BASELINE HYDROLOGY OF ASHLEY SPRING

by Paul Inkenbrandt, Janae Wallace, and Melissa Hendrickson

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Cover photo: *Upstream (north) view into Ashley Gorge; the white building in the foreground contains Ashley Spring.*

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ABSTRACT

Ashley Spring is an important water supply for most of the residents in the Vernal area of Uintah County, Utah. The Utah Geological Survey conducted a study to determine the baseline flow paths and water chemistry of the aquifer systems that provide water to the spring. Ashley Spring water is of high quality, which does not vary long term. Seasonal fluctuations in spring-water chemistry are due to snowmelt and precipitation patterns. A substantial part of the water emanating from Ashley Spring has been in the groundwater system less than one week, originating as recharge at areas along Dry Fork where water seeps into sinks and fractures. Groundwater in the area follows topography and fracture patterns, flowing dominantly from northwest to southeast.

INTRODUCTION

Objective

Ashley Spring is the primary water supply for most of the residents of the Vernal area in Uintah County, Utah. Local county government officials have expressed concern regarding the preservation of high quality groundwater in the Ashley Spring public supply system in northwest Uintah County. To address concerns of potential water quality degradation caused by a mining lease prospect within a half mile of the spring, the Utah Geological Survey (UGS) conducted a study to determine the baseline flow paths and water chemistry of the aquifer system(s) that provides water to the spring.

Location and Geography

The study area is in northwestern Uintah County (figure 1). Most of the study area is within the watershed having the eight-digit hydrologic unit code (HUC8) 14060010 (U.S. Department of Agriculture, 2013a), which encompasses Ashley Creek and Dry Fork, with the exception of Deep Creek Spring, which is within HUC8 14060003. The focus of this study is the Ashley Spring complex, a series of springs and seeps flowing into Ashley Creek along its banks and into its channel (Godfrey, 1985). The largest spring (greatest discharge) of the Ashley Spring complex is a municipal and irrigation water source on the east side of Ashley Creek, which in this study will be referred to as Ashley Spring. Most of the other springs in the complex are on the west side of Ashley Creek and will be referred to as the west-side springs. Ashley Spring is 670 feet (204 m) north and 1928 feet (588 m) west from the SE corner of section 1, T. 3 S., R. 20 E., Salt Lake Base Line and Meridian. The coordinates of the spring site are latitude 40.58° N and longitude 109.624° W (North American Datum 1983). Before reaching Ashley Spring, water flows through a karst network from the southeast flank of the Uinta Mountains.

History of Water Use

The history of interactions between the area's karst-influenced hydrology and civilization is complex. Various entities attempted to divert water around the losing portions of Dry Fork to increase the volume of available irrigation water elsewhere. First, in 1887, pioneers dug a diversion ditch around the large sinks to prevent water from being lost to the subsurface (U.S. Forest Service [USFS], 2014). Despite this, water was lost to other sinks. The second attempt to divert water around the sinks in Dry Fork also failed. The pioneers built a leaky wooden flume between 1894 and 1896 (USFS, 2014); wooden pilings from the flume remain along Dry Fork (figure 2). Between 1953 and 1954, the Mosby Irrigation Company oversaw the construction of the Mosby Canal (McFadden, 1979), which circumvented the loss of water into the sinks of Dry Fork by diverting it along the Mosby Mountain ridge marking the southeast border of the Dry Fork catchment. Between May 17 and May 18, 1997, part of the Mosby Canal failed (figure 3a) about 0.5 mile (0.8 km) upstream of Julius Park, creating erosional ravines along the upper Main Fork of Dry Fork (figure 3b). This event deposited approximately 1.5 million cubic yards (1.1×10^6 m^3) of glacial sediment into Dry Fork (Christenson, 1997).

The main spring has had a spring-collection box since about 1880 (Utah Division of Water Rights, 2013). The City of Vernal, Ashley Upper Irrigation Company, Island Ditch Company, Rock Point Canal and Irrigation Company, and Ashley Central Irrigation Company have an 1874 water right priority on Ashley Spring (Utah Division of Water Rights, 2013). Water is collected from the Ashley Spring diversion box (figure 4) by the Central Utah Water Conservancy District (CUWCD) and the Ashley Valley Water and Sewer Improvement District. The CUWCD distributes water to Vernal City, and the Ashley Valley Water and Sewer Improvement District provides water to other smaller communities and rural domestic locations throughout

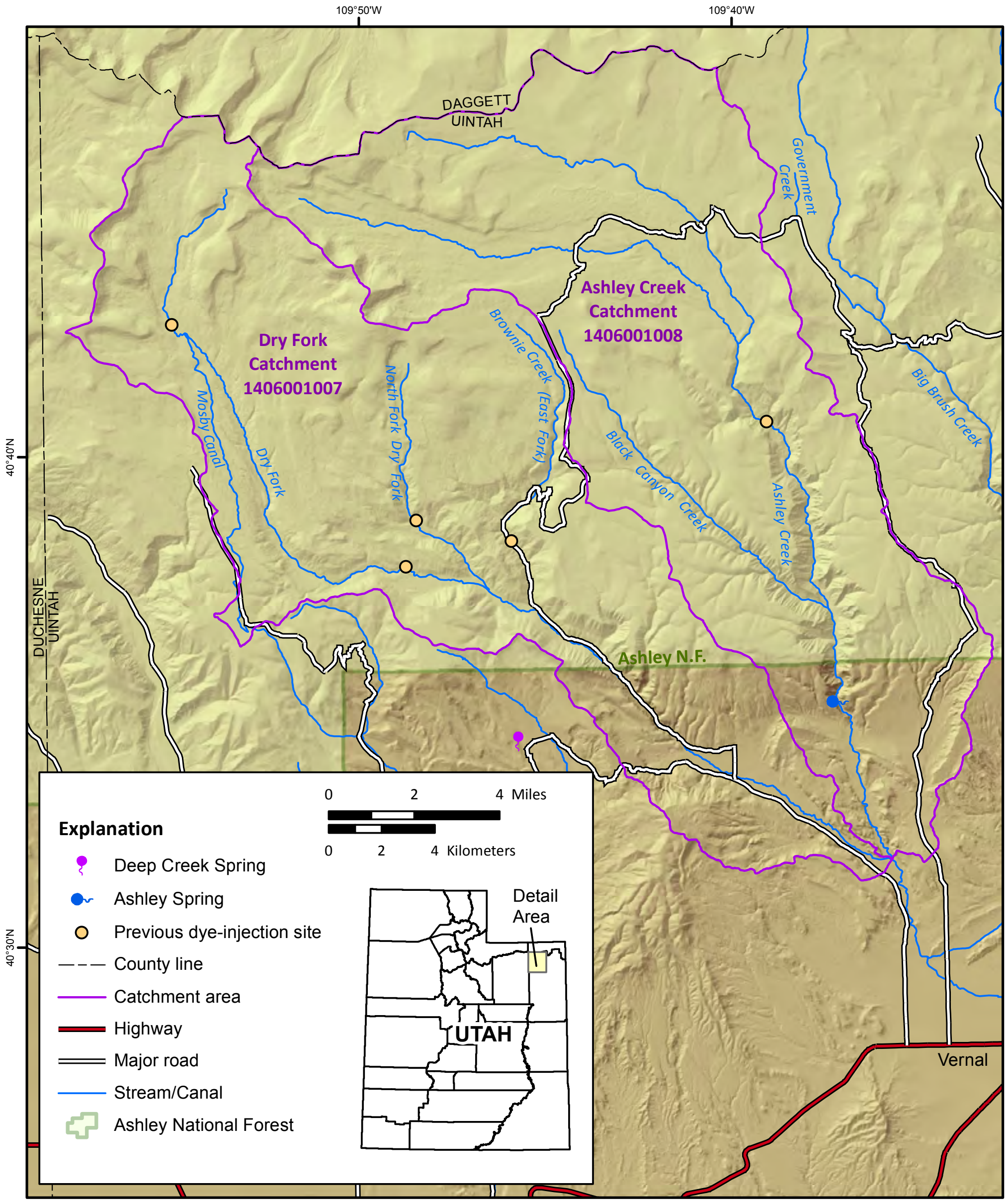


Figure 1. *The study area includes the Dry Fork catchment and Ashley Spring. The previous dye injection sites shown are where injected dye reached Ashley Spring (Maxwell and others, 1971).*

Figure 2. *Remnants of flume structure used to divert water from the Dry Fork sinks.*

the Ashley Valley area, as well as diversion to irrigation companies having priority rights to the water. The combined annual water use from Ashley Spring is between 2600 and 8200 acre-feet (320–1000 hectare-meters [ha-m]) (Utah Division of Water Rights, 2013; figure 5). Ashley Spring is currently associated with, but not necessarily limited to, the following water right numbers: 45-1646, 45-1647, 45-1691, 45-2259, 45-3384, 45-4444, 45-5109, 45-5110, 45-5134, 45-5135, 45-5161, 45-5212, 45-5213, 45-5797, and 45-5820 (Utah Division of Water Rights, 2013). The Utah Division of Drinking Water source code of Ashley Spring is 24013-01. The U.S. Environmental Protection Agency and U.S. Geological Survey (USGS) station identification numbers for the spring are 4937690 and 403448109372101, respectively. The assigned cadastral location identifier of the spring is (D-3-20) 1dcc-S1.

