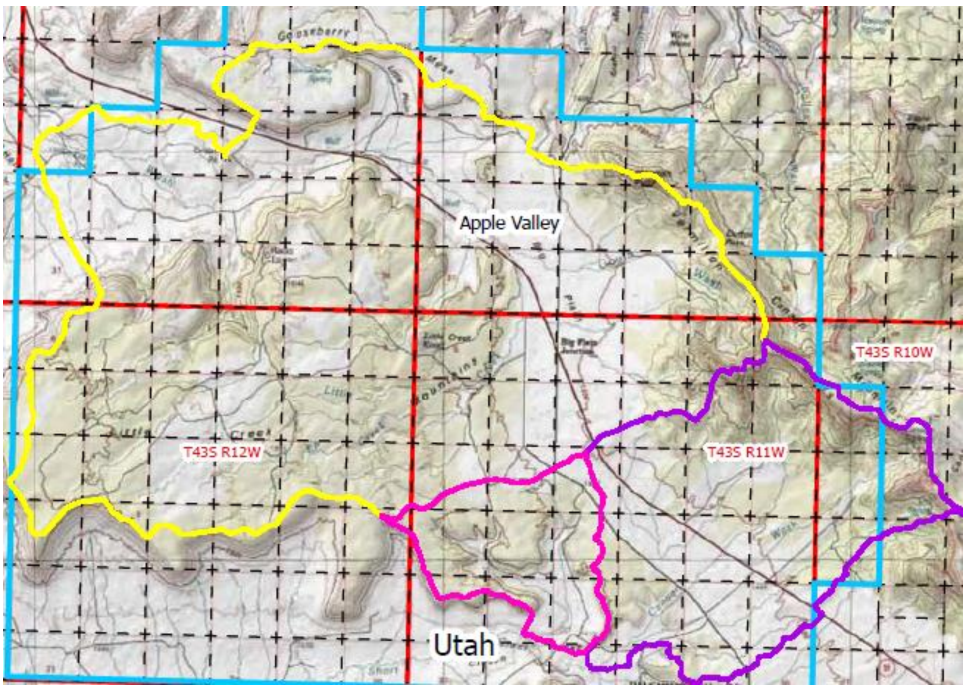
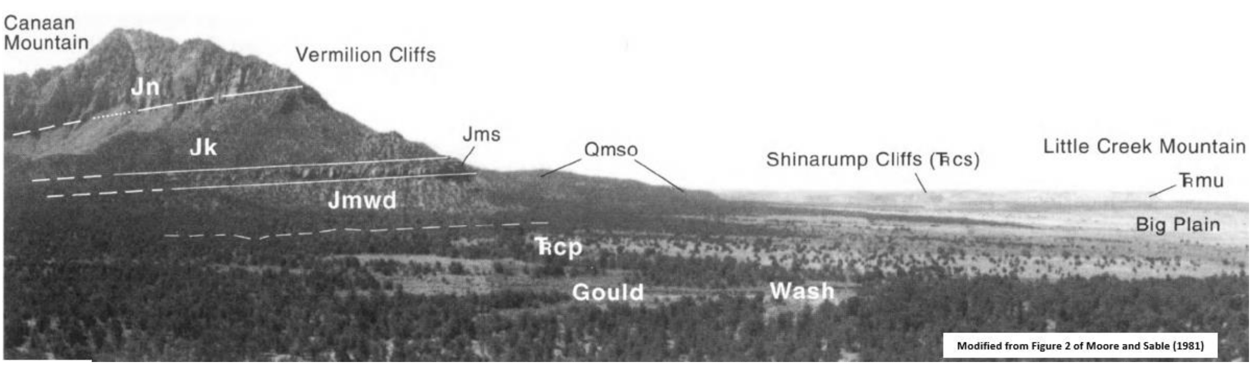
ASSESSMENT OF SUSTAINABLE YIELD
FOR
APPLE VALLEY AREA
FOR
WASHINGTON COUNTY
WATER CONSERVANCY DISTRICT
WASHINGTON COUNTY, UTAH





Prepared by:
Loughlin Water Associates, LLC
3100 Pinebrook Rd, Ste. 1100
Park City, UT 84098
(435) 649-4005

LOUGHLIN WATER ASSOCIATES LLC

Prepared for:
Washington Co. Water Conservancy Dist.
Attn: Mr. Corey Cram
Associated General Manager
533 E. Waterworks Dr.
St. George, Utah 84770

January 2023

LOUGHLIN
WATER ASSOCIATES LLC

January 14, 2023

Washington County Water Conservancy District
Attn: Mr. Corey Cram
533 E. Waterworks Dr.
St. George, UT 84770

Subject: **Transmittal – Assessment of Sustainable Yield**
Apple Valley Area, Washington County, Utah
For Washington County Water Conservancy District

Dear Corey:

Please find enclosed our assessment of sustainable yield of the Apple Valley area of Washington County, Utah for the Washington County Water Conservancy District (the Water District) dated January 14, 2023. We conducted our assessment in accordance with the Agreement between the Water District and Loughlin Water Associates, LLC (Loughlin Water) dated August 16, 2022.

If you have any questions or need more information, please do not hesitate to call me at (435) 649-4005 (office).

Loughlin Water Associates, LLC

William D. Loughlin, P.G.
Manager, Principal Hydrogeologist

Enclosure: Assessment of Sustainable Yield for Apple Valley Area

Cc: Zach Renstrom, General Manager – Washington Co. Water Conservancy District

ASSESSMENT OF SUSTAINABLE YIELD
FOR
APPLE VALLEY AREA
FOR
WASHINGTON COUNTY WATER CONSERVANCY DISTRICT
WASHINGTON COUNTY, UTAH

Prepared for:

Washington County Water Conservancy District
Attn: Corey Cram
Associate General Manager
533 E. Waterworks Dr.
St. George, Utah 84770

Prepared by:

William D. Loughlin, P.G.
Manager, Principal Hydrogeologist

LICENSED PROFESSIONAL GEOLOGIST
WILLIAM D. LOUGHLIN
5205683-2250
01.14.2023
STATE OF UTAH

Loughlin Water Associates, LLC
3100 Pinebrook Road, Suite 1100
Park City, Utah 84098
(435) 649-4005
www.LoughlinWater.com

Date: January 14, 2023

TABLE OF CONTENTS

TABLES

FIGURES

1.0 INTRODUCTION

Apple Valley (the study area) lies along and on both sides of the southeast-to-northwest trending Utah Highway 59, between the communities of Hurricane and Hildale, Utah. The study area includes almost all of Township 43 South, Ranges 12 and 11 West and portions of Township 42 South, Ranges 11 and 12 West, Salt Lake Base & Meridian (SLB&M). Figure 1 is a regional map and Figure 2 is a local map that show the study area. The Town of Apple Valley is the only incorporated community in the study area.

Water supply in Apple Valley is almost entirely from groundwater via wells and springs. Big Plains Special Service District (Big Plains) and the Little Creek Travel Center (Little Creek) are the only active Utah Division of Drinking Water (DDW) Public Water Systems (PWSs). Big Plains includes the Apple Valley, Canaan Springs (Canaan Ranch), and Cedar Point PWSs. Little Creek supplies two convenience stores. Areas not supplied by Big Plains or Little Creek obtain water mostly from individual wells. The Water District does not supply water to the Apple Valley area.

During 2015, Ensign Engineering (Ensign) conducted a study for Big Plains to (1) determine the status of the aquifer(s), (2) estimate recharge to and discharge from the aquifers, and (3) assess the feasibility of drilling new wells. Ensign (2015):

- Estimated total recharge in the study area to be 10,334 acre-feet per year (afy) and total discharge to be 10,651 afy which indicates a potential overdraft (discharge exceeding recharge) of 317 afy.
- Cautioned that there is uncertainty in their estimates of recharge and discharge.
- Concluded that "…*developing sustainable wells in Apple Valley is going to be very difficult because of the stress already on the aquifer."*

We understand that:

- Appropriated water rights have exceeded groundwater supplies causing groundwater levels to fall in other parts of Washington County.
- There has been and continues to be considerable growth along with the issuing of new water connections and permits to drill new wells in the Apple Valley area.
- The Water District seeks to assess and estimate the sustainable yield of groundwater supplies for comparison with current and estimated future water demand in the Apple Valley area.

2.0 OBJECTIVE AND APPROACH

To assess and estimate the sustainable yield of groundwater supplies for comparison with current and estimated future water demand in the Apple Valley area, we:

- Compiled and assessed publicly available geologic, hydrogeologic, water quality, and water right information;
- Evaluated data and reports provided by the Water District;
- Modified existing geologic cross sections;
- Estimated the potential recharge to area aquifers; and
- Prepared this report to summarize our findings, including our estimate of sustainable yield and provide our recommendations for follow-on aquifer analysis.

Utah Code, Title 73, Water and Irrigation (Utah Water Law), Section 73-5-15, defines *Safe Yield* as "*…the amount of groundwater that can be withdrawn from a groundwater basin over a period of time without exceeding the long-term recharge of the basin or unreasonably affecting the basin's physical and chemical integrity*." Although Utah Water Law does not define *Sustainable Yield*, *The Glossary of Terms* provided by the Utah Division of Water Rights (DWRi), also known as (aka) the *Utah State Engineer* states "*See Safe Yield*" for the definition of *Sustainable Yield*; see https://www.waterrights.utah.gov/wrinfo/glossary.asp.

Determination of the amount of groundwater that can be withdrawn without unreasonably affecting the physical and chemical integrity of the basin would require a numerical model and considerably more data than are available for the Apple Valley area. As such, for the purpose of this assessment, we define:

- Sustainable Yield as the amount of groundwater that can be withdrawn from the three principal aquifers of Apple Valley on an annual basis without exceeding the long-term recharge and

- The three principal aquifers as the unconsolidated (basin or valley fill) deposits, the basalt flows, and the Shinarump Conglomerate.

3.0 HYDROGEOLOGIC SETTING

The study area lies at the west end of Colorado Plateau physiographic province. The Hurricane Cliffs, located to the west, coincides with the Hurricane fault, which marks the transition between the generally gently dipping (tilting) geologic formations of Colorado Plateau and the complexly folded and faulted geologic units of the Basin and Range physiographic province (Heilweil and others, 2000). The Colorado Plateau has relatively high elevations, and deeply incised drainages.

The study area is at the north end of the Uinkaret plateau which is within the Grand Staircase portion of the Colorado Plateau. Rock layers within the Grand Staircase are relatively consistent in thickness and extent and dip gently (less than 10 degrees) to the north. The Grand Staircase consists of a step-like sequence of resistant layers that form escarpments (cliffs) and less resistant layers (shale and mudstones) that form valleys.

Local physiographic features within the Apple Valley study area include the Big Plain and Little Plain bajadas, Little Creek Mountain, Gooseberry Mesa, Smithsonian Butte, the Vermillion Cliffs, and Canaan Mountain; see Figure 2. Bates and Jackson (1987) define a bajada as "*A broad continuous alluvial slope or gently inclined detrital surface extending from the base of mountain ranges out into and around an inland basin, formed by the lateral coalescence of a series of separate but confluent alluvial fans, and having an undulating character due to the convexities of the component fans…*"

Elevations rise from about 4800 feet in Big and Little Plain to 5700 feet in the Little Creek and Gooseberry Mountains and as high as 6600 feet on Smithsonian Butte and 7299 feet on Canaan Mountain (Rowley, 2003).

Gould Wash drains the western and northern two thirds and Canaan Wash and an unnamed wash drain the southern and eastern third of the study area. Gould Wash, Canaan Wash, and the unnamed wash are ephemeral drainages within the study area. Canaan Wash and the unnamed wash are tributaries of Short Creek. Gould Wash flows generally to the northwest and joins the Virgin River to the south and west of Hurricane. Gould Wash drains about 60 square miles of the study area. Short Creek flows south into Arizona where it joins Fort Pearce Wash, which flows west and north back into Utah and St. George where it joins the Virgin River. Short Creek (Canaan Wash and the unnamed wash) drains about 23 square miles of the study area.

3.1 GEOLOGY

Moore and Sable (2001), Willis and others (2002), Hayden (2004), and Hayden and Sable (2008) mapped the geology of the Smithsonian Butte, Springdale West, Little Creek Mountain, and Virgin 7.5-minute U.S. Geological Survey (USGS) quadrangle maps, respectively at a scale of 1:24,000. Each of these four 7.5-minute quadrangle maps cover a portion of the study area. The entire study area lies within the St. George 30x60-minute quadrangle, 1:100,000-scale, geologic map of Biek and others (2009). Billingsley and Workman (2000) mapped the Littlefield 30x60-minute quadrangle at a scale of 1:100,000 which covers the area to the south in Arizona.

We modified Figure 3 from the geologic map of Biek and others (2009) and Billingsley and Workman (2000) to illustrate the geology of the study area. Table 1 lists and provides keys and descriptions of the geologic units shown on Figure 3.

