts or on the "greater" volumes suggested in this chapter, the only answer they can give to any doubters is by monitoring, as suggested in the chapter below on Recommendations.

From the North

Potentiometric-surface contours compiled in 1939 in southern Cedar basin showed that the groundwater divide between Cedar basin and northern Ash Creek basin was about 3.5 mi north of Kanarraville, in Sections 10 and 11, T. 37 S., R. 12 W. (Thomas and Taylor, 1946, Plate14). In contrast, the low east-west topographic lip between the two basins, seen on the Kanarraville 7.5-minute quadrangle, is about 1.5 mi north of Kanarraville, in Sections 22 and 23 (Figure 2). Therefore, as noted by Thomas and Taylor (1946, p. 106), some groundwater in the basin was moving southward out of the basin toward Kanarraville during and before 1939. Potentiometric-surface contours showed the groundwater divide to be close to the topographic divide in 1974, when groundwater issuing from Murie Creek (on the eastern part of the divide), at a fan created by the Creek, moved both northwest toward Quichapa Lake and south toward Kanarraville (Bjorklund and others, 1978, Plates 5 and 6). Although water levels fell during the growing season in 1974, they seemed to recover in the winter and early spring (Plate 5 versus 6). By March 2000, potentiometric contours showed that the groundwater divide between the two basins was about 1 mi north of Kanarraville, in Sections 26-27 (Brooks and Mason, 2005, Figure 5). At this time, the main well field for Cedar City had been operating for many years on the edge of Quichapa Lake, so a bulls-eye low of contours surrounded the well field, and pumping had moved the groundwater divide northward, toward the well field. At that time, and continuing, Cedar City has been mining its groundwater, and most well hydrographs show long-term declines in water levels in the basin (Brooks and Mason, 2005; Burden and others, 2006, 2015).

The older potentiometric-surface maps proved that, until about 1974, some groundwater from southern Cedar basin moved south into the Ash Creek basin. It is likely that this southward flow of the groundwater was by fracture flow along numerous northerly-trending basin-range faults (Rowley and others, 2006; Biek and Hayden, 2013) that underlie the entire east-trending topographic lip between the two basins. Of these, the Hurricane fault is the big one, and its main splay hugs the base of the Hurricane Cliffs at Kanarraville and trends north-northeast past the eastern side of the North Hills, then north along the eastern edge of Cedar City. A big splay of the Hurricane fault zone, however, is concealed beneath surficial sediments along the western sides of the North Hills and Cross Hollow Hills before joining the main splay of the fault zone south of the North Hills and north of the Cross Hollow Hills (Rowley and others, 2006). Between these two splays, both groups of hills are cut by additional faults that also can be considered part of a broad Hurricane fault zone. On the southwestern side of Cedar basin, a northwest-trending basin-range fault separates the basin from the Harmony Mountains and passes across the topographic lip into the Ash Creek basin. Just to the south, north-trending, down-to-the-east faults separate the Harmony Mountains from the narrow Ash Creek basin (Figure 2).

In the northern end of the Ash Creek basin, south of the topographic lip, groundwater clearly is flowing south down the steep topographic slope of the basin. It is clearly doing this along the faults mentioned above. Springs and ponds are abundant in the headwaters of Kanarra Creek just east of I-15, and high-yield production wells that supply irrigation systems are common. From Cedar City to Kanarraville, the land surface along the trace of the main splay of the Hurricane fault zone slopes southward, so it is likely that groundwater in that fault zone is also moving southward from as far north as Cedar City, where the large perennial stream Coal Creek debouches Cedar Canyon, and, farther south, where perennial Shurtz Creek debouches its canyon, both at the fault zone. Therefore, the volume of groundwater moving southward in the fault zone, from most of the eastern side of Cedar basin that contains the largest perennial streams and all in turn derived from high-precipitation areas of the Markagunt Plateau, must be large. And despite the post-1974 potentiometric-surface data, it seems possible that some of the deeper fracture flow is also moving south in the many other fault zones that continue south from Cedar basin.