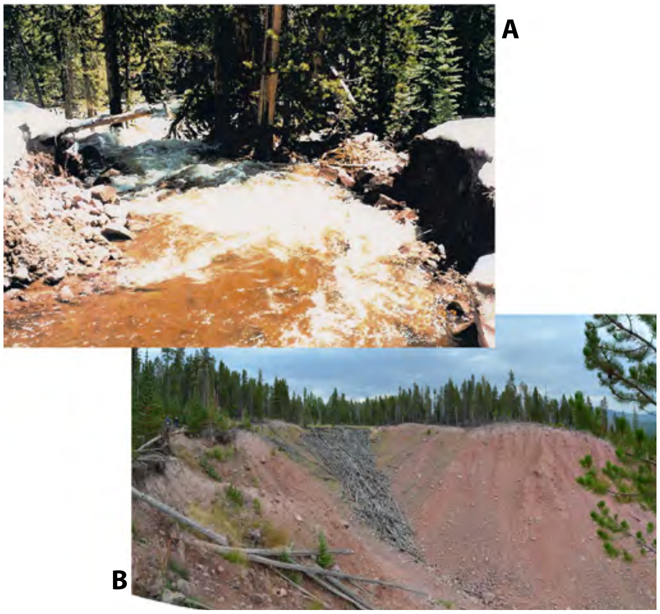


Figure 3. *(A) View of breach at Mosby Canal. Stream flows towards the present site of the Mosby Mountain landslide event into Dry Fork (unpublished photograph provided by the U.S. Forest Service). (B) Erosional gully created by canal breach.*

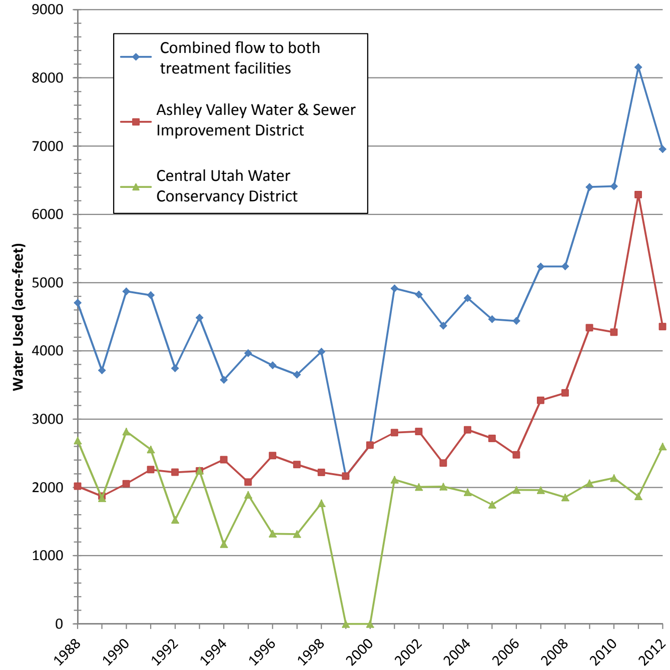


Figure 5. *Water use of Ashley Spring by public water suppliers (Utah Division of Water Rights, 2013).*

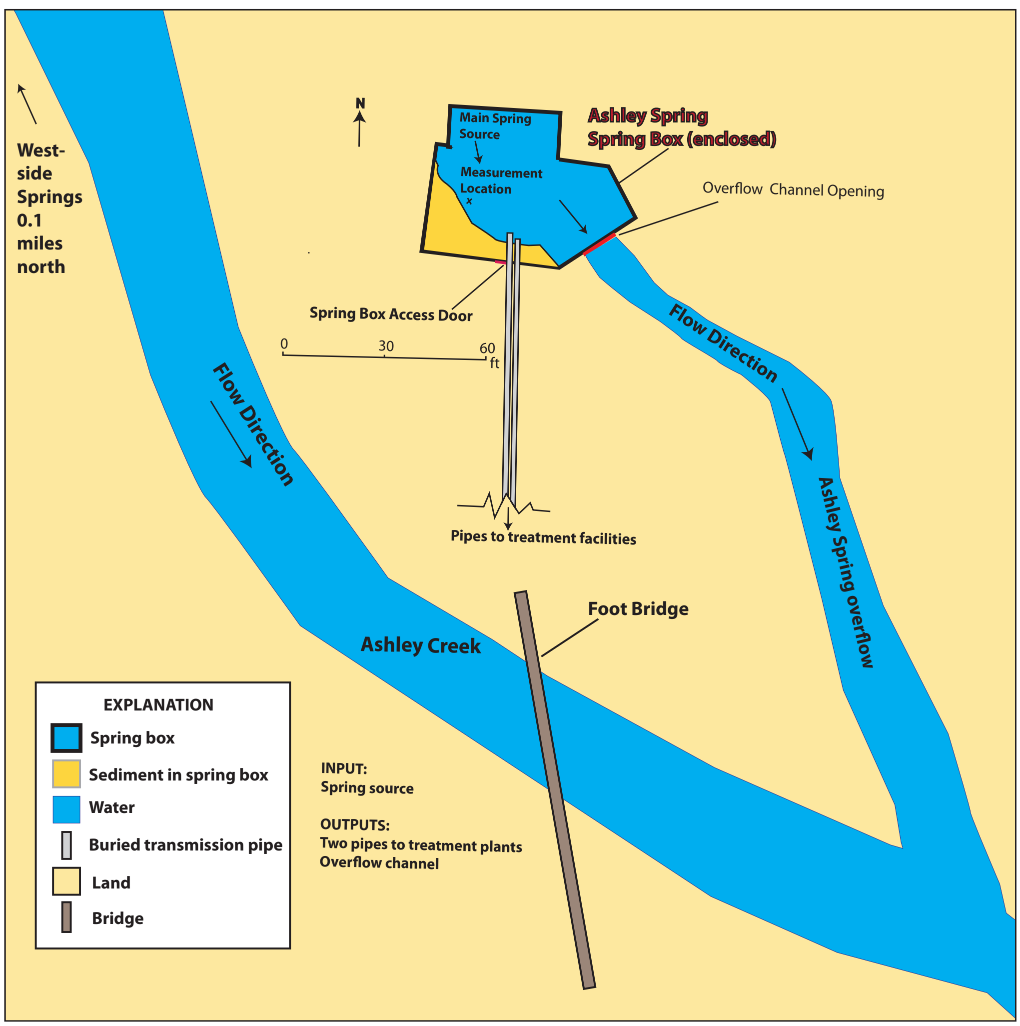


Figure 4. *Layout of inputs and outputs of water at the Ashley Spring box.*

Hydrogeology

The study area is on the southeast flank of the Uinta Mountains. Dry Fork, Ashley Creek, Little Brush Creek, and Big Brush Creek drain the south slopes of the Uinta Mountains north of the Vernal area. The water in these drainage basins enters mostly as snow at elevations of 10,000 to 11,000 feet (3050–3350 m) and eventually ends up in the Green River, east of Vernal. The headwaters of these streams originate on rocks of Precambrian-age Uinta Mountain Group, which consists primarily of conglomeratic sandstones. Because the dip of the geologic units is greater than the stream gradients, progressively younger units (figures 6, 7, and 8) are encountered downstream from the headwaters. When the streams cross the Mississippian Madison Limestone contact, they lose most or all of the water to swallow holes, sinks, and fissures in the bedrock underlying and adjacent to the streambeds (Godfrey, 1985; figures 9 and 10).