TABLE 1
DESCRIPTIONS OF GEOLOGIC UNITS [a]

Formation Name	Geologic Age	Thickness (feet)	Description
Stream Alluvium (Qa,)	Holocene	<100 [b]	Stratified, moderately to well-sorted gravel, sand, silt, and minor clay deposited in river and stream channels and flood plains; includes local small alluvial-fan and colluvial deposits, stream-terrace deposits
Fan Alluvium ($Qaf_{1,2}$, Qafo)	Holocene to Pleistocene	10 to 50	Poorly to moderately sorted, non-stratified, subangular to subrounded, boulder to clay-size sediment deposited at the mouth of streams and washes.
Eolian Sand (Qes, Qeo)	Holocene to upper Pleistocene	<20	Well sorted, fine- to medium-grained, well-rounded, frosted quartz sand; sand is recycled principally from the Navajo Sandstone and Kayenta Formation; locally forms small dunes partly stabilized by vegetation.
Alluvial and Eolian Deposits (Qae)	Holocene to upper Pleistocene	<20	Moderately sorted gravel, sand, and silt deposited in small channels and on alluvial flats, and well-sorted, fine- to medium-grained, reddish-brown eolian sand locally reworked by alluvial processes.
Alluvial and colluvial deposits (Qac, Qaco)	Holocene to upper Pleistocene	<30	Poorly to moderately sorted, generally poorly stratified, clay- to boulder-size, locally derived sediment deposited principally in swales, small drainages, and the upper reaches of large streams by fluvial, slope-wash, and creep processes; gradational with both alluvial and colluvial deposits.
Talus (Qmt)	Holocene to upper Pleistocene	<30	Poorly sorted, angular boulders and finer-grained interstitial sediment deposited principally by rock fall on and at the base of steep slopes; typically grades downslope into colluvial deposits and may include colluvial deposits.
Landslide Deposits (Qms)	Holocene to middle Pleistocene	0 to 100	Poorly sorted, clay- to boulder-size, locally derived material deposited by rotational and translational landslide movement; characterized by hummocky topography and small ponds, numerous internal scarps, and chaotic bedding attitudes.
Little Creek Cinder Cone (Qblcc) and Lava Flow (Qblc)	Middle Pleistocene	15 to 40	Medium-gray, fine-grained basalt to trachybasalt (Qblc) with sparse olivine phenocrysts; erupted from a vent at Gray Knoll cinder cone (Qblcc) and from a series of northwest-trending vents marked by spatter cones on top of Little Creek Mountain.
Gould Wash Cinder Cones (Qbgwc) and Lava Flow (Qbgw)	Middle Pleistocene	20 to 30	Dark-gray, fine-grained basalt (Qbgw) with abundant olivine phenocrysts; erupted from vents at two cinder cones (Qbgwc).
Crater Hill lava Flow (Qbc) and Cinder Cone (Qbcc)	Middle Pleistocene	40 to 80	Medium-gray basalt to trachybasalt (Qbc) with small olivine phenocrysts; erupted from a vent at Crater Hill, which is a large cinder cone (Qbcc) east of Virgin.

Formation Name	Geologic Age	Thickness (feet)	Description
Navajo Sandstone (Jn)	Lower Jurassic	1350	Pale-reddish-orange, reddish-brown, or white, cliff-forming, cross-bedded, quartz sandstone; forms spectacular sheer cliffs, deep canyons, and impressive spires, promontories, and monoliths; consists of well sorted, well-rounded, fine to medium-grained, frosted quartz sand; bedding consists of high-angle, large-scale cross-bedding; locally prominently jointed.
Kayenta Formation (Jk)	Lower Jurassic	550 to 700	Moderate- to dark-reddish-brown, thin- to thick-bedded siltstone, fine-grained sandstone, and mudstone with planar, low-angle, and ripple cross-stratification; contains several thin, light-olive-gray-weathering, light-gray dolomite beds in the lower third of the formation above the Springdale Sandstone; forms steep ledgy slope grading up to ledgy cliffs at top.
Kayenta Formation: Springdale Sandstone Member (Jks)	Lower Jurassic	90 to 150	Medium- to thick-bedded, fine- to medium-grained sandstone with planar and low-angle cross-stratification, and minor, thin, discontinuous lenses of intraformational conglomerate and thin interbeds of moderate-reddish-brown or greenish-gray mudstone and siltstone; contains locally abundant petrified and carbonized fossil plants; forms conspicuous cliffs.
Moenave Formation (JTRm)	Lower Jurassic to Upper Triassic	300 to 340	Consists of two undivided members: Whitmore Point Member and the Dinosaur Canyon Member. The Whitmore Point Member (Lower Jurassic) consists of pale-red-purple, greenish-gray, and blackish-red mudstone and claystone, lesser moderate-reddish-brown, fine-grained sandstone and siltstone, and uncommon dark-yellowish-orange micaceous siltstone. The Dinosaur Canyon Member (Lower Jurassic to Upper Triassic) consists of generally thin-bedded, moderate-reddish-brown and moderate-reddish-orange, fine-grained sandstone, fine-grained silty sandstone, and lesser siltstone and mudstone with planar, low-angle, and ripple cross-stratification.
Chinle Formation: Petrified Forest Member (TRcp)	Upper Triassic	400 to 650	Varicolored, typically gray to purple mudstone, claystone, and siltstone, lesser white to yellow-brown sandstone and pebbly sandstone, and minor chert and nodular limestone; regionally divisible into three parts, in ascending order: (1) the bentonitic Blue Mesa, (2) the pebbly sandstone of the Moss Back or Sonsela (depending on clast provenance), and (3) the bentonitic Painted Desert.
Chinle Formation: Shinarump Conglomerate Member (TRcs)	Upper Triassic	75 to 175	Medium- to coarse-grained sandstone, pebbly sandstone, and lesser pebbly conglomerate, locally with silty sandstone, claystone, and smectite claystone interbeds, that forms prominent cliffs, hogbacks, and mesas; clasts are subrounded chert and quartzite; mostly thick bedded with both planar and low-angle cross-stratification.

Formation Name	Geologic Age	Thickness (feet)	Description
Moenkopi Formation: Upper Red Member (TRmu)	Lower Triassic	200 to 280	Moderate-reddish-orange to moderate-reddish-brown, mostly thin- to medium-bedded siltstone, mudstone, and fine-grained sandstone with planar, low-angle, and ripple cross-stratification; locally contains thin gypsum beds and abundant discordant gypsum stringers and typically forms ledgy slopes.
Moenkopi Formation: Shnabkaib Member (TRms)	Lower Triassic	350 to 500	Forms "*bacon-striped*," ledgy slopes of laminated to thin-bedded, gypsiferous, pale red to moderate-reddish-brown mudstone and siltstone, resistant, white to greenish-gray gypsum, and minor thin, laminated, light-gray dolomite beds; gypsum is present.
Moenkopi Formation: Middle Red Member (TRmm)	Lower Triassic	450 to 550	Interbedded, slope-forming, laminated to thin-bedded, moderate-reddish-brown to moderate-reddish-orange siltstone, mudstone, and fine-grained sandstone with thin interbeds and veinlets of greenish gray to white gypsum; lower part includes several thick gypsum beds.
Moenkopi Formation: Virgin Limestone Member (TRmv)	Lower Triassic	250	Light-gray, light-olive-gray, and yellowish-brown limestone and silty limestone that typically forms three thin, resistant ledges at the base, middle, and top of the member.
Moenkopi Formation: Lower Red Member (TRml)	Lower Triassic	300	Interbedded, slope-forming, laminated to thin-bedded, moderate-reddish-brown mudstone, siltstone, and fine-grained sandstone with local, thin, laminated, light-olive-gray gypsum beds and veinlets.
Moenkopi Formation: Timpoweap Member (TRmt)	Lower Triassic	50 to 180	Lower part consists of light-brown-weathering, light gray to grayish orange, thin- to thick-bedded limestone, and cherty limestone; chert occurs as small, disseminated blebs, thus giving weathered surfaces a rough texture; upper part consists of grayish-orange, thin- to thick-bedded, slightly calcareous, fine-grained sandstone, siltstone, and mudstone.
Kaibab Formation: Harrisburg Member (Pkh)	Lower Permian	350	Thin- to thick-bedded limestone and cherty limestone, and medium- to thick-bedded, laminated gypsum and gypsiferous mudstone.

[a] Descriptions and thicknesses are modified principally from Biek and others (2009) with local variations from Moore and Sable (2001), Willis and others (2002), Hayden (2004), and Hayden and Sable (2008).
[b] Cordova (1981) reports that the unconsolidated deposit aquifer in the study area is 100 to 300 feet thick which is considerably thicker than the less than 100 feet reported by Moore and Sable (2001) and Biek and others (2009).

The Big Plain and Little Plain bajadas consist of coalesced alluvial fans that extend southward from the Vermillion Cliffs and northward from the Little Creek Mountains into the Gould Wash and Short Creek drainages. Figure 4 delineates Gould Wash and the Canaan and Unnamed washes, which are tributaries of the Short Creek drainage. Erosion has removed the Triassic-age (about 200 to 250 million years ago) bedrock and deposited up to about 100 feet of Quaternary-age (younger than about 2.6 million year) unconsolidated sediments within these two drainages.

We modified Figure 5, inserted below, from Figure 2 of Moore and Sable (2001) to show some of the geologic units and related physiographic features of the study area.

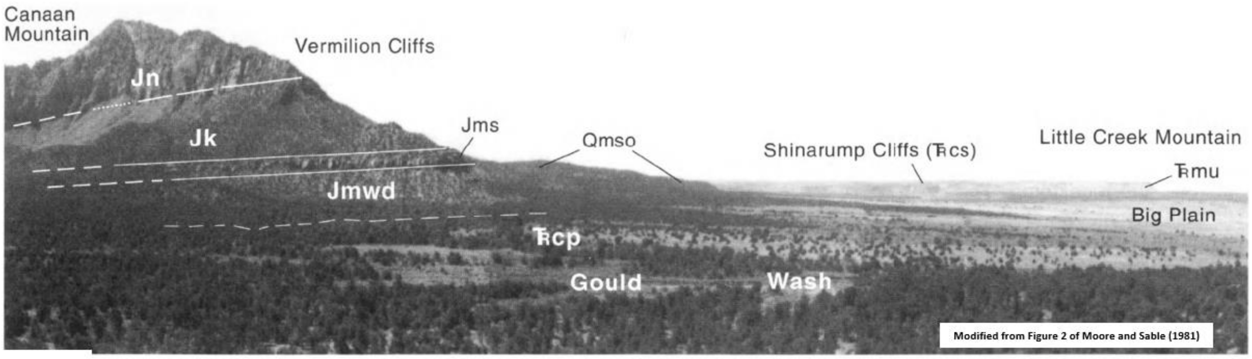


Figure 5. *View south from Smithsonian Butte toward Arizona state line on right skyline. On left, 1,200 feet (366 m) of eroded Jurassic Navajo Sandstone (Jn) caps Canaan Mountain, which is about 2,000 feet (610 m) higher than the plain in middle ground. Units under the Navajo are: Kayenta Formation (Jk), Moenave Formation consisting of the Springdale Sandstone Member (Jms), Whitmore Point and Dinosaur Canyon Members (Jmwd), Triassic Chinle Formation consisting of the easily eroded Petrified Forest Member (Ŧcp) and resistant Shinarump Member (Ŧcs), and the upper red member of the Moenkopi Formation (Ŧmu). The latter forms slopes under the distant Shinarump Cliffs. Some unconsolidated surficial deposits include an old megaslide complex (Qmso), merged alluvial fans (Big Plain), and colluvium and talus (not labeled) on steep slopes.*

Note that there are minor differences between the geologic unit names and symbols used by Moore and Sable (2001) and shown on Figure 5 and those shown on Figure 3 and listed in Table 1.

Rocks exposed in the Apple Valley area consist primarily of Jurassic-age (about 150 to 200 million years ago) and Triassic-age (about 200 to 240 million years ago) sedimentary rocks covered by a thin veneer (less than about 300 feet) of unconsolidated Quaternary alluvial, colluvial, and land slide deposits and eolian (windblown) deposits. Basaltic (lava) flows of Pleistocene age (about 0.01 to 2.6 million years ago) are exposed in the western part of Apple Valley in the Little Creek Mountains and in Gould Wash.

3.2 HYDROGEOLOGY

Cordova and others (1972), Cordova (1978), Sandburg and Sultz (1985), Hurlow (1998), Heilweil and others (2000), Rowley (2003), and Inkenbrandt and others (2013), among other authors, describe the regional groundwater and surface water resources of the area. Rowley (2003) reports that "*There is no permanent surface-water supply, so all water resources are from ground water.*"

3.2.1 Aquifers

The three principal aquifers, in sequence from younger/shallower to older/deeper are the (1) unconsolidated valley-fill (basin-fill) deposits, (2) Little Creek and Gould Wash basalt/lava flows, and (3) Shinarump Conglomerate Member of the Chinle Formation (the Shinarump Conglomerate). The aquifers are formed in layers of permeable sedimentary and igneous strata. The C and R aquifers are present at depths of more than 1600 feet (Inkenbrandt and others, 2013) in the area, but are not included in the principal aquifers because they are deep, have not been developed, and have yields and water quality that are unknown (Rowley, 2003).