From the East

Cordova and others (1972), Cordova (1978, 1981), Clyde (1987, Figure 6), Hurlow (1998), and Inkenbrandt and others (2013, p. 23) have suggested westward groundwater flow from high-precipitation areas of the Colorado Plateau (Cordova, 1981, Plate 1) across the Hurricane fault (Figures 2, 3, 5, and 6) to the Ash Creek basin. Unfortunately, virtually no potentiometric-surface data exist, so our "evidence" is simple logic based on the typical movement of groundwater from high areas (Colorado Plateau) to low areas (the I-15 lowland).

Dutson (2005) and Nelson and others (2009, Figure 8) did a study of the structure and isotopes of LaVerkin Hot Springs. They suggested that the Hot Springs received their flow from precipitation in the Kolob Terrace, some of which got into fractures in the footwall of the Hurricane fault and moved south-southwest and south along the east wall (footwall) of the fault to discharge at the hot springs. Their isotopic data support the likelihood that residence time for the groundwater must have been many years, and discharge by the springs is not influenced by local precipitation, so flow is relatively constant over the years. The discharge point in Timpoweap Canyon (Figure 10) coincides with confining units in the hanging wall there, notably the Moenkopi Formation (Nelson and others, 2009, Figure 2), that would seem to have blocked any flow there west of the fault and instead forced it to discharge from fractures east of the fault. Elsewhere along the Hurricane fault, westward flow does not appear to have been blocked by the fault or downthrown confining units in the hanging wall.

From the West

The Pine Valley Mountains climb to more than 10,000 ft elevation (Figures 3 and 7), the highest range in southern Utah and a wilderness area, with precipitation contours of as much as 30 inches per year (Heilweil and others, 2000, Figure 2). Not only do the three perennial tributaries discussed above drain this high area, but major aquifers define the top and eastern flanks of the range. These aquifers are the Pine Valley laccolith/Pine Valley Latite on the top and high flanks and the Navajo Sandstone (see Figure 2 of Heilweil and others, 2000) on the middle part of the eastern flank at the 14-16 inch precipitation contours. Even the 2000-3000 ft thick Cretaceous Iron Springs Formation, which in the Iron Springs mining district is a confining unit because of its shale and siltstone, is a major aquifer on the western flank of the Pine Valley Mountains (Rowley, 2007) and probably also on the eastern flank. In fact, the presence of these permeable aquifer rocks exposed at the surface lessens the runoff that would have taken place if the range were underlain by confining units. Therefore, the three perennial streams appear smaller than one would expect from draining such a large high area.

Largely unrecognized in all hydrologic and geologic studies previous to ours is the extent to which the Pine Valley Mountains is a typical basin-range horst, uplifted by large normal faults on both its eastern and western sides. Even our summary geologic map of the St. George 1:100,000-scale quadrangle (Biek and others, 2009) did not adequately show the number of basin-range faults that clearly exist in the southern part of the eastern flank, such as in and south of the Leeds area. The detailed 1:24,000-scale geologic quadrangles that were used as the basis for the St. George quadrangle also missed many of these faults. Yet north-trending fault scarps can clearly be seen on topographic maps within rocks mapped as the Navajo Sandstone, especially in the shaded-relief topographic base of the St. George 1:100,000 geologic quadrangle (Biek and others, 2009), and on Google Earth images. The old 1:250,000-scale geologic map (Hintze, 1963) did a better job than the more recent and more detailed geologic maps. And Montgomery (2000) also recognized the faults. Therefore, we show some of the lineaments visible on Google Earth and we extend faults, named the Water Canyon fault, southward to the Washington fault on Figure 8.

The significance of a heavily faulted eastern flank to the Pine Valley Mountains is that fractures (secondary permeability) increase the overall permeability greatly, as noted from our study of the Sand Hollow area (Rowley and others, 2004). In the Pine Valley Mountains, the Pine Valley laccolith and Pine Valley Latite are extremely brittle rocks that fracture readily when faulted. Yields on wells drilled on the downthrown sides of faults in this rock type on the western side of the New Harmony basin, extending from New Harmony to the Sawyer Spring area, have initial-test yields of as much as 2000 to 3500 gpm (Rowley and others, 2012). These same faults that supply these big wells in the Sawyer Spring area continue south along the eastern part of the Pine Valley Mountains. Therefore, virtually the entire eastern flank of the Pine Valley Mountains is a faulted aquifer that is providing groundwater that must flow eastward from the high range into the low Ash Creek basin. Because of a lack of wells in the wilderness and forest service lands of the area, no potentiometric surface has been constructed across this eastern flank. Yet clearly the greatest recharge to the basin, most of it unrecognized and unquantified, is from the west. Tritium values indicate modern or near-modern water in all perennial streams and springs (except LaVerkin Springs) in Ash Creek basin, as well as in shallow groundwater from wells there. Such a wide extent of modern water is best interpreted to indicate high recharge to the basin.