Ashley Spring issues from alluvium overlying the Weber Sandstone at the bottom of Ashley Gorge near its entrance. The west-side springs of the Ashley Spring complex discharge directly from the Weber Sandstone. Fluorescent dye tracers show waters from both Ashley Creek and Dry Fork are the source for Ashley Spring (Maxwell and others, 1971; Godfrey, 1985). Water seeps through stream channel deposits consisting mostly of large boulders into underlying solution-enhanced and fractured Madison Limestone, then travels southeast through solution-enhanced fracture networks in the limestone below Ashley Spring (Spangler, 2005). The water likely mixes with water lost upstream of the spring in Ashley Creek, then rises through about 1400 feet (430 m) of fractured sandstone, limestone, and shale, until it surfaces at the bottom of Ashley Gorge (Godfrey, 1985).

Other hydrologic connections between Dry Fork and upper Ashley Creek, and Ashley Spring have been confirmed by multiple dye tests (Maxwell and others, 1971; Godfrey, 1985; Spangler, 2005) and by the presence of red silt found downgradient in Ashley Spring following the 1997 Mosby Canal failure (Wallis, 1997). The Main Fork of Dry Fork also contributes water to Deep Creek Spring, five miles (8 km) southeast of the USGS gauging station on the Main Fork of Dry Fork (Maxwell and others, 1971). In addition, the Main Fork of Dry Fork and upper Ashley Creek contribute water to Brush Creek Spring to the east of Dry Fork basin (Spangler, 2005).

From Dry Fork to Ashley Spring, water travels through the Madison Limestone, and exits through fractures in the Weber Sandstone. The Weber Sandstone is a conduit for upward movement of water to Ashley Spring, and not necessarily a source of water to the spring (Godfrey, 1985). Although the Weber Sandstone may not be the primary source of water to Ashley Spring, it is considered an important aquifer within the study area (Hood, 1976; Chidsey and Sprinkel, 2005).

Because the Weber Sandstone is both an important aquifer and an oil producing unit (Chidsey and Sprinkel, 2005), its hydraulic properties have been researched extensively. The primary hydraulic conductivity of the Weber Sandstone ranges from 2.1×10^{-5} to 0.28 feet per day (6.4×10^{-6}–0.09 m/d), and porosities range from 11 to 19% (Hood, 1976; Lund, 1981). Fracture zones in the sandstone have a higher hydraulic conductivity than unfractured sandstone (Chidsey and Sprinkel, 2005), and the bulk hydraulic conductivity of the formation is between 0.01 and 20 feet per day (0.003–6 m/d) (Chidsey and Sprinkel, 2005). South of the study area, within the Ashley Valley oil field, porosity of the Weber Sandstone ranges between 8 and 20%, having an average of 13% (Chidsey and Sprinkel, 2005). Based on specific capacity (pumping-drawdown) tests conducted by Vernal City and summarized by Lund (1981), the approximate transmissivity of the Weber Sandstone at the mouth of Ashley Gorge is 17 feet squared per day (1.6 m^2/d). The thickness of the Weber Sandstone in Ashley Gorge is 790 feet (240 m) (Lund, 1981), resulting in a hydraulic conductivity of 0.02 feet per day (0.006 m/d).

Fractures in bedrock contributing to groundwater flow are hypothesized to be related to a series of northwest-southeast trending, near-vertical oblique-slip normal faults (figure 11) called the Deep Creek fault zone (Haddox and others, 2005). The age of faulting is bracketed between the early Paleocene and the Oligocene (Haddox and others, 2005). Folds in the region include the relatively large-scale Uinta uplift (the south limb of this is displayed in figure 8) and subsidiary folds (figure 11), which, like the faults, are likely related to the Laramide Orogeny (Hintze, 1988). The combination of deformation from faults and folds contributes to the fractures observed in the study area (Haddox, 2005).

METHODS

Hydrologic Analysis

Hydrologic analysis allows for an understanding of baseline water quantities, including amount of precipitation, the nature of the karst system, and the approximate discharge of Ashley Spring. We compiled hydrologic measurements from PRISM precipitation data, the Utah Climate Center, the National Land Data Assimilation System (NLDAS), and several USGS stream gauging sites and examined them for specific trends. We determined an approximate mean annual water budget and a water budget specific to years for which sufficient data exist. We examined hydrographs from USGS gauging stations to determine basic characteristics of the nature of groundwater flow and statistics for spring flow.

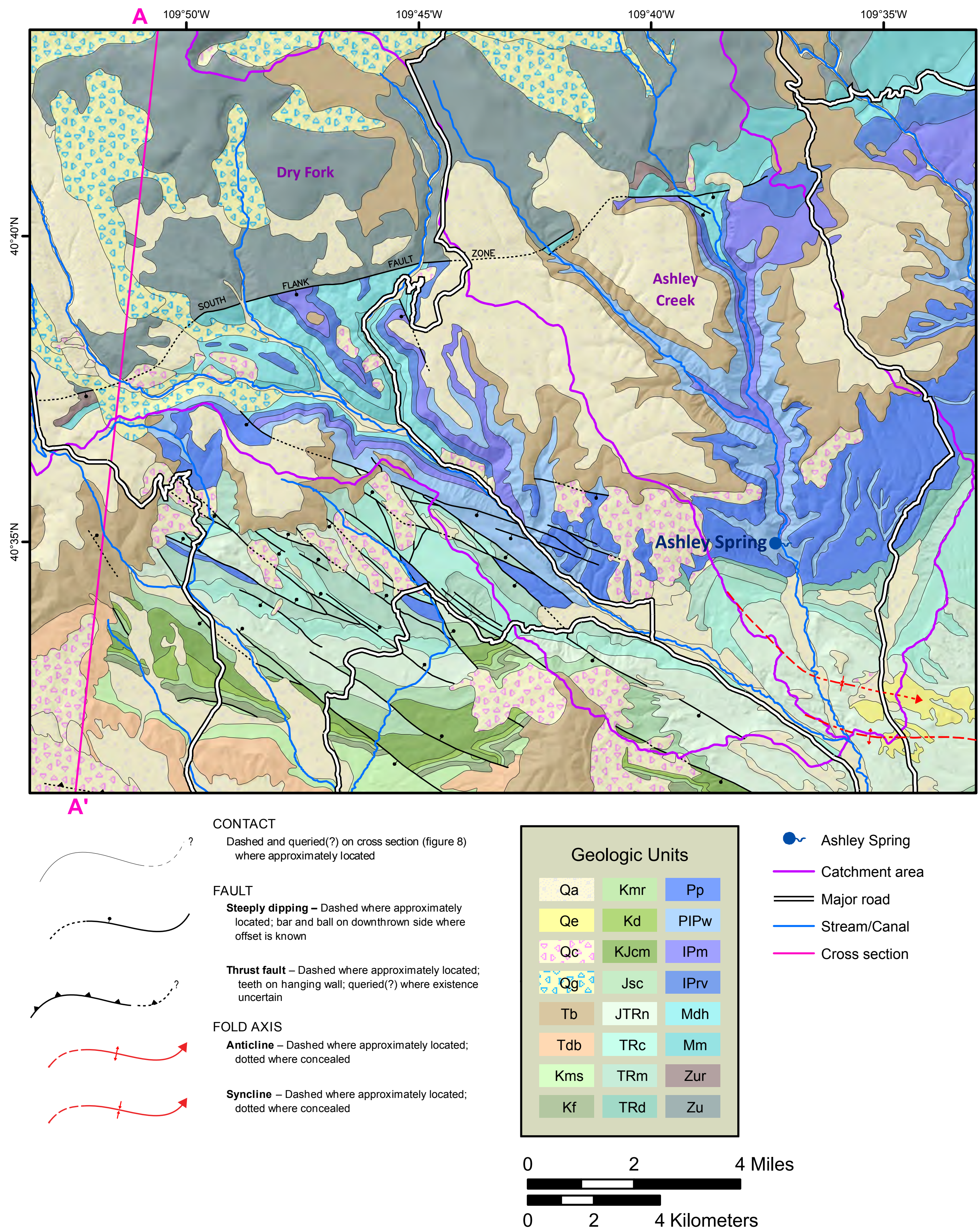


***Figure 6.** Geology of the study area (modified from Sprinkel, 2006). Refer to the stratigraphic column in figure 7 for geologic unit names and figure 8 for cross section A–A'.*