We modified Figure 6, inserted below, from Figure 20 of Inkenbrandt and others (2013) to show the relative position of the aquifers in cross section.

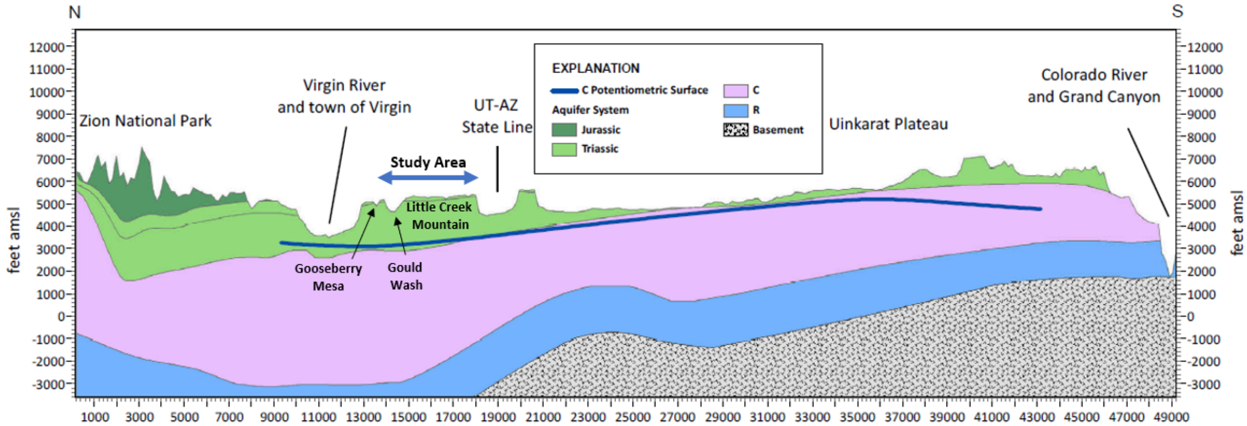


Figure 6. Hydrostratigraphic cross section; modified from Figure 20 of Inkenbrandt and others (2013)

Rowley (2003) reports that (1) most of the water supply is from the "*…unconsolidated alluvial sediments that underlie the broad valley of Gould Wash…,"* (2) permeable, water producing zones within these sediments occur in narrow "*shoestring"* sands that are interbedded with less permeable zones if silt and clay, and (3) these shoestring sands are narrow, irregular in shape and location, and their location is difficult to predict from the surface.

Figure 3 shows that basalt/lava flow (Qbgw and Qblc) and associated cinder cones (Qbgwc and Qblcc) are present overlying (1) the Shinarump Conglomerate in the north central part of Little Creek Mountain and (2) unconsolidated deposits in the western part of the Little Plain area. These volcanic units are buried/overlain by unconsolidated deposits in some areas and, according to Rowley (2003), "*…make excellent aquifers…"* with low total dissolved solids (TDS) concentrations and individual wells producing as much as 800 gallons per minute (gpm).

Well Driller Reports (well logs) available from the DWRi online website and Drinking Water Source Protection (DWSP) plans for area wells that we obtained from the DDW through a Government Records Access and Management Act (GRAMA) indicate that in the Little Plain area, unconsolidated deposits and basalt are interbedded and groundwater comingles in these aquifers.

Figure 3 shows that the Shinarump Conglomerate Member of the Chinle Formation (Shinarump Conglomerate) forms the caprock (resistant erosional surface) of the Little Creek Mountains and Gooseberry Mesa. According to Rowley (2003) wells in the Shinarump Conglomerate can produce as much as 500 gpm; however, Ensign (2015) reports that few wells produce more than 50 gpm. Yields from the Shinarump Conglomerate are greater where the aquifer is thicker (Ensign, 2015). The Shinarump Conglomerate thins from about 150 feet in the eastern part to 40 feet in the western part of the study area.

Table 2 summarizes properties of the principal aquifers.

TABLE 2
HYDROGEOLOGIC PROPERTIES OF PRINCIPAL AQUIFERS [a]

Aquifer	Thickness (feet)	Reported Yields (gpm)	Specific Capacities [b] (gpm/ft)	Transmissivities (ft^2/day)	TDS Concentrations (mg/L)
Unconsolidated Deposits	100 to 300	100 to 600	0.4 to 12	80 to 2700[d]	<1000 to 10,000
Basalt	50 to 150	3 to 800	≤10 to 40[c]	≤200 to 2700[d]	<1000 to 3000
Shinarump Conglomerate	75 to 175	10 to 500	0.3 to 10.5	120 to 6800	<1000 to 3000

ft^2day = feet squared per day; gpm/ft = gallons per minute per foot; TDS = Total Dissolved Solids; mg/L = milligrams per liter.
[a] Except where noted, data are from Cordova (1981), Rowley (2003), Hayden (2004), InSite Engineering, P.C. (2007a, 2007b, 2007c), Inkenbrandt (2013), Ensign (2015), RM² Consultant Engineering (2020), and from Well Driller Reports (well logs).
[b] Specific capacity is pumping rate in gpm divided by drawdown in feet for a specific duration of pumping and typically decreases with increased pumping duration (time since pumping started) and increased pumping rate.
[c] Specific capacity of 40 gpm/ft is from pumping test of Well Identification Number (WIN) 35571.
[d] Transmissivity estimated from pumping test and specific capacity of WIN 8181 using method of Driscoll (1986).

We modified Figure 7, inserted below, from Figure 20 of Inkenbrandt and others (2013) to show the relative position of the three principal aquifers.

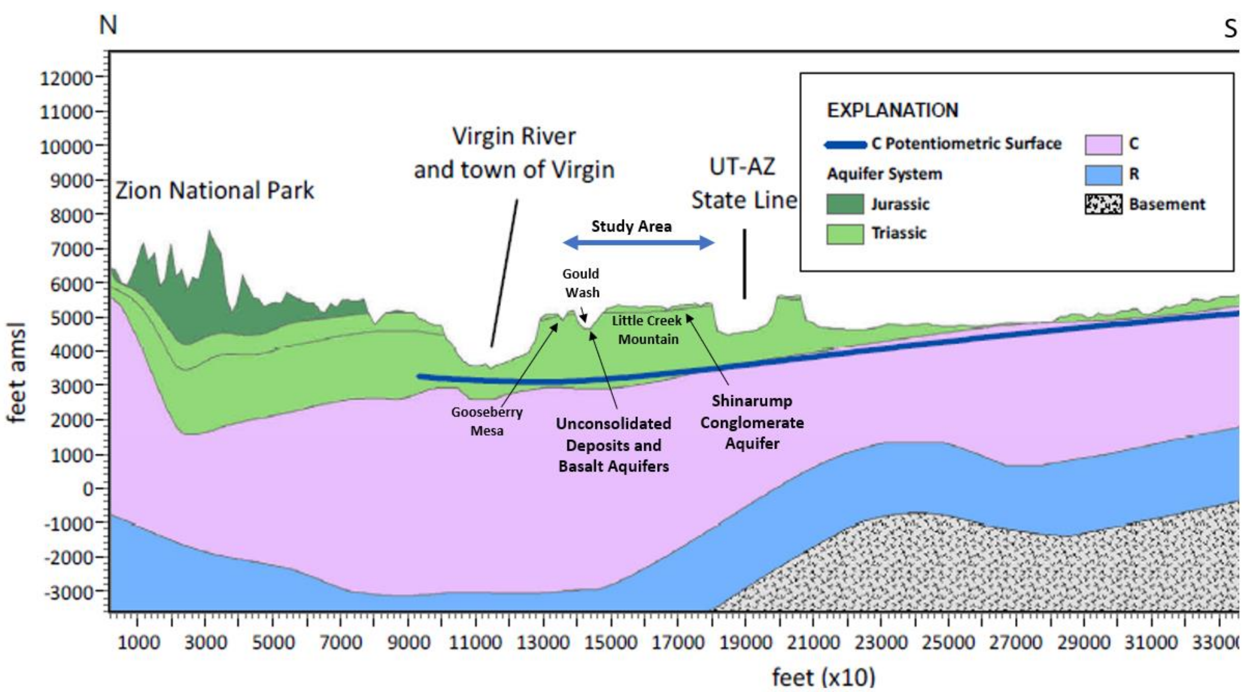


Figure 7. Hydrostratigraphic cross section, northern portion; modified from Figure 20 of Inkenbrandt and others (2013)

The Shinarump Conglomerate is part of the larger "*Triassic Aquifer System*" described by Inkenbrandt and others (2013). The lower part of the Triassic Aquifer System consists of the Moenkopi Formation which contains abundant gypsum beds and poor quality (high TDS) groundwater; see Rowley (2003) and Inkenbrandt and others (2013).

We modified the Figure 8, inserted below, from Figure 7 of Inkenbrandt and others (2013) to illustrate the stratigraphic position of the Shinarump Conglomerate relative to underlying aquifers, including the Moenkopi Formation and the "*C*" and "*R*" aquifers.

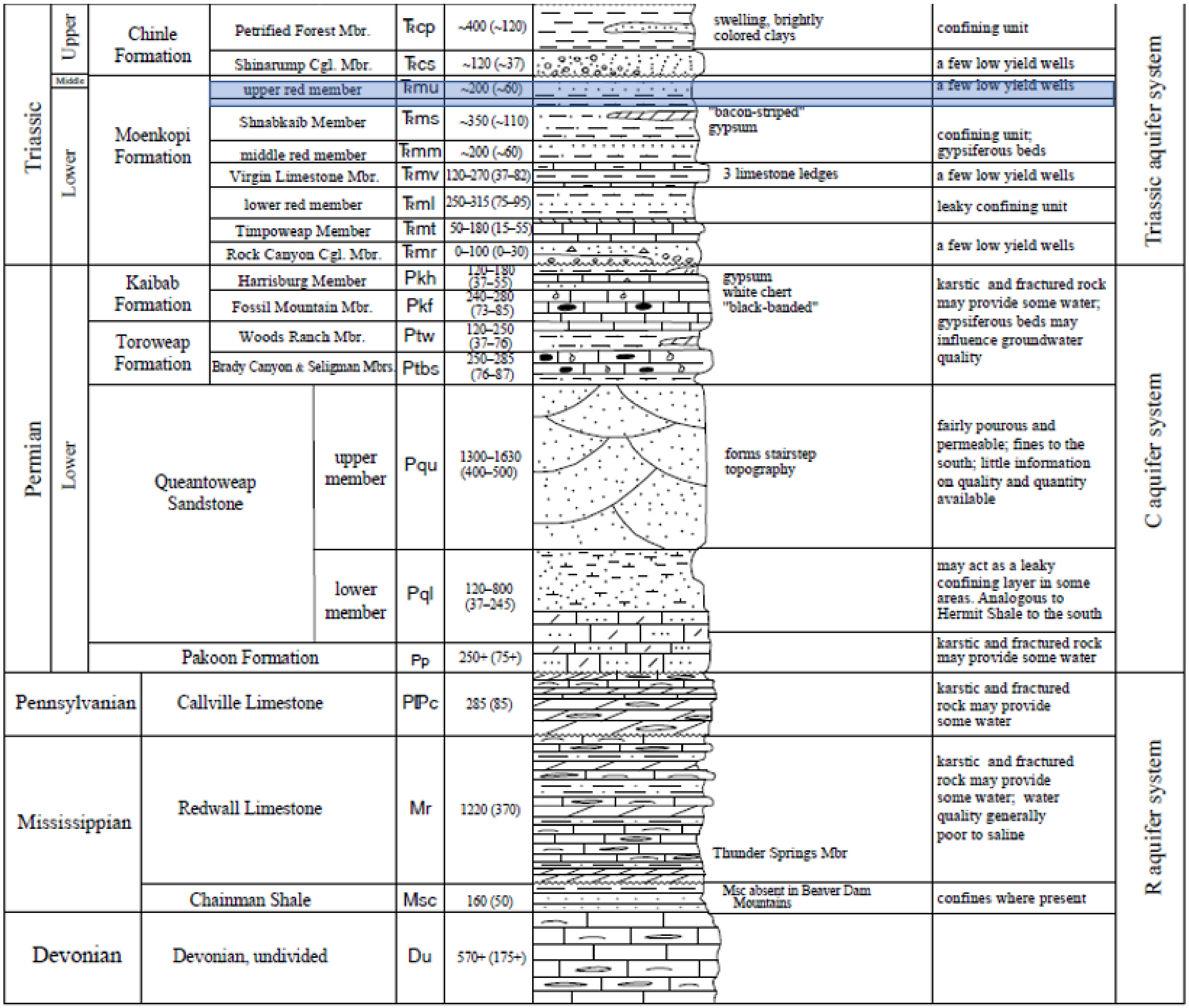


Figure 8. Stratigraphic column; modified from Figure 7 of Inkenbrandt and others (2013)

The C aquifer consists of the Lower Permian-age (about 250 to 300 million years ago) Kaibab Formation, Toroweap Formation Queantoweap Sandstone, and Pakoon Limestone. We do not include the C aquifer in our assessment of sustainable yield of the study area because (1) the top of the aquifer occurs below an elevation of 3000 to 1600 feet (depth of 1600 to 2000 feet), (2) TDS concentrations are likely high to the presence of highly soluble gypsum beds, and (3) we did find records any area wells completed in the C aquifer.