In Storage Within the Basin Itself

The Ash Creek basin is a complex graben that consists mostly of highly faulted pieces of aquifers, notably the Navajo Sandstone, Pine Valley laccolith/Pine Valley Latite, basin-fill sediments, and basalt flows and interbedded basin-fill sediments. Other aquifer units of lesser volume include the Shinarump Member of the Chinle Formation, the Springdale Sandstone Member of the Kayenta Formation, some sandstone beds in the upper part of the Kayenta Formation, and probably many sandstone beds in the Iron Springs Formation. Yet the many faults brecciate both aquifers and confining units, turning almost all rocks into aquifers. The simplified geologic map of the basin shown by previous workers, consisting of the Navajo Sandstone and Kayenta Formation wrapping around the northern nose of the Virgin anticline (e.g., Heilweil and others, 2000, Figure 6), was necessary for groundwater models (compare with their more realistic Plate 1) but is hardly a good thought picture of the geology.

The thickness (depth) of the basin-fill sediments deposited in New Harmony basin is unknown. The best attempt to understand the thickness of these sediments is the report by Hurlow (1998, Plate 2-3, p. 9-11), who bravely constructed 9 geologic cross sections oriented perpendicular to the trend of the basin and then discussed some of the results. He considered the basin fill beneath Kanarraville and New Harmony basin to be at least 2600 ft and 1500 ft thick (his cross sections showed still greater thicknesses), respectively. Yet no wells penetrate more than a few hundred feet into these two subbasins, nor into any other parts of the graben to the south and west of the Hurricane fault. Elsewhere, gravity surveys are commonly useful for estimating thicknesses of basin fill (e.g., Mankinen and McKee, 2009; Mankinen and others, 2016). Unfortunately, neither the gravity maps of Blank and Kucks (1989, Plate 2) or Inkenbrandt and others (2013, Figures 21 and 23) in the Ash Creek basin are of much help for this purpose. This probably has to do with the abundance of basalts and Jurassic and older sedimentary rocks (high density) in the basin and perhaps with an inadequate detail in the gravity surveys.

Hurlow's (1998) cross sections south of Ash Creek Reservoir show basin fill plus interbedded basalts to be locally more than 1000 ft thick, but information apparently is not sufficient to allow any text discussion. Most of his cross sections show at least 1000 ft of the Pine Valley laccolith/Pine Valley Latite aquifer in the hanging wall beneath basin fill, but no well or other information can confirm this interpretation. In places the Navajo Sandstone is shown beneath the basin fill but, like the Pine Valley igneous rocks, we cannot predict thicknesses of eroded fault blocks because the internal stratigraphy of these thick aquifers does not exist. Clearly, nearly all rocks beneath the surface in the I-15 corridor are aquifers. Therefore, the amount of groundwater in storage must be high.

As a general impression, water tables in wells in the Ash Creek basin are relatively shallow and yields on water wells in the Ash Creek basin seems to be high (compare these factors in Table 1 of Wilkowske and others, 1998). Of these two parameters, yields are not always given, are out of date, or depend on the amount allowed by the water right or the diameter of the well, so this impression cannot be demonstrated by data. Regarding water levels, an average of those presented in Table 1of Wilkowske and others (1998) from the Ash Creek basin gives a depth to the water table of 87 ft, and those depths in the area south of the Ash Creek basin (south of the Virgin River, west of Volcano Mountain, and east of Harrisburg dome) are virtually identical. Yet no recharge area exists for the area south of the Virgin River. Therefore this area can be considered part of the Ash Creek basin north of the Virgin River because recharge is from the Ash Creek basin. From Table 1 of Wilkowske and others (1998), we calculated an average depth to the water table from elsewhere in the central Virgin River basin at 177 ft. In summary, groundwater levels and therefore volumes in the Ash Creek basin are high.