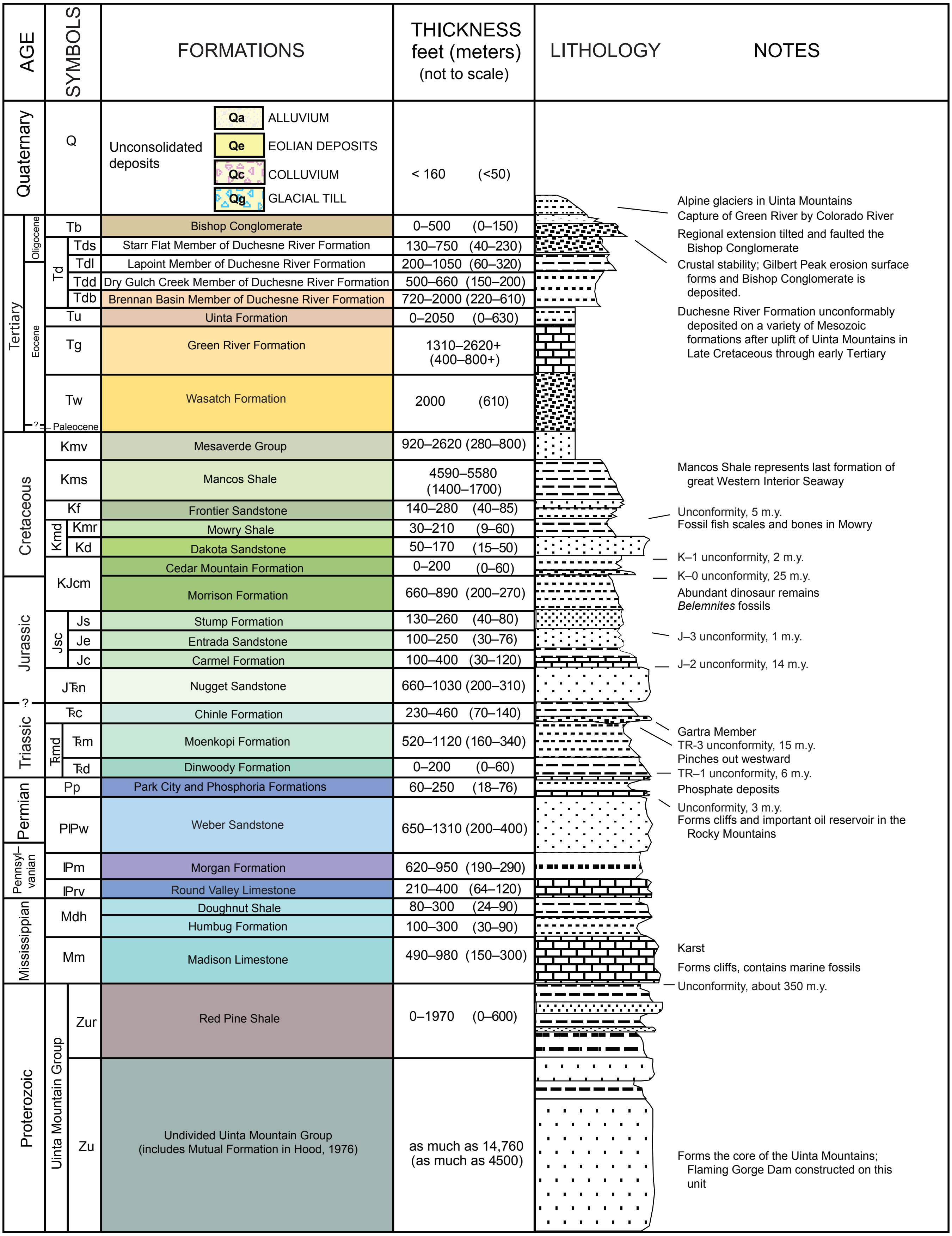


Figure 7. *Stratigraphic column of geologic units in the study area. Units without a color in the "formations" column are not shown on the map in figure 6 or the cross section in figure 8 (modified from Sprinkel, 2006).*

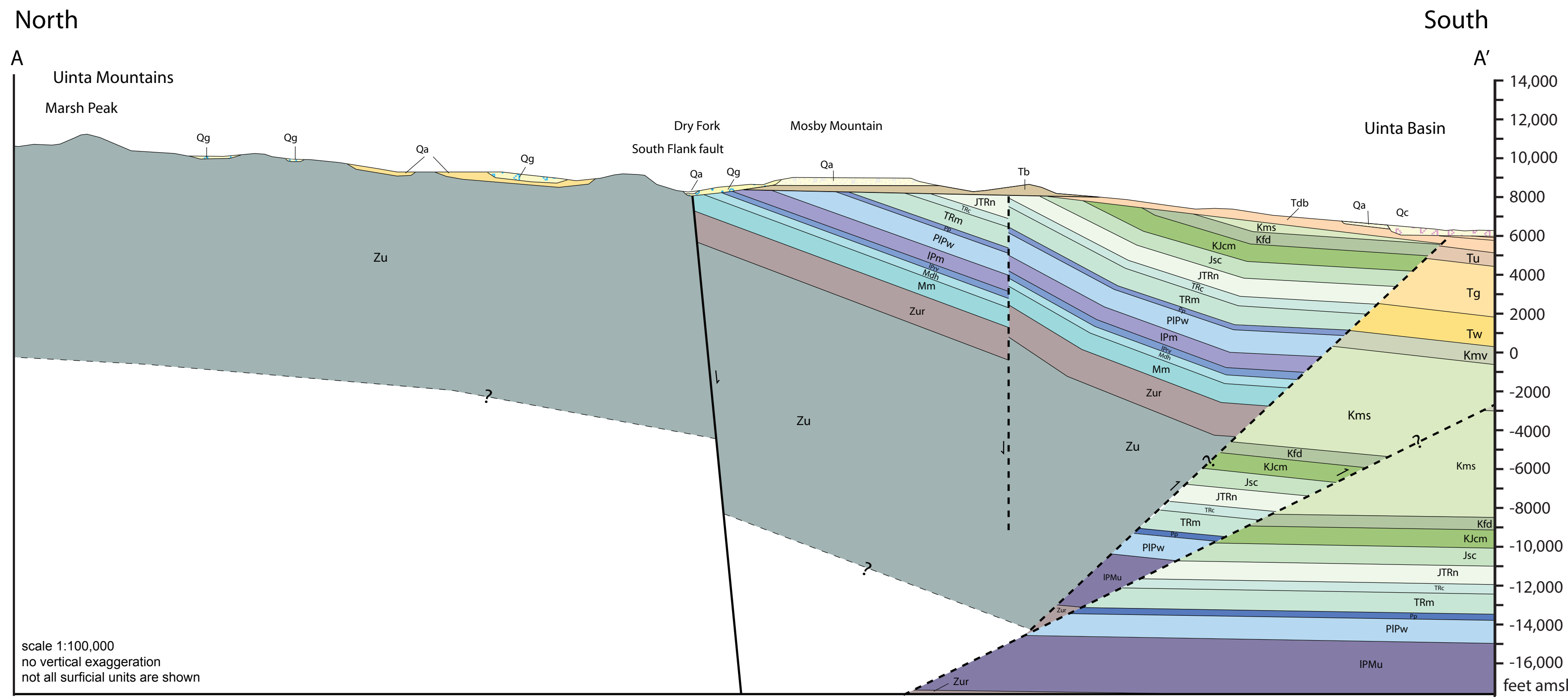


Figure 8. *Geologic cross section across the study area (modified from Sprinkel, 2006). See figure 6 for the location of the cross section and figure 7 for the names of the geologic units.*

__Figure 9.__ Sinkhole near USGS gauging station adjacent to the channel of the Main Fork of Dry Fork.

__Figure 10.__ Solutionally enlarged fractures exposed in the streambed of the losing reach of the Main Fork of Dry Fork about half a mile below the original dye injection site.