The R aquifer underlies the C aquifer and consists of the Pennsylvanian-age (300 to 320 million years ago), Mississippian-age (about 320 to 360 million years ago) Callville and Redwall limestones, and undivided Devonian-age (about 360 to 420 million years ago) carbonate rocks.

3.2.2 Groundwater Flow

Figure 9, inserted below, is modified from Plate 1 of Cordova (1981) to illustrate the direction of groundwater flow in the unconsolidated deposits aquifer. Figure 9 shows that the direction of groundwater flow in the unconsolidated deposits is to the northwest and west, toward the Hurricane Cliffs, and approximately follows Gould Wash.

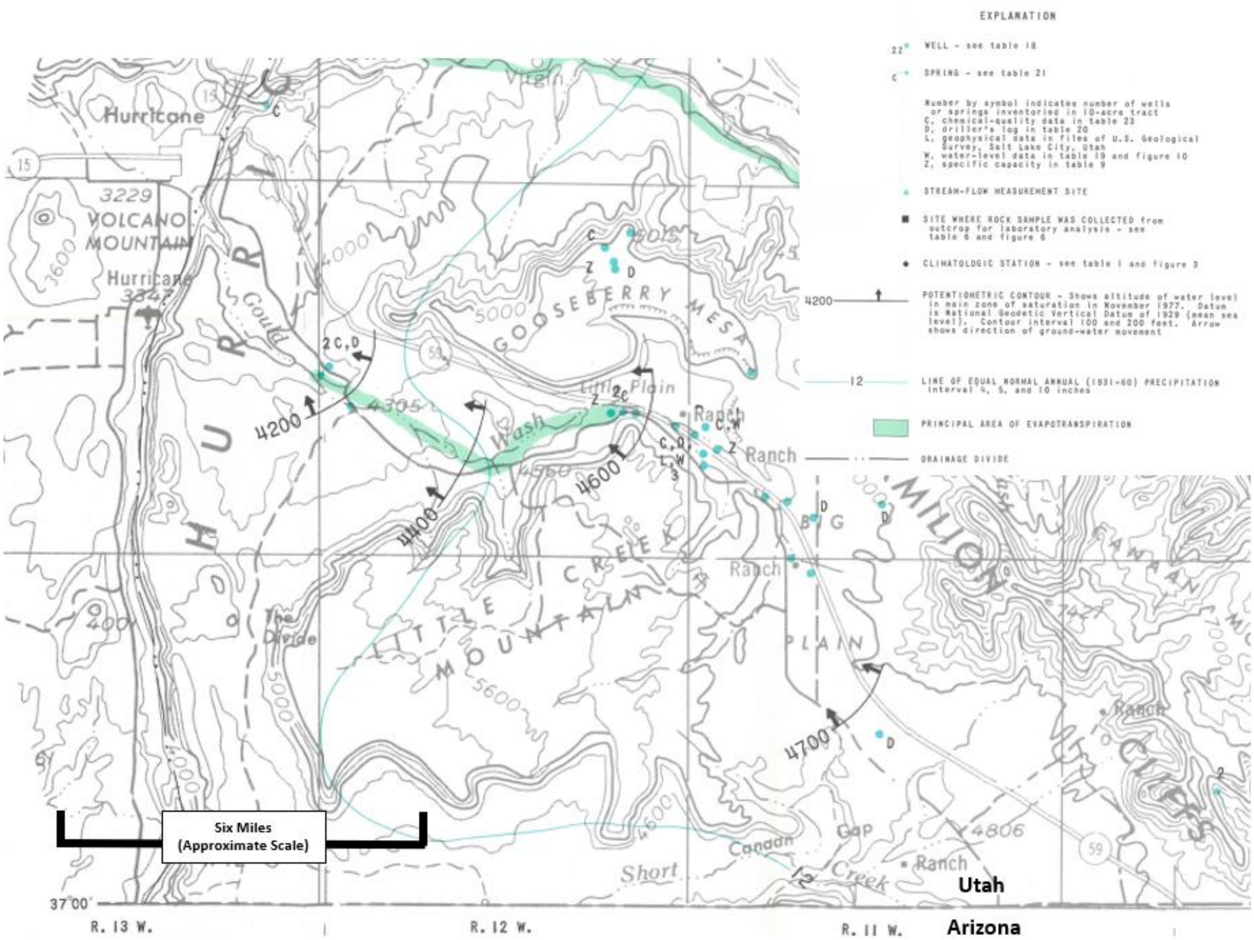


Figure 9. Potentiometric surface in unconsolidated deposits aquifer; modified from Plate 1 of Cordova (1981)

We did not find published water level elevation or flow direction data or maps for the basalt aquifer; however, Ensign (2015) reports and we concur from our review of well logs and DWSP plans for area wells that this aquifer is interbedded and in hydraulic connection with the unconsolidated deposits and has similar groundwater flow directions.

Figure 10, inserted below, is modified from Figure 13 of Inkenbrandt and others (2013) to show the direction of groundwater flow in the Triassic-age rocks, which includes the Shinarump Conglomerate aquifer. Figure 10 shows that groundwater flow in the Shinarump Conglomerate aquifer within (1) most of the study area is approximately west and northwest, towards the Hurricane Cliffs, (2) the southern part of the study area is generally towards the south, towards Arizona, and (3) the Gooseberry Mesa is mostly northward toward the Virgin River and away from the study area.

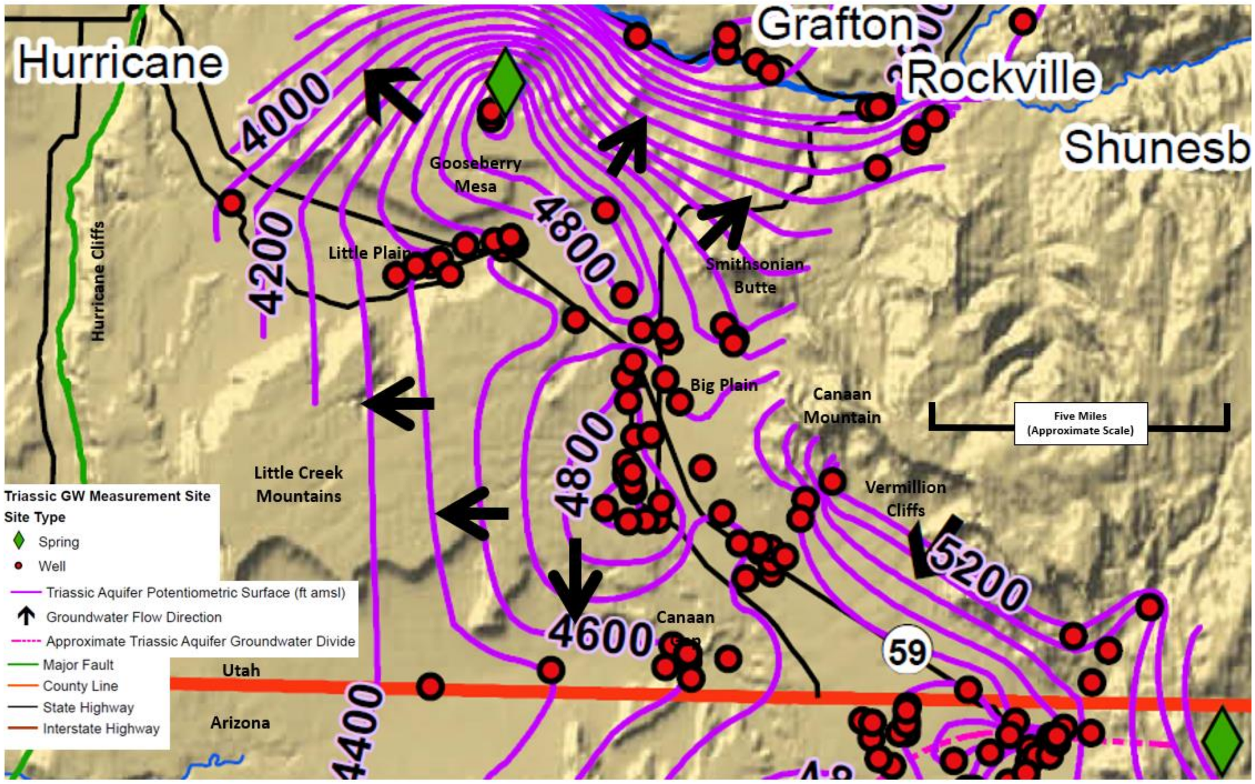


Figure 10. Potentiometric surface in Triassic-age aquifers; modified from Figure 13 of Inkenbrandt and others (2013)

The geologic map on Figure 3 shows that erosion has removed the Shinarump Conglomerate from the Big and Little Plain areas and from the western part of the Canaan Gap area. Therefore, the groundwater flow directions shown above for these areas reflect the underlying deeper Triassic-age rock aquifers and not for the Shinarump Conglomerate.

4.0 WATER BALANCE

For this assessment, we define:

- Sustainable Yield as the amount of groundwater that can be withdrawn from the three principal aquifers of Apple Valley on an annual basis without exceeding the long-term recharge and

- The three principal aquifers as the unconsolidated (basin or valley fill) deposits, the basalt, and the Shinarump Conglomerate.

Ensign (2015) calculated a water balance for the three principal aquifers over a 50,000-acre area and estimated (1) recharge at 10,334 acre-feet per year (afy), (2) withdrawal (discharge) at 10,651 afy, and (3) an overdraft (withdrawal greater than recharge) of 317 afy. The Sustainable Yield of Ensign (2015) using our definition, is 10,334 afy. We followed a similar approach as Ensign (2015) to develop independent estimates of recharge (Sustainable Yield), withdrawal, and water balance.

4.1 ESTIMATE OF GROUNDWATER RECHARGE

Precipitation within and seepage from streams that originate in the study area are the source of nearly all recharge to the three principal aquifers. There is no significant surface water inflow or groundwater underflow into the aquifers from outside of the study area.

According to Heilweil and others (2007), (1) net water infiltration is percolation flux that passes beneath the depth of the root zone and is not lost to evaporation or consumed by evapotranspiration and (2) groundwater recharge is water that reaches the aquifer at the water table.

4.1.1 Precipitation

Cordova (1981) reports that most precipitation occurs during midwinter as snow and late summer as rain. Snow accumulates on the highest plateaus during winter and then melts, runs off, and slowly seeps into the ground during late spring-early summer. Heavy rain that falls during late summer thunderstorms typically runs off rapidly in flash floods. Figure 11, inserted below is modified from Plate 1 of Cordova (1981) to show that average annual precipitation is greater than 12 inches in most of the study area. Cordova (1981) used annual precipitation data for 1931 through 1960.

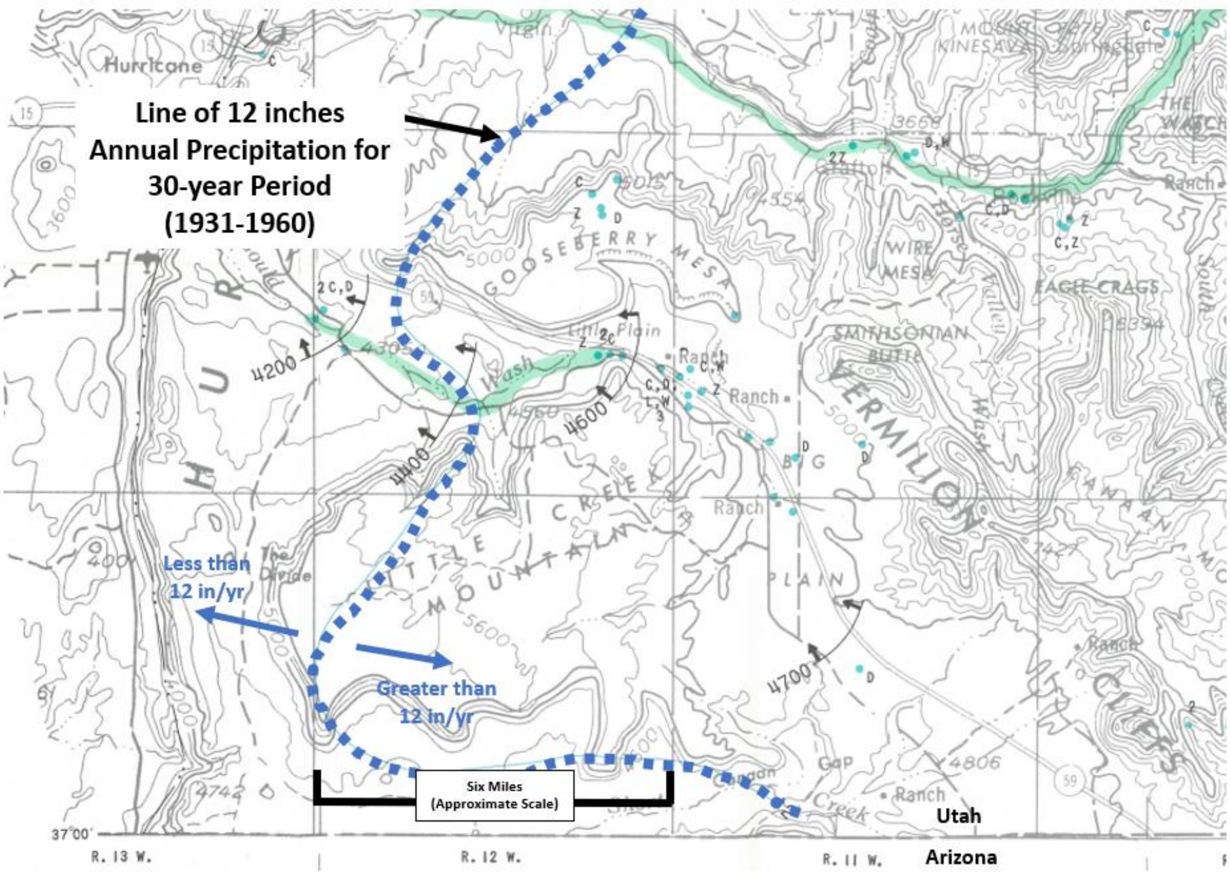


Figure 11. Map of average annual precipitation; modified from Plate 1 of Cordova (1981)

Table 3 summarizes average annual precipitation estimated by Ensign (2015) for "*Uplands*" and "*Valley Floor*" drainage areas. Ensign (2015) defined (1) Uplands as Little Creek Mountain, Gooseberry Mesa, Smithsonian Butte, Canaan Mountain, and the Vermillion Cliffs and (2) Valley Floor as Big and Little Plains. According to Ensign (2015) average annual precipitation in the study area is 61,670 afy.