CLIMATE CHANGE

Few people who go out of doors doubt that climate change is real, with the most notable observational evidence that any person can easily make being the gradual, but at times abrupt, rise in temperature from one year to the next. There are other effects besides temperature increase, of course. This report, however, is not the place to go into the literature on climate change, although scientific reports that provide the evidence and make predictions on future changes are voluminous. The Ash Creek drainage basin is no different from the rest of the world, and it would seem that in addition to temperature increases here, there will be corresponding decreases in the volume of surface water and groundwater. But so far the evidence for this is slim. Part of the reason is the current lack of monitoring of both types of water resources. In fact, even long-term precipitation and temperature monitoring stations are few and they seem to be decreasing in number, if anything. Another part of assessing the effects of climate change is how to separate any decrease in water resources from the greater use of water from the rapidly growing population in Washington County. And a final reason why the evidence for a decrease is that groundwater volumes in Ash Creek basin are high and have yet to show a significant fall.

Carole Burden and other hydrologists at the USGS each year publish an inventory of groundwater conditions in Utah (e.g., Burden and others, 2006, 2015). Although each of 20 groundwater basins gets as little as a half dozen pages of review and many other smaller basins get much less attention, at least the annual reports provide a snapshot--based on incomplete data--of groundwater. Our basin of interest is called the central Virgin River area, which includes the same area covered by Cordova and others (1972), namely the Ash Creek basin and the Santa Clara River basin, as well as other tributaries and the main stem of the Virgin River in Utah west of the Hurricane fault. In the central Virgin River area, only 16 wells are monitored by the USGS, and 11 of these have hydrographs published each year in the reports. Most of these monitoring and hydrograph wells are along the Virgin and Santa Clara Rivers. Only 4 monitoring wells (2 hydrograph wells, neither showing long-term declines in water levels) are in the Ash Creek drainage basin. The annual reports contain a table (e.g., Burden and others, 2015, Table 3) that provides estimates of water withdrawal from wells each year and, as expected, volume of groundwater withdrawn is in general going up. In the latest report, that volume is 43 cfs (31,000 afy) for 2014, with only three other past years having equal or greater withdrawals (32,000 afy in 2006, 33,000 in 2007, and 33,000 in 2009). In comparison, the total (upper Ash Creek basin added to the main and Gunlock parts of the Navajo/Kayenta aquifer) well withdrawals in 1998 (Heilweil and others, 2000, Tables 17, 22, 25) under their conceptual model was 16.4-24.7 cfs (11,800 to 17,900 afy) and under their digital model was 21.9 cfs (15,840 afy cfs).

Fortunately for WCWCD, the Ash Creek drainage basin does not have the spectacularly falling water tables (overdrafting of its groundwater) of the Beryl-Enterprise area, Cedar Valley, Milford area, or Parowan Valley. The only falling water tables in the central Virgin River area, according to the latest report (Burden and others, 2015), are between Ivins and Washington, with none shown in the Ash Creek basin. Does that mean that the Ash Creek basin is in equilibrium in its water budget (steady state)? We think that is probably the case, based on our speculations about water resources given elsewhere, but we can certainly not provide any positive evidence for that.

CONCLUSIONS

At first approximation, the Ash Creek drainage basin is a small basin whose limited surface water now is mostly appropriated and decreasing as supplies are increasingly being diverted to agriculture and culinary use. Many other basins in Utah, even those that contain only modest cities and towns and are far larger than that of Ash Creek, are over appropriated. Water levels in these basins are decreasing already, with few solutions in sight for water districts, and with looming problems that can be expected from rising populations and climate change, whose effects are clearly accelerating. Yet the picture of relatively limited surface water in the Ash Creek basin is deceiving, for groundwater resources in Ash Creek basin, in the opinion of the authors, are likely large and of high quality.