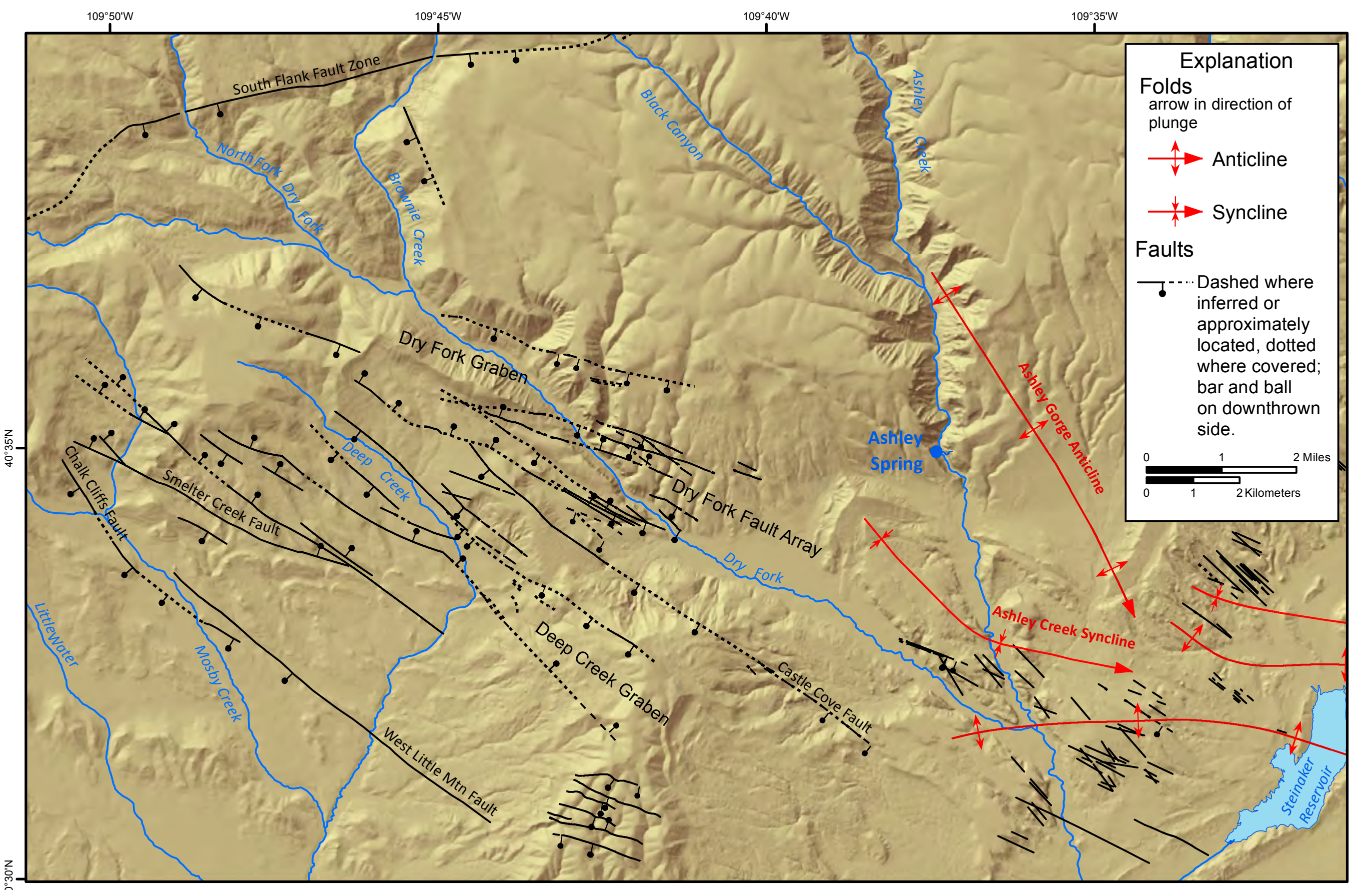


__Figure 11.__ Faults and folds in the Deep Creek fault zone. Modified from Haddox and others (2005), Sprinkel (2006), and Haddox and others (2010a and b).

Water Budget

To determine a water budget for Ashley Creek and Dry Fork basins, we used subdivisions of the basins of the named watersheds (figure 12). The watersheds define hydrologic surface-water boundaries within the basins.

We determined the average yearly output for each watershed by averaging daily discharge measurements from hydrologic stations (USGS, 2013) for each month and summing those averages for total average yearly flow (table 1). Although the data are log-normally distributed, we did not do a transformation, in order to preserve the standard deviation and mean of the data; a transformation results in the geometric mean of the data. The mean flow values might be higher than true central values of the distribution. We calculated summary statistics of the station data so that we could compare values at different stations that were not measured at the same time (figure 13), meaning that many of data are asynchronous.

We also calculated average annual precipitation and average annual evapotranspiration for each watershed. Using digital raster data (continuous surface data) from PRISM (2013), we calculated the cumulative precipitation for each watershed by multiplying the average precipitation within the boundaries of each watershed by the area of each watershed. We conducted a similar calculation using NLDAS (NASA, 2013) evapotranspiration data. We compiled PRISM data from 1940 to 2013, and available NLDAS data (1979 to 1989 and 1995 to 2012). We averaged monthly data and summed them to compute yearly averages (table 1).

We used National Hydrography Dataset (NHDPlus; Horizon Systems Corporation, 2013) data to determine predicted flow

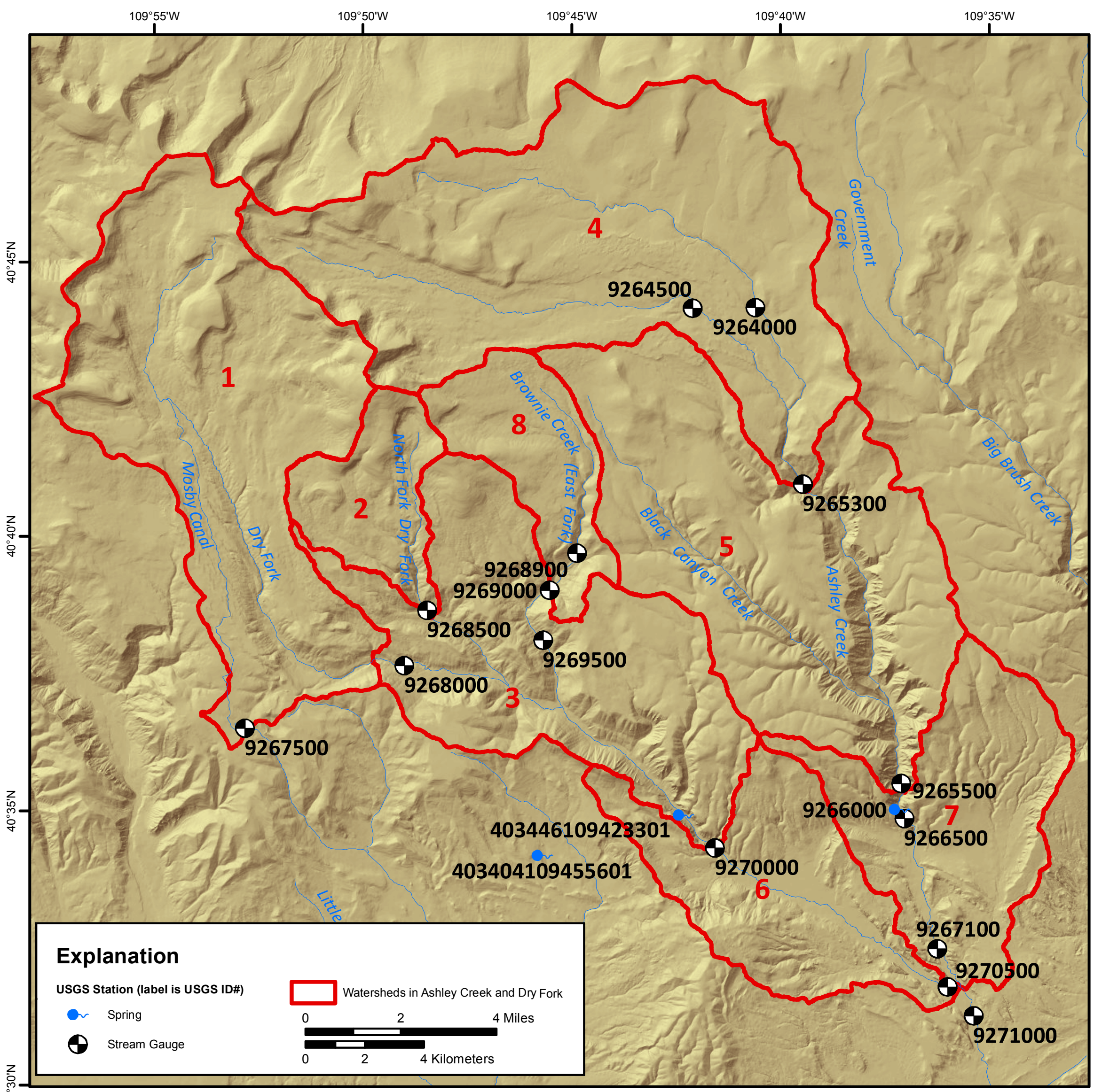


Figure 12. Watersheds and gauging stations used to estimate water budget of Dry Fork and Ashley Creek basins.

Table 1. Monthly averages of data used to calculate the water budget.