TABLE 3
ESTIMATES OF AVERAGE ANNUAL PRECIPITATION BY ENSIGN (2015)

Drainage	Surface Area (acres)	Precipitation Rate (in/yr)	Precipitation Amount (afy)
Uplands	30,000	16	40,000
Valley Floor	20,000	13	21,670
Totals	***50,000***		***61,670***

[a] in/yr = inches per year

Table 4 lists the National Weather Service (NWS) weather stations used by Ensign (2015). Ensign (2015) did not provide the period of record for their precipitation data.

TABLE 4
NATIONAL WEATHER SERVICE (NWS) STATIONS USED BY ENSIGN (2015)

Weather Station	Approximate Distance and Direction from Apple Valley (miles)	Average Annual Precipitation (in/yr)
Zion National Park	11 to Northeast	16.1
La Verkin	10.5 to Northwest	11.6
Colorado City	11 miles to Southeast	13.5

We estimated precipitation separately for the Gould Wash, Canaan Wash, and unnamed wash drainages (the three drainages). Figure 4 delineates the extents of the three drainages on a topographic base map.

We estimated average annual precipitation for the study area using data for the 30-year period from 1991 to 2020 that are available from the Natural Resources Conservation Service (NRCS) Parameter-elevation Regressions on Independent Slopes Model (PRISM). Heilweil and others (2007) and Heilweil and McKinney (2007) describe PRISM which is available from the Oregon State University Spatial Climate Analysis Service (http://www.ocs.oregonstate.edu/prism/).

Figure 12, inserted below, is output from PRISM that shows the outline of individual cells and average annual precipitation for individual cells. Each PRISM cell model is 800 x 800 meters, which is 640,000 square meters (m^2) and equivalent to an area of about 158 acres. The 312 cells cover the three drainages in the PRISM model of the study area for a total area of 49,340 acres. We delineated the three drainages and show average annual precipitation (1991 to 2020) on Figure 12 for Gould Wash (14.5 in/yr), Canaan Wash (14.6 in/yr), and the unnamed wash (14.1 in/yr).

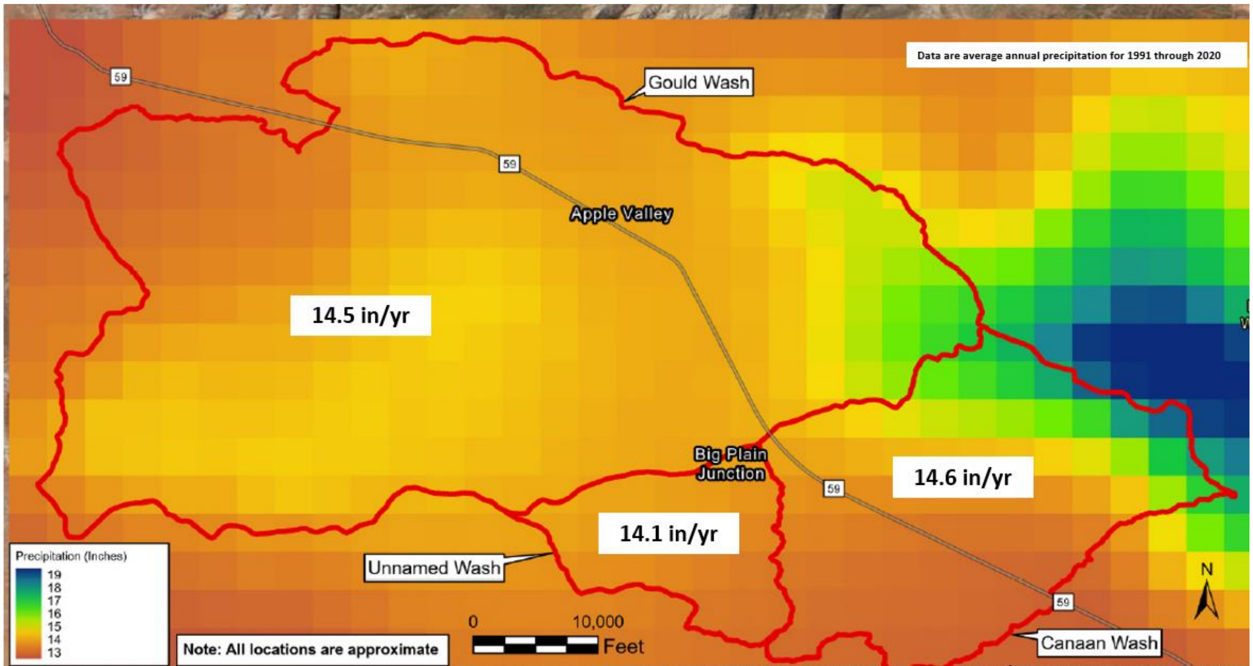


Figure 12. Average annual precipitation modified from PRISM (2022) output

We used PRISM to estimate a total annual precipitation of 57,590 afy for the three drainages which is slightly less than the 61,670 afy of precipitation estimated by Ensign (2015). Note that (1) Ensign (2015) estimated average precipitation to be about 1.23 acre-feet per year in their 50,000-acre study area and (2) we estimated average precipitation to be about 1.17 acre-feet per year in our 49,340-acre study area.

4.1.2 Recharge from Precipitation

The percentage of precipitation that infiltrates the ground, reaches the water table, and becomes groundwater recharge depends on many factors including the amount and duration of precipitation, topographic setting, elevation, temperature, aspect, vegetation, latitude, and others; see Heilweil and others (2000). Most precipitation in the study area is lost to evaporation and evapotranspiration. Estimates of the percentage of precipitation that recharges aquifers in the region range from less than 4 to 15 percent; see Cordova (1981); Danielson and Hood (1984), Heilweil and others (2000), and Heilweil and others (2007).

Heilweil and others (2007) calculated a recharge rate of 10 percent from detailed infiltration studies of the Navajo Sandstone that they conducted at Sand Hollow Reservoir and surrounding areas. Sand Hollow Reservoir is about 5 to 6 miles to the west of Apple Valley.

Ensign (2015) assumed a recharge rate of 15 percent for precipitation for both their Upland and Lowland areas to estimate a combined total recharge from precipitation of 9,250 afy for the study area.

We estimated average annual recharge from precipitation using the (1) Maxey-Eakin (1949) approach (the Maxey-Eakin Method), (2) PRISM/infiltration rate approach described by Heilweil and others (2007), and (3) a range of recharge rates.

The Maxey-Eakin Method assumes that (1) there is a linear relationship between precipitation and recharge and (2) a larger proportion (percentage) of precipitation results in recharge in areas where precipitation is greater. Table 5 summarizes the Maxey-Eakin Method recharge coefficients (percent of annual precipitation) for ranges in annual precipitation.

TABLE 5
MAXEY-EAKIN RECHARGE COEFFICIENTS

Precipitation Ranges of Average Annual Precipitation (in/yr)	Maxey-Eakin Recharge Coefficients (percent of precipitation)
>20	25
15-20	15
12-15	7
8-12	3
<8	0

To estimate annual recharge using the Maxey-Eakin Method, we:

- Downloaded elevation data from the USGS Earth Explorer tool from the GISGeography website.
- Digitized the point data and created a digital elevation model in ArcGIS Pro.
- Generated and assigned latitude and longitude coordinates to each point.
- Calculated annual precipitation in inches using coordinate attributes and elevations in feet in a linear regression equation.
- Calculated the percent of precipitation that infiltrates and recharges local aquifers by applying the conditional Maxey-Eakin coefficients provided in Table 5 to the precipitation data.
- Estimated the total annual recharge from precipitation in the study area by (1) averaging the percent of recharge from precipitation for each drainage, (2) multiplying that average by the area of each drainage, and (3) totaling the recharges from the individual drainages.

We estimated average annual recharge from precipitation to be 4,720 afy using the Maxey-Eakin Method. Flint and Flint (2007) (1) developed the Basin Characterization Model (BCM) to estimate recharge and runoff potential in the Basin and Range Carbonate-Rock Aquifer System (BARCAS) of Nevada and adjacent areas in Utah, (2) compared their estimates of recharge to those using the Maxey-Eakin Method, and (3) found their estimates of recharge to be about 60 percent greater than recharge estimated using Maxey-Eakin Method.

For the PRISM/infiltration rate approach, we multiplied the annual precipitation calculated for each cell using PRISM by (1) the area of each cell (158 acres) and (2) recharge rates of 4, 10, and 15 percent. Our estimates of average annual recharge from precipitation using this method range from 2,300 afy for a recharge rate 4 percent, to 5,760 afy for a rate of 10 percent, to 8,640 afy for rate of 15 percent.

Table 6 compares the annual recharge from precipitation using the PRISM approach to recharge values estimated using the Maxey-Eakin Method and by Ensign (2015).

TABLE 6
ESTIMATES OF AVERAGE ANNUAL RECHARGE FROM PRECIPITATION

Method	Recharge Rate (percent of precipitation)	Average Annual Recharge from Precipitation (afy)
Ensign (2015)	15	9,250
Maxey-Eakin (1949)	7 to 15	4,720
PRISM/Infiltration Rate Approach	4	2300
	10	5760
	15	8640

4.1.3 Recharge from Ephemeral Streams

Gould Wash, Canaan Wash, and an unnamed wash drain the study area; see Figure 4. Although none of these drainages are perennial, they can carry large volumes of water for short periods of time in response to heavy rain. There are no perennial streams that bring surface water into the study area. Studies in western Washington County by Wolkowsje and others (1998) and Heilweil (2000) indicate that recharge from ephemeral streams averages about 3.2 afy per mile. Ensign (2015) used this rate to estimate total recharge of 64 afy for the 20 miles of ephemeral streams in Apple Valley.

4.1.4 Recharge from Irrigation Return

Ensign (2015) reports that unconsumed irrigation water contributes about 1,020 afy of recharge to the principal aquifers in the study area. However, we believe that there is essentially no net recharge from unconsumed irrigation water in the study area because most of the (1) water for irrigation is groundwater pumped from wells or diverted from springs located in the study area and (2) recharge to groundwater is from precipitation. Therefore, we believe that this recharge is already included in the estimate of recharge from precipitation.

4.1.5 Recharge from Interbasin Flow and Underflow

There is essentially no groundwater flow into the study area within the principal aquifers.

4.1.6 Total Estimated Groundwater Recharge

Total groundwater recharge in the study area is the sum of recharge from precipitation and seepage from ephemeral streams. There is no significant recharge from irrigation return or from surface water or groundwater inflow to the principal aquifers from outside the study area. Due to the level of uncertainty and lack of data, our estimate of the long-term recharge to the principal aquifers in the study area is a range from about 4790 for the Maxey-Eakin Method to about 8700 afy using the PRISM data and a recharge rate of 15 percent. This estimate includes both recharge from precipitation and recharge from ephemeral streams. The high end of our estimate (8700 afy) is less than the Ensign (2015) estimate of 10,334 afy. Note that the Ensign (2015) estimate of recharge is 9,314 afy if irrigation return is not included.

4.2 ESTIMATE OF GROUNDWATER DISCHARGE

To estimate groundwater discharge (withdrawal) for comparison with recharge, we compiled the following information for Apple Valley:

- Approved water right diversions;
- Reported diversions by PWSs;
- Estimates of evapotranspiration;
- Discharge to streams; and
- Discharge to groundwater outflow.