We find that the volume of groundwater in the Ash Creek basin is substantially more than has been estimated in the past. First of all, the amount of groundwater coming out of Cedar Valley to the north along the Hurricane fault into the Ash Creek basin has not been previously recognized. Furthermore, the amount of groundwater coming out of the Colorado Plateau highland to the east also has been much underestimated (if it has been estimated at all) because Paleozoic aquifers east of the fault are in contact with basin-fill sediments, Miocene igneous aquifers, and the Navajo Sandstone west of the fault. And more importantly, the amount of groundwater coming out of the high Pine Valley Mountains, made up of the highly faulted and fractured Miocene igneous aquifer, is much greater than has been estimated. Finally, highly faulted major aquifers underlie the axis of the basin so they contain large volumes in storage. These aquifers beneath the surface are huge because, to begin with, they had high primary permeability but, due to the faults, secondary permeability has compounded the storage. Therefore, considering the high precipitation values from adjacent highlands, a rapid and large contribution from fracture flow into and within the basin, the huge volume of aquifer rocks beneath the basin, the high water levels and well yields despite the steep southward hydraulic gradient, the near-universal presence of modern (high recharge) water throughout the basin, and the limited population and agricultural draws on the groundwater, we consider that the Ash Creek basin has groundwater resources that are several times greater than any previously estimated. Some of these groundwater volumes are likely continuing southward at depth into Arizona.

The stream water that seeps out through the floor of Ash Creek Reservoir is probably not recharging any local down-gradient springs, streams, or groundwater; instead it probably enters the adjacent Hurricane fault and moves southward beneath the Virgin River, and on to Arizona. If so, more stream water could be diverted from the reservoir without affecting the Ash Creek ecosystem. On the other hand, some of the stream water from Leap Creek, South Ash Creek, and Wet Sandy that seeps into the ground below their current diversions likely recharges Toquerville Springs and Ash Creek Spring as well as the local groundwater.

Water-quality data, as plotted on piper diagrams, indicate the following: (1) the highest quality water is on the western side of the Ash Creek basin, where recharge is by far the greatest; (2) wells on faults not only have higher yields but have higher quality water because fracture flow is rapid and residence times correspondingly shorter; (3) water quality is greater in shallower (higher water table) wells; (4) water quality is greater in wells in younger rocks, especially the Pine Valley laccolith/Pine Valley Latite; and (5) water quality is worse in wells in pre-Navajo Jurassic and Triassic rocks. Water chemistry, as given in piper diagrams, also suggests that, prior to construction of the Sand Hollow Reservoir, that the source of the water in wells in that area was the Ash Creek basin north of the Virgin River. Water chemistry is lacking for rocks of the C aquifer (Permian) and R aquifer (Mississippian and Devonian) because these aquifers have not been developed but likely could for "new" (unappropriated) groundwater.

Deep wells searching for oil have discovered something more important: fresh-water groundwater resources at depth. Furthermore, these wells--most of which penetrated the footwall of the Hurricane fault-- revealed that the groundwater is in the C aquifer and R aquifer, which have not been tested or appropriated in southwestern Utah. The shallowest places that these aquifers can be reached by drilling water wells, as with the oil wells, is in the footwall of the Hurricane fault. The footwall is best accessed by drilling in the hanging wall near the trace of the dipping fault. Inasmuch as this groundwater has not been appropriated or tested, standard rules that prevent authorization of additional water rights in this part of Utah may not apply. WCWCD is urged to investigate, then secure such water rights for deep water. If successful in the Hurricane fault, drilling several anticlines in the Ash Creek basin should follow.

A new north-northeast-trending fault zone, here appropriately called the Water Canyon fault zone, was discovered high along the eastern flank of the Pine Valley Mountains. In fact, it is partly responsible for the uplift of these mountains as a basin range during basin-range tectonism that created the present topography. Most of the trace of this fault zone is in the Navajo Sandstone. Secondary (fault-derived) permeability allows yields on water wells to be an order of magnitude better than in unfaulted Navajo Sandstone. The presence of the faulted Navajo not only here but at many other places along the axis of the Ash Creek basin suggests high yield wells if water rights can be purchased. Artifical-recharge reservoirs, with adjacent well fields, that sit astride Navajo Sandstone are a particularly effective way to develop groundwater resources.