		Area[1] or Station[2]	January	February	March	April	May	June	July	August	September	October	November	December	Annual ac-ft	95% Conf. Limit ac-ft
			Monthly Average Amount of Water (ac-ft)													
PRISM Precipitation Estimates		1	4804	5664	6210	6586	6177	4566	4467	4799	5360	5808	4985	4795	64221	781
PRISM Precipitation Estimates		2	810	987	1064	1106	1077	777	740	784	946	1021	855	832	11000	141
PRISM Precipitation Estimates		3	2323	2650	2947	3142	3124	2514	2189	2385	2983	3227	2418	2360	32263	423
PRISM Precipitation Estimates		4	5604	6566	7831	8182	7456	6093	5654	5730	6222	6808	6173	5600	77918	931
PRISM Precipitation Estimates		5	3197	3533	4135	4430	4292	3524	3049	3380	3911	4346	3402	3204	44403	564
PRISM Precipitation Estimates		6	859	894	1042	1175	1228	1137	882	972	1291	1421	908	865	12676	184
PRISM Precipitation Estimates		7	814	806	954	1143	1210	1107	837	990	1274	1493	857	850	12334	187
PRISM Precipitation Estimates		8	1064	1271	1412	1471	1409	1058	996	1056	1231	1335	1132	1084	14517	181
NLDAS Evapotranspiration Estimates		1	717	1203	2113	2362	2701	2767	3411	3275	2324	1377	713	525	23487	714
NLDAS Evapotranspiration Estimates		2	143	228	401	461	547	589	704	692	487	276	141	101	4770	304
NLDAS Evapotranspiration Estimates		3	354	552	1119	1535	2151	2646	3272	3073	2090	1041	438	244	18513	103
NLDAS Evapotranspiration Estimates		4	1087	1737	2798	3185	3688	3756	4204	4276	3206	1967	1053	775	31731	1691
NLDAS Evapotranspiration Estimates		5	555	914	1639	2210	3005	3384	3874	3744	2780	1534	679	394	24712	1045
NLDAS Evapotranspiration Estimates		6	150	205	551	856	1273	1518	1697	1548	1081	564	217	97	9759	276
NLDAS Evapotranspiration Estimates		7	157	228	618	987	1505	1896	2080	1837	1261	638	246	115	11567	232
NLDAS Evapotranspiration Estimates		8	172	277	473	561	687	753	884	871	629	354	173	121	5954	157
USGS Stations	Upper Brownie Creek	9268900	102	80	87	229	2671	3369	1275	584	389	336	207	144	9473	148
USGS Stations	Mosby	9267500	14	–	2	40	434	964	872	719	535	277	103	27	3987	1839
USGS Stations	Dry Fork Below Dry Fork Spring	9270000	–	–	–	646	8200	12751	2976	654	348	738	248	–	26561	1708
USGS Stations	Confluence	9270500	119	115	157	146	5177	10458	2451	458	148	229	175	147	19780	1672
USGS Stations	Lower Brownie Creek	9269500	12	11	12	23	2122	3345	825	233	104	41	10	12	6752	396
USGS Stations	Middle Brownie Creek	9269000	36	41	49	118	1896	2265	638	249	182	132	71	44	5722	84
USGS Stations	North Fork	9268500	56	42	44	140	1398	1604	671	304	192	162	104	75	4792	407
USGS Stations	Upper Dry Fork	9268000	385	315	336	737	7636	9725	2591	1349	982	911	633	460	26060	511
USGS Stations	Ashley Spring	9266000	1117	949	1015	1092	2432	2606	2009	2196	1845	1592	1412	1265	19532	492
USGS Stations	Ashley Creek	9266500	1187	953	997	2670	20708	18232	7741	4991	3596	2771	1888	1449	67184	227
USGS Stations	Middle Ashley Creek	9265300	355	280	295	536	14231	20628	6391	2507	1496	841	555	422	48537	278
USGS Stations	Ashley Creek upstream of Spring	9265500	261	168	187	2401	17192	17720	5461	3393	2472	2091	897	441	52685	107

[1] The single-digit numbers refer to the watersheds in figure 12.
[2] The seven-digit numbers refer to USGS surface water gauging stations in figure 12.

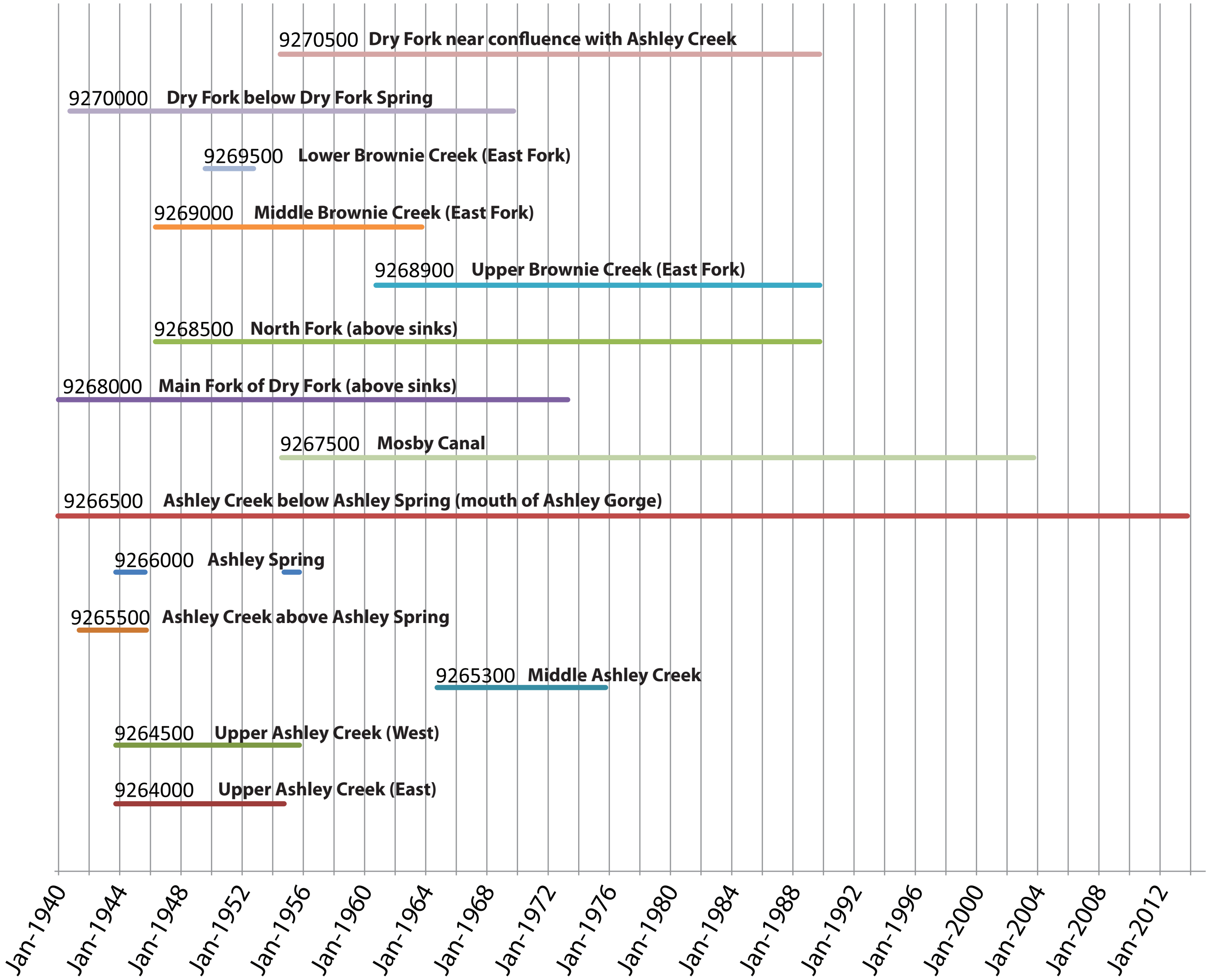


Figure 13. *Temporal range of data collection at hydrologic stations in the area of study (USGS, 2013). Refer to figure 12 for station locations.*

accumulation at each watershed boundary. NHDPlus offers estimates of watershed flow accumulation based on the Extended Unit Runoff Method (EROM). Watershed flow accumulation is an estimate of the average flow in a creek based on the characteristics of the watershed and the local climate. However, the EROM method assumes diversions or unaccounted losses from the creek, typical of karst environments, do not occur. We compared the EROM watershed flow accumulation estimate from the NHDplus data for a given drainage to the streamflow gauging station measurement in that drainage in order to predict creek discharge and estimate water loss to the karst system.

Hydrograph Analysis

We examined Ashley Spring and Ashley Creek discharge data to describe characteristics of the Ashley Spring flow system. Because discharge measurements of Ashley Spring are limited (figure 13), we performed regression analyses between Ashley Creek discharge and Ashley Spring discharge to help model spring flow based on Ashley Creek flow. We used that Ashley Creek as a predictor for Ashley Spring discharge trends because they had a higher correlation coefficient than Dry Fork and Ashley Spring. We examined the seasonality and statistics of the spring discharge data.