4.2.1 Discharge to Wells and Springs

To estimate the amount of groundwater potentially discharged to wells and springs, we (1) inventoried approved water right diversions and (2) compiled diversion records for area water systems. We inventoried the DWRi online database and found approximately 9,270 afy of approved water right diversions located within the study area. This is slightly greater than the 9,085 afy of approved diversions reported by Ensign (2015). Pending (unapproved) water rights consist mostly of changes of points of diversion (POD) located within the study area and will not add significant new diversions.

Not all the approved water right diversions are being fully used. For example, Table 7 summarizes approved water right diversions and actual diversions for area water systems.

TABLE 7
REPORTED DIVERSIONS BY AREA WATER SYSTEMS [a]

Water System	Number of Connections (2021)	Number of Sources (2021)	Water Rights [a] (afy)	Total 2021 Diversions (ac-ft)	Range of Annual Diversions [b] 2017 to 2021 Minimum (ac-ft)	Maximum (ac-ft)
Big Plains – Apple Valley	258	2	564	114	83	131
Big Plains – Canaan Springs [b]	14	2	45	177	11	177
Big Plains – Cedar Point	148	3[c]	[g]	80	36	80
Tru South	NR [d]	6	1155	0	0	0
Little Creek Travel Center	NR [e]	2	NR [e]	NR [e]	NR [e]	NR [e]
Apple Valley Water Co.	NR [f]	NR [f]	[g]	0 [f]	0 [f]	0 [f]
Gubler Family Trust	NR [f]	NR [f]	[g]	0 [f]	0 [f]	0 [f]
Thirsty Stone Resources, Inc.	NR [f]	NR [f]	2	0 [f]	0 [f]	0 [f]
Totals	***420***	***15***	***1766***	***371***	***130***	***388***

NR = Not Reported; gpm = gallons per minute; afy = acre-feet per year; ac-ft = acre feet
[a] *DWRi website* https://www.waterrights.utah.gov/asp_apps/generalWaterUse/WaterUseList.asp.
[b] *Data are for 2018 to 2021 (there are no data for 2017).*
[c] *DDW lists four sources (wells); one source (Jessup Well) was inactive in 2021.*
[d] *DWRi (1) does not report any connections, (2) shows all six sources (wells) as "active" but no diversions for 2021 or any other year; DDW reports that Tru South serves a population of 314.*
[e] *Little Creek Travel Center not listed in DWRi database; however, DDW reports that they are a Transient Non-Community PWS, serve a population of 250 have one source (Travel Center Well 1).*
[f] *Reported by DWRi to be inactive; water system not listed in DDW database.*
[g] *Included in total for Big Plains – Apple Valley*

Note from Table 7 that:

- Eight water systems are listed, but it appears that Big Plains – Apple Valley, Canaan Springs, and Cedar Point and Little Valley Travel Center were the only active systems that diverted water from 2017 to 2021.

- A total of 371 acre-feet was diverted during 2021 which is considerably less than the 1766 afy that is allowed to be diverted by the approved water rights of these systems.

4.2.2 Discharge by Evaporation and Evapotranspiration

As discussed by Ensign (2015), discharge by evaporation and evapotranspiration is accounted for in the estimated of recharge rates of Cordova (1981); Danielson and Hood (1984), Heilweil and others (2000), and Heilweil and others (2007).

4.2.3 Discharge to Streams

As discussed by Ensign (2015), there are no perennial streams that flow out of the study area.

4.2.4 Groundwater Outflow from Unconsolidated Deposits and Basalt Aquifers

Figure 13, inserted below, is modified from Plate 1 of Cordova (1981) to show that essentially all groundwater in the unconsolidated deposits aquifer flows to the west northwest, out of the study area. Well logs and DWSP plans for Apple Valley Wells (Alpha Engineering Company, 1998) indicate that groundwater in the unconsolidated and basalt aquifers comingle in the Little Plain area before flowing out of the study area.

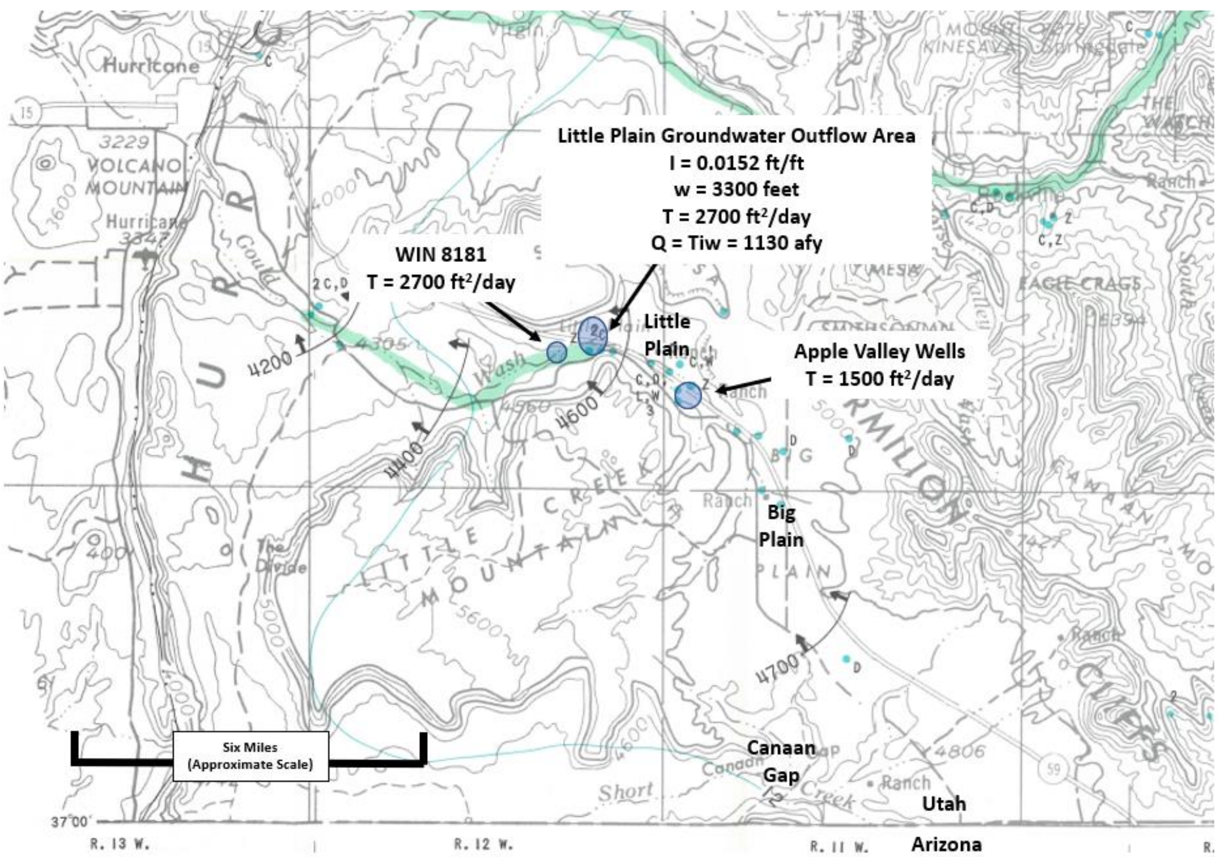


Figure 13. Estimated groundwater flow in unconsolidated deposits aquifer; modified from Plate 1 of Cordova (1981)

As indicated on Figure 13, we estimate that groundwater in the unconsolidated deposits and basalt aquifers leaves the study area at an average annual rate of about 1130 afy. The Darcy equation, as described by Cordova (1981) and Driscoll (1986) is:

Q = TIw, where

Q = groundwater outflow in afy,
T = Transmissivity in ft^2/day,
I = Hydraulic gradient, and
w = Width of section through which groundwater flows in feet.

Figure 13 indicates that we used the following input parameters: (1) hydraulic gradient (I) of about 0.0152 ft/ft, (2) width of the aquifer (w) of about 3300 feet, and (3) transmissivity (T) of 2700 ft^2/day. We used the method of Driscoll (1986) to estimate a transmissivity of 2700 ft^2/day from a specific capacity of 10 gpm/ft that we calculated from the 10 feet of drawdown produced by an 800-gpm, 36-hour constant-rate pumping test of WIN 8181. Note that Alpha Engineering Company (Alpha, 1998) estimated a transmissivity of 1500 ft^2/day for Apple Valley Water Company Well Nos. 1 and 2 (the Apple Valley wells) that are located about 2.5 miles to the southeast. WIN 8181 and the Apple Valley wells are completed in and produce groundwater from both the unconsolidated deposits and basalt aquifers (Alpha, 1998).

Our estimate of 1130 afy is less than the 1449 afy of aquifer outflow estimated by Ensign (2015) for the Little Plain area.

Ensign (2015) estimated that an additional 117 afy flows out of the study area in the unconsolidated deposits aquifer in the Canaan Gap area. However, we believe that very little groundwater leaves the study area through the unconsolidated deposits in Canaan Gap because this aquifer is very narrow, thin, and clayey and appears to be discontinuous in this area; see Figure 3.

4.2.5 Groundwater Outflow from Shinarump Conglomerate Aquifer

Figure 14, inserted below, is modified from Figure 13 of Inkenbrandt and others (2013) to (1) show the direction of groundwater flow in the Triassic-age rocks, which includes the Shinarump Conglomerate aquifer and (2) estimate groundwater outflow within the Shinarump Conglomerate. As noted earlier, erosion has removed the Shinarump Conglomerate from the Big and Little Plain areas and from the western part of Canaan Gap. Therefore, (1) the groundwater flow directions shown below for these areas are for the underlying deeper Triassic-age rock aquifers and are not for the Shinarump Conglomerate, (2) very little if any groundwater in the Shinarump Conglomerate aquifer leaves the study area through Canaan Gap, and (3) almost all the outflow in the Shinarump Conglomerate aquifer is through the narrow area shown below.

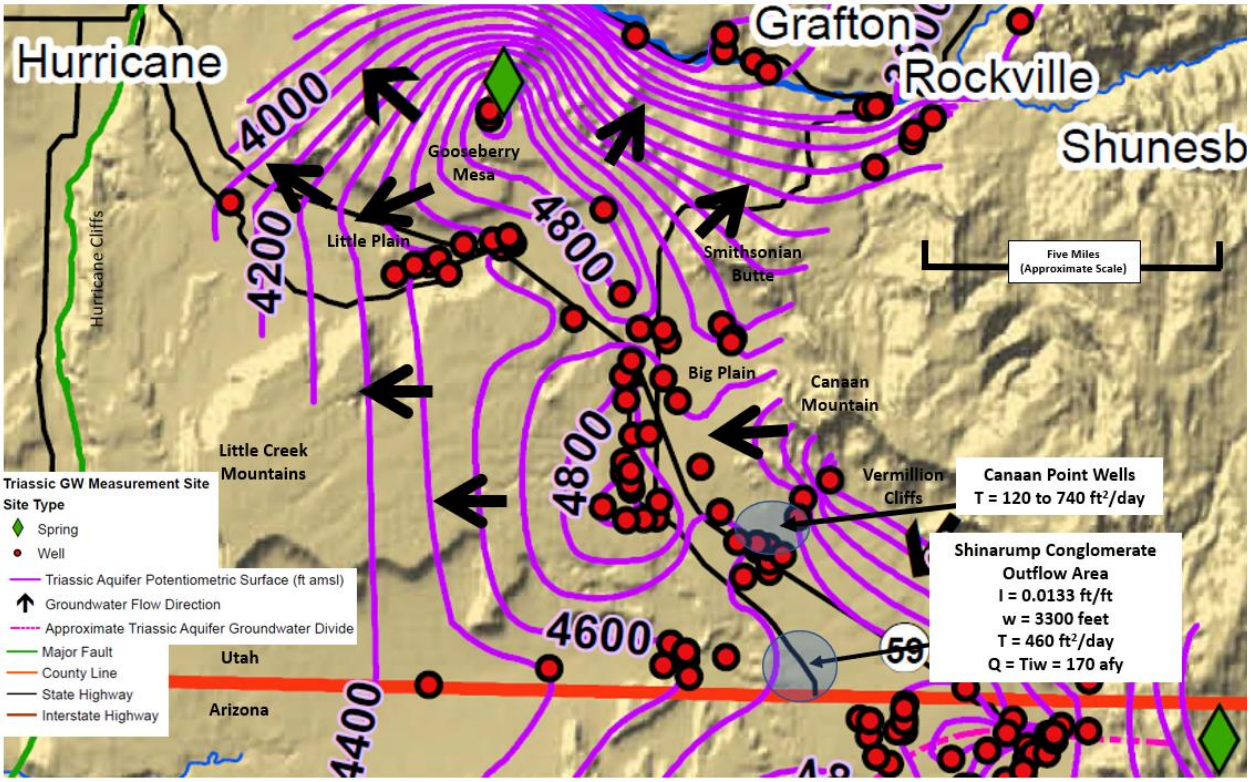


Figure 14. Estimated groundwater flow in Triassic-age aquifers; modified from Figure 13 of Inkenbrandt and others (2013)

We used the Darcy equation and the following input parameters to estimate that about 170 afy of groundwater leaves the southern part of the study area in the Shinarump Conglomerate: (1) hydraulic gradient (I) of about 0.0133 ft/ft, (2) width of the aquifer (w) of about 3300 feet, and (3) transmissivity (T) of 460 ft^2/day. Our estimated transmissivity of 460 ft^2/day is the average of four transmissivities reported for the Shinarump Conglomerate aquifer in DWSP plans for four Cedar Point Water Company wells by InSite Engineering, P.C. (InSite, 2007a, 2007b, and 2007c) and RM^2 Consultant Engineering (RM^2, 2020).