The high southward topographic slope of Ash Creek basin and the many faults beneath the basin that are generally parallel to the Hurricane fault, allow rapid southward flow of large amounts of groundwater. Rapid flow decreases residence times, so water quality is good along the faults. Only about 10 cfs gets into the Virgin River, at least in November. Other groundwater must pass beneath the Virgin River. Some of it is moving at moderate depth along the footwall and hanging wall of the Hurricane fault. Other groundwater is moving along parallel but smaller faults and fractures west of the Hurricane fault. This groundwater recharges the Navajo Sandstone south of the river, although in the Sand Hollow area, the reservoir itself now does that job. The Navajo Sandstone does not continue south of Sand Mountain, so the older pre-Navajo aquifers, including the C and R aquifers, that are accessed by the smaller faults, are recharged farther south. Does some groundwater in the Hurricane or Grand Wash faults get to the Grand Canyon? We suspect so but the evidence is not conclusive.

RECOMMENDATIONS

(1) Considering the large size of the Ash Creek basin groundwater resource, other artificial-recharge reservoirs in the I-15 corridor should be considered, such as the Toquer Reservoir currently being proposed by WCWCD. Artificial recharge is an excellent way to develop an extraordinary aquifer such as the Navajo Sandstone, especially using off-stream reservoirs. Because we conclude that the Ash Creek basin is such an important resource for the future, WCWCD should consider buying water rights and wells as they become available and as funding allows, under a yearly philosophy of searching for and securing good, high-yield wells that could serve WCWCD's municipal customers. The wells that would be best in terms of yields and water quality would be along faults on the western side of the basin, closest to what is by far the largest and best-quality recharge area.

(2) Montgomery (1999) and Inkenbrandt and others (2013) have made a substantial part of their reports the recommendation that "new" unappropriated groundwater be developed in Washington County. We agree and therefore urge that the two highest-priority wells recommended by Inkenbrandt and others be drilled as they proposed, the second one depending upon the success of the first. These two will also test the concept of fracture flow in the Hurricane fault, possibly heading toward the Grand Canyon. If these are successful, the same deep groundwater could be sought in over a dozen other places along the Hurricane fault in Washington County. The third-priority well of Inkenbrandt and others (2013), to test the Virgin anticline, will indicate whether drilling to the C and R aquifers in areas other than the Hurricane fault is feasible not only here but in other parts of Washington County.

(3) Almost any predictions - including those given in this report - about volumes of available future groundwater would hardly get consensus from even the most positive experts. Some experts, in fact, would consider most such predictions to be gross speculation. And others, whether experts or non-expert citizens, may belong to groups that are inclined to reject any such predictions for environmental or political reasons. Groundwater resources cannot be proved, and any predictions--especially if they advocate development of a water resource--will be called "opinion only" by most persons. WCWCD's only response to skepticism is to put greater effort into monitoring groundwater resources by use of monitoring wells and perhaps stream gages, with a promise of (1) transparency and honesty, and (2) an

agreement to decrease withdrawal when or if water levels show a significant (multiyear) decrease. Currently the USGS maintains a tiny monitoring network in the basin of only 4 wells, only two of which have long-term records (Burden and others, 2015). That is not sufficient if WCWCD wants to develop more water resources in the basin.

(4) Ash Creek below (south of) Toquerville Springs, which formerly was perennial, now has been diverted to such an extent that little flow remains. Presumably native fish could once find their way as far up the channel as the springs, but currently we have virtually no knowledge of how much water, or at what time of year, is in this reach, let alone how many fish are there. No stream gages currently exist in the reach. Compounding the problem is the fact that most of this reach has been suburbanized, and some adjacent homeowners doubtless use some of the stream water even though they have no water right. It would seem logical to put at least one stream gage in the reach, one of which should be just upstream of the confluence of Ash Creek with the Virgin River.

(5) The USGS has a pricing policy for outside funding (perhaps due to being always underfunded and understaffed by Congress) that is extremely high. Therefore, we have previously recommended that WCWCD contract work by the Utah Geological Survey (UGS), which gives reports and other products of comparable quality at half or a third of the price. The UGS could be hired to do your monitoring.

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