We also performed slope analysis (Taylor and Greene, 2002) to determine the nature of flow through the Mississippian carbonate system. The Taylor and Greene (2002) analyses use the slope of a hydrograph to record response of a spring's discharge to precipitation events. We used precipitation data recorded during the fall months to eliminate the buffering (time delay-release) effect of snowmelt.

Mapping

Surface Contours

Structure contours represent the elevations of the tops of geologic units, whereas potentiometric surface contours represent the elevation of the total head in an aquifer. Using the best available geologic maps (Kinney, 1955; Sprinkel, 2006; Haddox and others, 2010a and b), data from oil wells (well completion reports in UDOGM, 2013), water well logs (Utah Division of Water Rights, 2013), and a digital elevation model (DEM) (Gesch and others, 2002; Gesch, 2007), we created structure contour maps for the Weber Sandstone and the Madison Limestone. Based on the DEM, our structure contours, and water well drillers' logs, we determined the source aquifers for several wells, and then determined the approximate potentiometric surface for water in the Weber Sandstone.

We used ArcGIS 10.1 (ESRI, 2012) to create the contours. We first converted the geologic contacts on the Dutch John 1:100,000-scale geologic map (Sprinkel, 2006) to lines and converted the vertices of those lines to points. We then extracted elevations from the 1/3 arc-second resolution (10 m; 30 ft) DEM (Gesch and others, 2002; Gesch, 2007) to the points. We also digitized the Dry Fork and Steinaker Reservoir 1:24,000-scale geologic maps (Haddox and others, 2010a, and b) and the geologic cross sections of the 1:24,000-scale maps (Haddox and others, 2010a and b), assigning unit tops' elevations based on the elevations listed on the cross sections. We included 57 point elevations of formation tops from 20 oil wells (table 2; UDOGM, 2013).

After converting formation top data to points and assigning elevations, we interpolated by applying a natural neighbor (Watson, 1992) interpolation technique in ArcGIS10.1 (ESRI, 2012), which creates continuous raster surfaces made up of cells. We then converted the raster surface to contour lines, and manually removed contour lines in areas where the lines did not accurately define the structure surface. We deemed the lines inaccurate if they extended beyond the extent of the mapped geologic units, or if the contours were not smooth.

We applied similar methods to create potentiometric contours for water in the Weber Sandstone using 32 wells in the region (table 3). We also calculated the average areal flow direction and flow gradient of the groundwater in the Weber Sandstone based on an aspect (direction of greatest dip) raster. The aspect raster was created using the natural neighbor (Watson, 1992) interpolation of the potentiometric surface.

Lineaments

Lineaments are useful in hydrologic studies because they can provide information on subsurface characteristics that may influence groundwater flow. Because we were most interested in the fracture patterns of the Paleozoic units, and due to the availability of exposed lineaments and the coverage of 1-foot resolution aerial imagery, we concentrated lineament mapping within the northern halves of the Steinaker Reservoir and Dry Fork 1:24,000-scale topographic quadrangles. We traced 2032 lineaments, 1469 in the Weber Sandstone, 406 in the Chinle Formation, and 157 in the Park City Formation.

We also determined the orientations of drainages and tributaries in the area of the Steinaker Reservoir, Taylor Mountain, Dry Fork, and Dyer Mountain 1:24,000-scale quadrangles. We first simplified the lines of NHDPlus stream vectors from the Utah Automated Geographic Reference Center (gis.utah.gov), to reduce processing time and to eliminate smaller variations in the streams' directions. We simplified the lines of the streams using the Simplify Line tool in ArcGIS 10.1 (ESRI, 2012), which removes extraneous bends while preserving essential shape. We allowed for offset of up to 100 feet (30 m) from the original line. Decreasing the allowable offset increases the number of bends in lines smaller than about 30 feet (9 m), the trends of which are not considered as important as the larger, regional trends. We then split the streams into segments at each bending point and measured the orientation of each segment. Canal systems were included in this set, but they only make up a small portion of the channels in the four quadrangles.

Depressions

Using VrTwo photogrammetry software (made by Cardinal Systems), 1-meter resolution true color and infrared aerial photography (USDA, 2013b), and the Dutch John 30′ x 60′ geologic map (Sprinkle, 2006), we manually mapped apparent depressions likely related to karst processes. Depressions were qualified as karst features if they overlie or are within the Mississippian carbonates mapped on the Dutch John geologic map and did not appear to be the result of mass wasting (i.e., a slump or slide). Larger depressions were mapped using polylines, while smaller depressions were marked using points. Known karst areas that influence hydrology, including Little and Big Brush Creek Caves, were also included. Caves not receiving water or higher in elevation than the potentiometric surface were not included, as our interest was to understand the elevation of active karst features and surface-water drains.

Dye Tracing

During a dye trace, dye is released (injected) into a watershed while monitoring for dye presence at downgradient locations. Detection of the dye can indicate flowpaths and velocity of water traveling from the injection point(s) to the monitoring location(s).

Site and Dye Selection

We chose two sites to inject fluorescent dyes, using different wavelength dyes at each site so that they could be differentiated. We chose the first site in the main fork of Dry Fork in an attempt to reproduce results reported by Maxwell and others (1971), and used Rhodamine WT as the dye. We selected the second site in Rock Canyon because the fractured Weber Sandstone is vertically above Ashley Spring, it is in the middle of a proposed mining area, and the natural drainage of Rock Canyon meets Ashley Creek downstream of Ashley

Table 2. *Oil wells (UDOGM, 2013) used to construct structure contours.*

UDOGM API	Formation	Depth to Fm Top (ft below ground)	X (m NAD83)	Y (m NAD83)	Surface Elevation (ft amsl)	Fm Top Elevation (ft amsl)
4304710262	Moenkopi	6915	620857	4480264	5526	-1389
4304710262	Phosphoria	7807	620857	4480264	5526	-2281
4304710262	Weber	7860	620857	4480264	5526	-2334
4304710332	Moenkopi	2888	635506	4479122	5057	2169
4304710332	Phosphoria	3636	635506	4479122	5057	1421
4304710332	Weber	3748	635506	4479122	5057	1309
4304710367	Moenkopi	3030	636746	4483536	5243	2213
4304710702	Moenkopi	4530	628485	4486908	5782	1252
4304710702	Phosphoria	5272	628485	4486908	5782	510
4304710702	Weber	5480	628485	4486908	5782	302
4304710734	Moenkopi	6940	626283	4475567	5292	-1648
4304710734	Phosphoria	7625	626283	4475567	5292	-2333
4304710734	Weber	7808	626283	4475567	5292	-2516
4304710937	Moenkopi	4310	627214	4489451	5681	1371
4304710939	Moenkopi	4620	635632	4474232	5202	582
4304710939	Phosphoria	5325	635632	4474232	5202	-123
4304710939	Weber	5475	635632	4474232	5202	-273
4304710964	Moenkopi	4474	636895	4473828	5063	589
4304711175	Phosphoria	6959	627888	4474414	5214	-1745
4304711175	Weber	7059	627888	4474414	5214	-1845
4304711423	Moenkopi	150	617824	4486587	6023	5873
4304711423	Park City	1046	617824	4486587	6023	4977
4304720307	Moenkopi	4436	629933	4476065	5116	680
4304720307	Phosphoria	5155	629933	4476065	5116	-39
4304720307	Weber	5228	629933	4476065	5116	-112
4304720366	Moenkopi	65	608405	4491157	7596	7531
4304720366	Park City	730	608405	4491157	7596	6866
4304720366	Weber	876	608405	4491157	7596	6720
4304720366	Mississippian	2588	608405	4491157	7596	5008
4304720370	Moenkopi	1430	616703	4483130	5886	4456
4304720370	Park City	2255	616703	4483130	5886	3631
4304720370	Weber	2300	616703	4483130	5886	3586
4304720390	Moenkopi	3873	633542	4481959	5400	1527
4304720390	Phosphoria	4560	633542	4481959	5400	840
4304720390	Weber	4742	633542	4481959	5400	658
4304720392	Moenkopi	4197	631094	4481110	5317	1120
4304720392	Phosphoria	5130	631094	4481110	5317	187
4304720392	Weber	5276	631094	4481110	5317	41
4304720394	Moenkopi	3421	634844	4477545	5275	1854
4304720394	Phosphoria	4107	634844	4477545	5275	1168
4304720394	Weber	4280	634844	4477545	5275	995
4304720396	Phosphoria	4746	631040	4476013	4976	230
4304720396	Weber	4907	631040	4476013	4976	69
4304720398	Park City	4591	634681	4476111	5234	643
4304720398	Phosphoria	4597	634681	4476111	5234	637
4304720398	Weber	4765	634681	4476111	5234	469
4304730090	Moenkopi	2487	617206	4481814	5834	3347
4304730090	Park City	3340	617206	4481814	5834	2494
4304730090	Weber	3460	617206	4481814	5834	2374
4304730090	Humbug	5955	617206	4481814	5834	-121
4304730110	Moenkopi	4520	635632	4474587	5203	683
4304730110	Phosphoria	5232	635632	4474587	5203	-29
4304730110	Weber	5372	635632	4474587	5203	-169
4304730110	Humbug	7546	635632	4474587	5203	-2343