4.2.6 Total Estimated Groundwater Discharge

Our estimate of total potential groundwater discharge from the study area is about 10,570 afy and is the sum of potential discharge from wells and springs (9,270 afy) and groundwater outflow in the unconsolidated deposits and basalt aquifers (1,130 afy) and Shinarump Conglomerate aquifer (170 afy). We do not include groundwater discharge via evaporation and evapotranspiration or surface water outflow because (1) there are no perennial streams that carry surface water out of the study area and (2) our estimate of net recharge already considers evaporation and evapotranspiration. Our estimate of 10,570 afy is essentially the same as the Ensign (2015) estimate of 10,651 afy.

We consider our estimate to be potential discharge because it assumes that all approved water right diversions are used to their allowed maximum amounts and the water is 100 percent consumed.

4.3 GROUNDWATER BALANCE

Our estimate of long-term recharge of about 4790 to 8700 afy is considerably less than our estimate of potential groundwater discharge of 10,570 afy and indicates a potential deficit (groundwater withdrawal greater than recharge) of 1870 to 5790 afy. If this were the case, then there would be significant mining of and a decline in groundwater levels. Rowley (2003) refers to anecdotal reports of wells going dry; however, we did not find any USGS observation wells in the area that would provide a long-term record of groundwater levels.

Although our estimate of groundwater discharge of 10,570 afy is essentially the same as the estimate of Ensign (2015) of 10,651 afy, our estimated potential deficit of 1870 to 5790 afy is significantly greater than the estimated deficit of Ensign (2015) of 317 afy due to our lower estimates of groundwater recharge.

5.0 ASSESSMENT OF SUSTAINABLE YIELD

Our estimate of the Sustainable Yield of the three principal aquifers in Apple Valley is the same as our estimate of long-term recharge which is about 4790 to 8700 afy. Our high end is less than the estimate of long-term recharge by Ensign (2015) of 10,334 afy. Both estimates of sustainable yield are less than estimated potential groundwater discharge of 10,570 to 10,651 afy.

6.0 RECOMMENDATIONS FOR FURTHER STUDY

The wide range in our estimate of long-term recharge and Sustainable Yield (about 4790 to 8700 afy) for Apple Valley is an indication of the high level of uncertainty in all our estimates. We recommend the following to refine our estimate of Sustainable Yield:

- Conduct a more detailed hydrogeologic study which would include the collection of field data;
- Construction of a water budget model such as the Utah Basin Model (UBM) that the Utah Geological Survey (UGS) has developed to estimate large water budget components; and
- Construction and calibration of a numerical groundwater model.

Collection of field data would, at a minimum, include measurements of:

- Soil properties, such as soil water content, field capacity, wilting point, and permeability;
- Climatological factors, such as precipitation, temperature, evaporation, and the like;
- Groundwater levels through the installation and monitoring of observation wells; and

- Stream flow through the installation and monitoring of surface water gages.

7.0 REFERENCES CITED

Alpha Engineering Company (Alpha), 1998, *The Little Plains Water Company, Apple Valley Culinary Wells, Washington County, Utah, Preliminary Evaluation Report:* Unpublished consultant report prepared by Alpha for Little Valley Water Company, dated September 21, 1998.

Bates, R.L. and Jackson, J.A., 1987, *Glossary of Geology*: Published by the American Geological Institute (AGI), 3rd edition.

Biek, R.F., Rowley, P.D., Hayden, J.M., Hacker, D.B., Willis, G.C., Hintze, L.F., Anderson, R.E., and Brown, K.D., 2009, *Geologic map of the St. George and east part of the Clover Mountains 30' x 60' quadrangles, Washington and Iron Counties, Utah*: Utah Geological Survey Map 242, scale, 1:100,000.

Billingsley, G.H., and Workman, J.B., 2000, *Geologic map of the Littlefield 30' x 60' quadrangle, Mohave County, northwestern Arizona*: U.S. Geological Survey Geologic Investigations Series Map I-2628, version 1.0, 25 p., 2 plates, scale 1:100,000.

Cordova, R.M. 1978, *Ground-Water conditions in the Navajo Sandstone in the central Virgin River Basin*: Utah Department of Natural Resources Technical Publication No. 61.

Cordova, R.M. 1981, *Ground-Water Conditions in the upper Virgin River and Kanab Creek basins area, Utah, with emphasis on the Navajo Sandstone*: Utah Department of Natural Resources Technical Publication No. 70.

Cordova, R.M., Sandberg, G.W., and McConkie, W., 1972, Groundwater conditions in the central Virgin River basin: Utah Department of Natural Resources Technical Publication No. 40.

Driscoll, F.G., 1986, Groundwater and wells: published by Johnson Division, S. Paul, Minnesota.

Ensign Engineering (Ensign), 2015, B*ig Plains aquifer evaluation*: Consultant report prepared by Ensign for Big Plains Water and Sewer Special Service District and Utah Division of Drinking Water, dated July 29, 2015.

Flint, A.L., and Flint, L.E., 2007, Application of the basin characterization model to estimate in-place recharge and runoff potential in the Basin and Range carbonate-rock aquifer system, White Pine County, Nevada, and adjacent areas in Nevada and Utah: U.S. Geological Survey Scientific Investigations Report 2007–5099.

Hayden, J.M., 2004, *Geologic map of the Little Creek Mountain quadrangle, Washington County, Utah*: Utah Geological Survey Map 204, 2 plates, scale 1:24,000.

Hayden, J.M., 2008, *Geologic map of the Virgin quadrangle, Washington County, Utah*: Utah Geological Survey Map 231, 2 plates, scale 1:24,000.

Heilweil, V.M., Freethey, G.W., Wilkowske, C.D., Stolp, B.J., and Wilberg, D.E., 2000, *Geohydrology and numerical simulation of groundwater flow in the central Virgin River* *basin of Iron and Washington Counties, Utah, Utah*: Department of Natural Resources Technical Publication No. 116.

Heilweil, V.M., McKinney, T.S., Zhdanov, M.S., and Watt, D.E., 2007, *Controls on the variability of net infiltration to desert sandstone*: Water Resources Research, v. 43, no. 7.

Heilweil, V.M., McKinney, T.S., Zhdanov, M.S., and Watt, D.E., 2007, *Controls on the variability of net infiltration to desert sandstone*: Water Resources Research, v. 43, no. 7.

Heilweil, V.M. and McKinney, 2007, *Net-infiltration map of the Navajo Sandstone outcrop area in western Washington County, Utah*: U.S. Geological Survey Scientific Investigations Map 2988.

Inkenbrandt, P., Thomas, K., and Jordan, J.L., 2013, *Regional groundwater flow and water quality in the Virgin River basin and surrounding areas, Utah and Arizona*: Utah Geological Survey Report of Investigation 272.

InSite Engineering, P.C. (InSite), 2007a, *Preliminary Evaluation Report for Cedar Point Water Company Source Number 4, Apple Valley City, Washington County, Utah, Utah Drinking Water System Number 27089:* Unpublished consultant report prepared by InSite for Cedar Point Water Company, dated June 2007.

InSite Engineering, P.C. (InSite), 2007b, *Drinking Water Source Protection Plan for Cedar Point Water company Source No. 1 (Cook Well), Apple Valley City, Washington County, Utah, Utah Drinking Water System Number 27089:* Unpublished consultant report prepared by InSite for Cedar Point Water Company, dated March 2007.

InSite Engineering, P.C. (InSite), 2007c, *Drinking Water Source Protection Plan for Cedar Point Water Company Source No. 2 (Jessop Well), Apple Valley City, Washington County, Utah, Utah Drinking Water System Number 27089:* Unpublished consultant report prepared by InSite for Cedar Point Water Company, dated March 2007.

Masbruch, M.D., Gardner, P.M., Nelson, N.C., Heilweil, V.M., Solder, J.E., Hess, M.D., McKinney, T.S., Briggs, M.A., and Solomon, D.K., 2019, *Evaluation of groundwater resources in the Spanish Valley Watershed, Grand and San Juan Counties, Utah*: US. Geological Survey Scientific Investigations Report 2019-5062.

Marston, T.M., and Nelson, N.C., 2018, *Assessment of managed aquifer recharge at Sand Hollow Reservoir, Washington County, Utah, updated to conditions through 2016*: U.S. Geological Survey Open-File Report 2018–1140, 1-37 p.

RM^2 Consultant Engineering (RM^2), 2020, *Drinking Water Source Protection Plan for Big Plains Water and Sewer Special Service District (BPWSSD) Source No. WS003, Apple Valley City, Washington County, Utah, Utah Drinking Water System Number 27089:* Unpublished consultant report prepared by RM^2 for BPWSSSD, dated April 13, 2020.

Rowley, P.D., 2003, *Hydrogeology of Apple Valley area, Washington County, Utah:* Unpublished consultant report prepared by P.D. Rowley for Washington County Water Conservancy District, dated July 30, 2003.

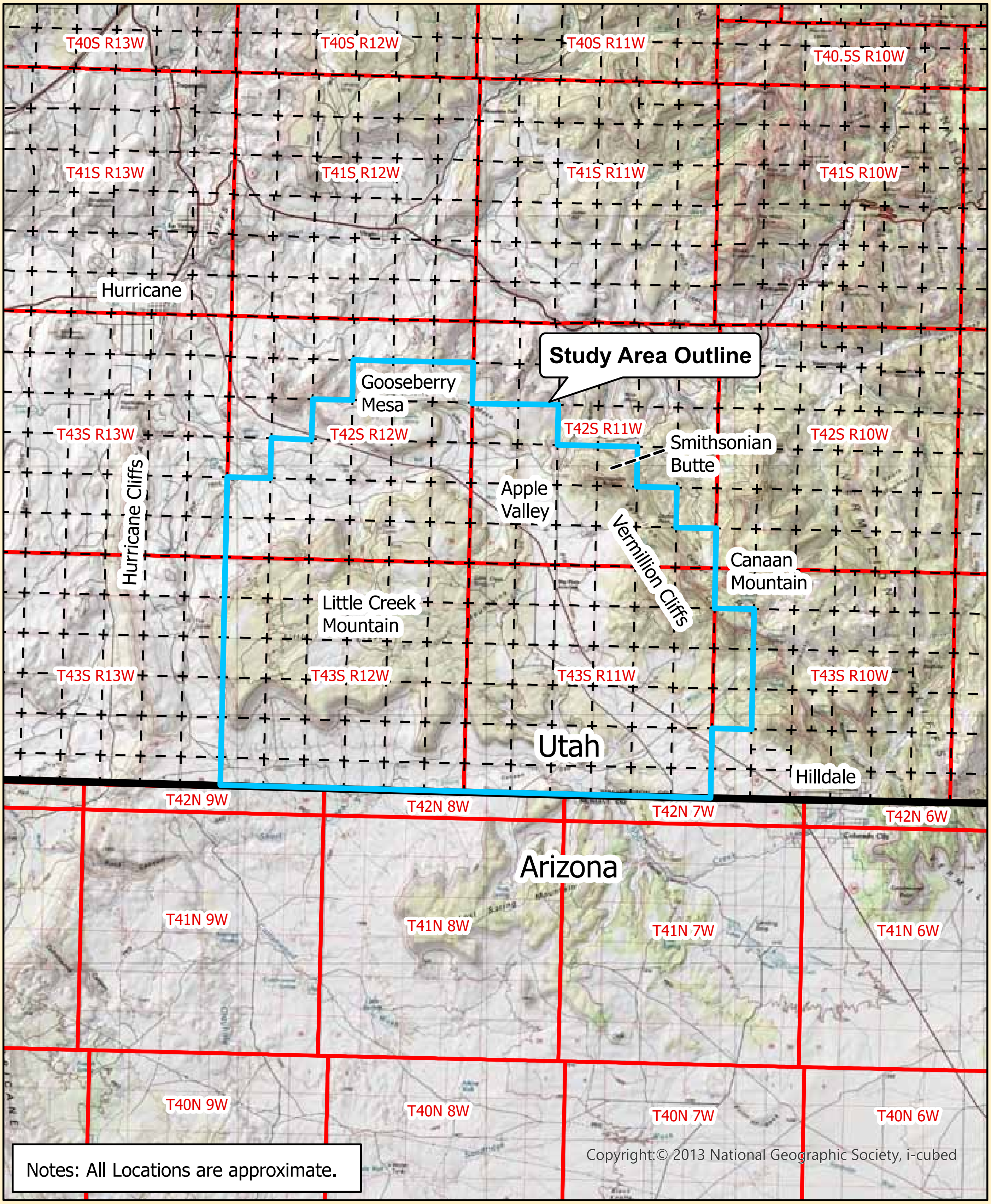
Sandberg, G.W., and Sultz, L.G., 1985, Reconnaissance of the quality of surface water in the upper Virgin River basin, Utah, Arizona, and Nevada, 1981-1982: Utah Department of Natural Resources Technical Publication No. 83.

White, W.N., 1932, *A method of estimating ground-water supplies based on discharge by plants and evaporation from soil*: Results of investigations in Escalante Valley, Utah: Water Supply Paper 659-A, 77-81 p.

Welch, A.H, and Bright, D.J., 2007, *Water resources of the Basin and Range carbonate-rock aquifer system, White Pine County, Nevada and adjacent areas in Nevada and Utah – Draft Report:* U.S. Geological Survey Open-File Report 2007-1156.

Willis, G.C., Doelling, H.H., Solomon, B.J., and Sable, E.G., 2002, *Interim geologic map of the Springdale West quadrangle, Washington County, Utah*: Utah Geological Survey Open-File Report 394, 19 p., scale 1:24,000.

FIGURES

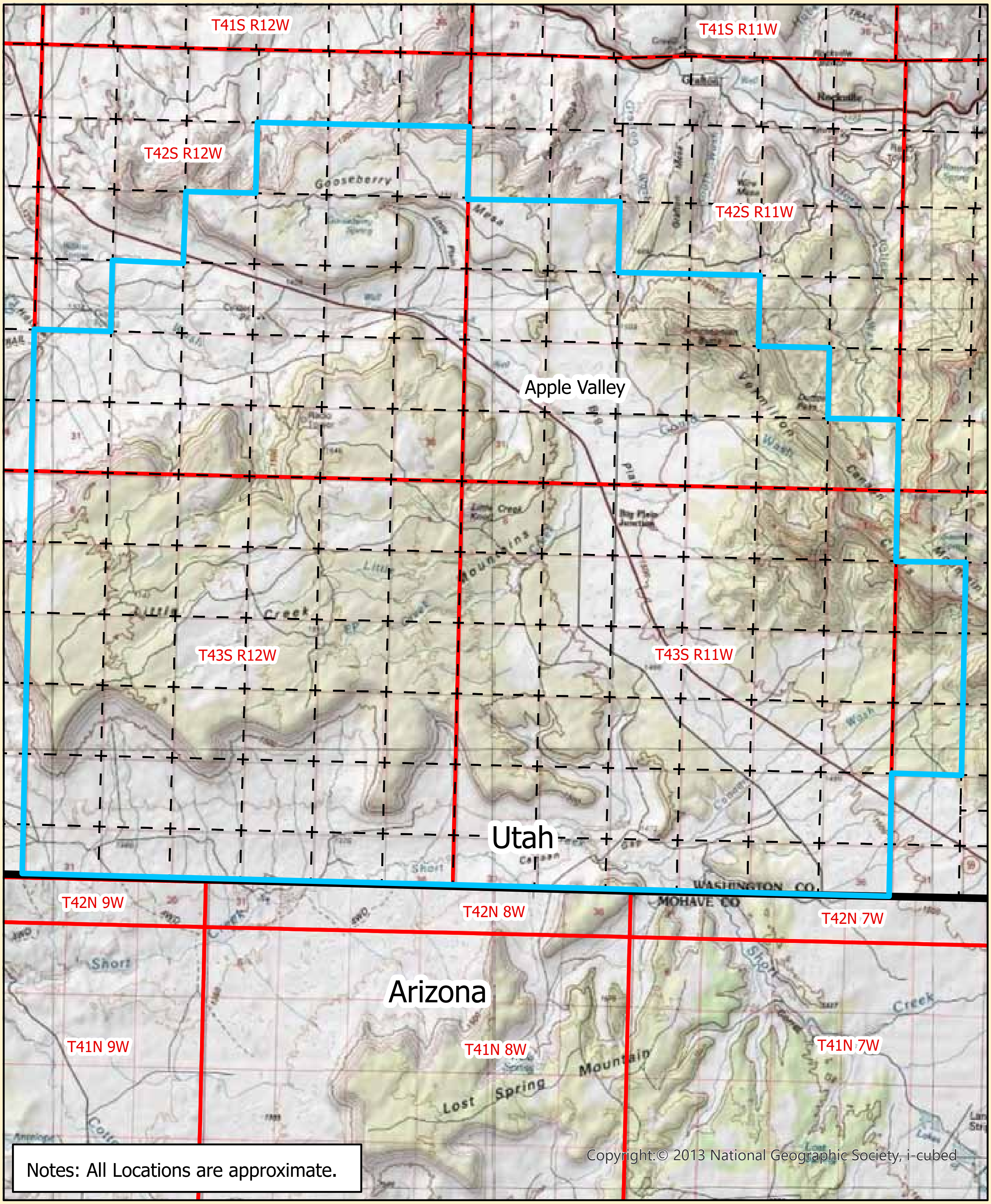


Prepared by Connor Smith

N

0 25,000 Feet

Washington County WCD
Apple Valley
Regional Map
Figure 1



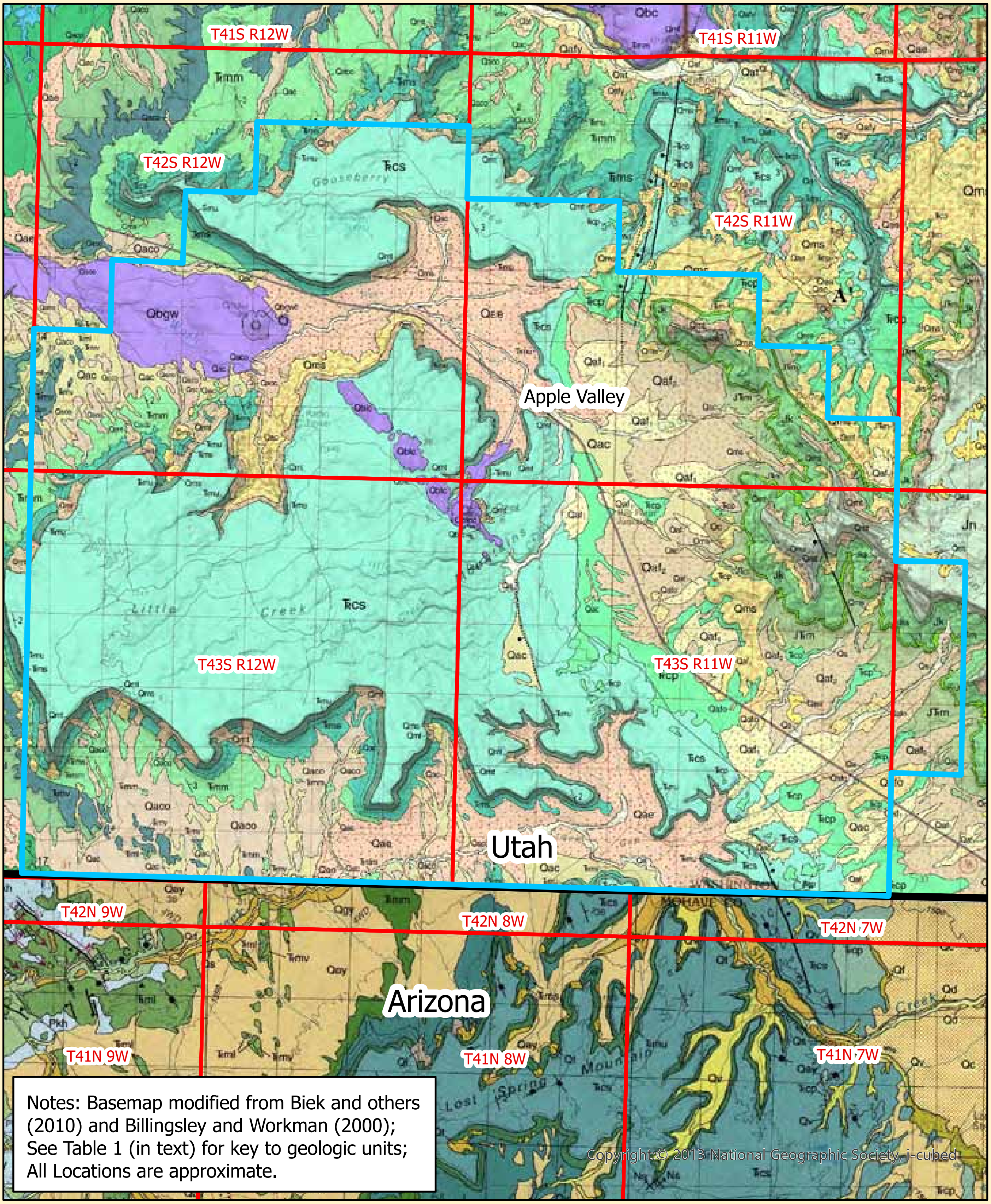
LOUGHLIN WATER ASSOCIATES LLC

Prepared by Connor Smith

N

0 10,000 Feet

Washington County WCD
Apple Valley
Location Map
Figure 2

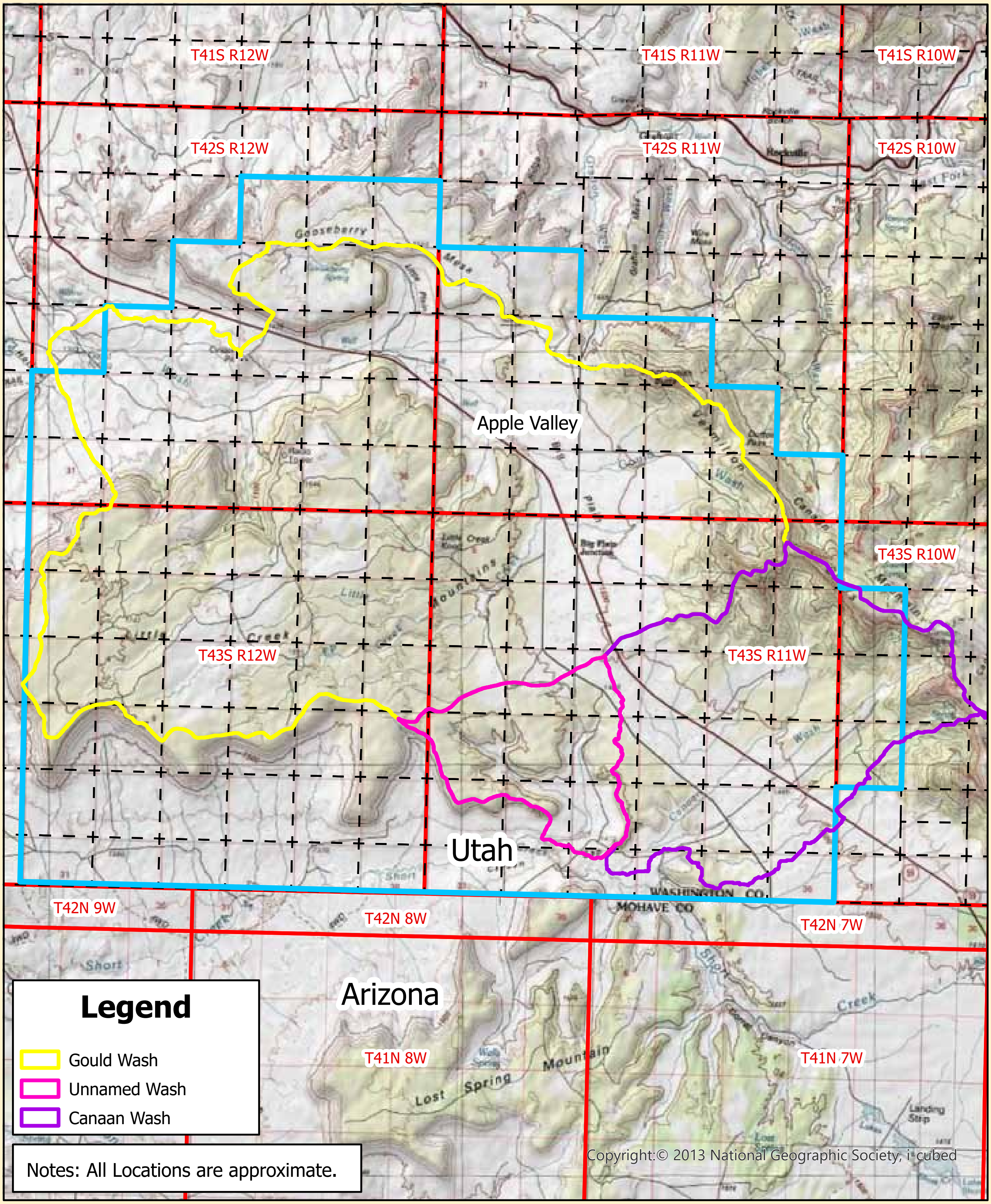


Notes: Basemap modified from Biek and others (2010) and Billingsley and Workman (2000); See Table 1 (in text) for key to geologic units; All Locations are approximate.

LOUGHLIN WATER ASSOCIATES LLC

Prepared by Connor Smith

Washington County WCD
Apple Valley
Geologic Map
Figure 3



LOUGHLIN WATER ASSOCIATES LLC

Prepared by Connor Smith

N

0 10,000 Feet

Washington County WCD
Apple Valley
Drainage Map
Figure 4