Table 2. *Continued.*

UDOGM API	Formation	Depth to Fm Top (ft below ground)	X (m NAD83)	Y (m NAD83)	Surface Elevation (ft amsl)	Fm Top Elevation (ft amsl)
4304730110	Deseret	7640	635632	4474587	5203	-2437
4304730110	Madison	7850	635632	4474587	5203	-2647
4304730114	Moenkopi	4285	609778	4486536	8535	4250
4304730114	Phosphoria	4865	609778	4486536	8535	3670
4304730114	Weber	4988	609778	4486536	8535	3547
4304730159	Moenkopi	3238	601559	4487246	6725	3487
4304730159	Park City	3640	601559	4487246	6725	3085
4304730159	Weber	4400	601559	4487246	6725	2325
4304730177	Moenkopi	3820	633093	4477318	5089	1269
4304730177	Phosphoria	4507	633093	4477318	5089	582
4304730177	Weber	4740	633093	4477318	5089	349
4304730184	Moenkopi	4232	642540	4476486	4751	519
4304730184	Phosphoria	5010	642540	4476486	4751	-259
4304730184	Weber	5466	642540	4476486	4751	-715
4304730487	Phosphoria	4425	612419	4483308	6764	2339
4304730487	Weber	4590	612419	4483308	6764	2174
4304730693	Moenkopi	2622	637451	4483694	5316	2694
4304730697	Phosphoria	4100	637026	4483680	5132	1032
4304730697	Weber	4250	637026	4483680	5132	882
4304730697	Madison	7700	637026	4483680	5132	-2568
4304731438	Moenkopi	166	618620	4486366	5790	5624
4304731438	Park City	1062	618620	4486366	5790	4728
4304731438	Weber	1195	618620	4486366	5790	4595
4304731438	Madison	3490	618620	4486366	5790	2300
4304731725	Moenkopi	6646	626818	4474387	5294	-1352
4304731725	Phosphoria	7372	626818	4474387	5294	-2078
4304731725	Weber	7550	626818	4474387	5294	-2256
4304731825	Moenkopi	6520	627199	4473884	5281	-1239
4304731825	Phosphoria	7218	627199	4473884	5281	-1937
4304731825	Weber	7376	627199	4473884	5281	-2095
4304734541	Phosphoria	7552	618378	4480781	5682	-1870
4304734541	Weber	7638	618378	4480781	5682	-1956

Spring, eliminating the probability of overland flow contaminating samples collected at Ashley Spring (figure 14). We chose Eosine fluorescent dye to conduct the test at the second site. Table 4 summarizes the order of events for the tests.

Injection

All dye and most of the sample packets were provided by Ozark Underground Laboratory. The dyes were injected by Melissa Hendrickson (U.S. Forest Service), who wore protective clothing and used tarps for dye mixing. We followed the protocol outlined in Taylor and Greene (2002) to determine the approximate amount of dye needed for each test.

On Monday, September 24, 2012, at 13:26, we poured 3 pounds (1.3 kg) of Rhodamine WT dye into the main fork of Dry Fork as a slug injection (figure 15A). The exact coordinates of the injection site are 600347 m E and 4497942 m N (UTM, Zone 12, NAD 1983). By 14:45, dye was visible 750 feet downstream from the injection site at coordinates 600776 m E and 4497834 m N (UTM, Zone 12, NAD 1983).

On Thursday, September 27, 2012, at 16:27, 4 pounds (1.8 kg) of powdered Eosine dye were mixed with 3000 gallons (11 m^3) of water provided by a Uintah County water truck, and poured into Rock Canyon, located at 618255 m E and 4493345 m N (UTM, Zone 12, NAD 1983). Before the dye was poured, approximately 1000 gallons (4 m^3) of water was released from the truck. Then, the rest of the water was released with the dye (figure 15B). The truck emptied a total of 3000 gallons (11 m^3) onto the ground within 7 minutes. Dye-laden water traveled down the canyon from the injection site

Table 3. *Water wells used to create Weber Sandstone potentiometric surface.*

	Site Identification Number	X (m)	Y (m)	Water Level Date	Depth to Water (ft)	Well Depth (ft)	Hole Depth (ft)	Elevation (ft amsl)	Water Level Elevation (ft amsl)
Utah Division of Water Rights Well Idenfication Number (WIN)	277	609719	4490832	5/16/92	200	330	330	6860	6660
	6295	612025	4490927	11/16/83	20	240	240	6593	6573
	10618	610334	4491650	10/12/95	43	92	92	6746	6703
	18115	629034	4494853	8/26/98	3	35	35	5687	5684
	18118	629003	4495005	8/30/98	10	35	35	5687	5677
	18119	628881	4495219	8/29/98	8	38	38	5697	5689
	18334	620052	4492081	11/5/98	75	137	350	6329	6254
	25172	611182	4491158	5/11/02	108	130	130	6689	6581
	25322	622412	4488574	5/17/02	-404	1590	1590	5701	6105
	25641	610456	4491271	7/29/02	85	306	306	6718	6633
	27565	610387	4491638	7/8/03	30	105	105	6754	6724
	30199	610049	4490881	12/10/82	150	252	252	6796	6646
	30217	611680	4491047	9/24/80	60	160	160	6652	6592
	30566	612168	4491076	5/14/81	20	135	135	6595	6575
	30629	611826	4490907	5/6/81	64	200	200	6600	6536
	30900	611702	4490952	11/13/80	30	180	180	6604	6574
	31105	610034	4490525	8/27/79	170	270	285	6809	6639
	33685	611323	4491076	3/18/05	100	180	180	6695	6595
	69119	619517	4491314	7/26/97	-46	353	–	6280	6326
	431236	618677	4486354	5/6/08	-162	1842	0	5801	5963
	432355	629460	4494411	2/11/09	40	100	100	5662	5622
	432638	616870	4487292	4/17/09	-339	96	2750	5996	6346
	432726	618683	4488189	5/20/09	-253	2373	2373	6007	6260
	433149	611963	4490855	10/5/09	10	225	225	6577	6567
	437065	619285	4491730	10/22/13	14	210	212	6294	6280
	437067	620032	4492453	10/22/13	75	206	210	6356	6281
	437126	620378	4492821	9/27/13	138	210	210	6418	6280
USGS Station Identification Number	403141109334501	621698	4487356	12/1/36	-207	2552	–	5910	6117
	403444109423201	609216	4492806	3/1/65	8	170	–	6864	6856
	403556109310701	625283	4495280	10/13/81	192	1303	1308	5700	5508
	403636109280101	629634	4496588	4/3/85	162	630	–	5986	5824
	403636109280101	629634	4496588	9/21/83	201	630	–	5986	5785

for about 0.25 miles (400 m) before completely infiltrating into the Weber Sandstone.

Sampling

To detect the dye at the spring and at the wells, we used activated carbon packets (commonly referred to as “bugs”) and collected water samples. The packets were attached to 10-gauge steel wire loops mounted in about 3-pound (1.8 kg) concrete blocks (referred to as “gumdrops”). We placed packets in the Ashley Spring collection box (figure 4), the west-side springs about 100 feet (30 m) upstream along Ashley Creek, the Vernal (Ashley Gorge) well, Deep Creek Spring, and in Ashley Creek in an area thought to be upstream from the influence of Ashley Spring and the west-side springs (figure 14).

At four locations, only one bug was used during the entire sampling period. At the Ashley Spring collection box, bugs were exchanged at varying intervals (table 4; appendix A). Also, at the spring box, we collected samples before the dye trace was conducted to detect any ambient fluorescence in the spring water. For the carbon packets, we used one duplicate sample and one trip blank sample to ensure sample integrity. Paul Inkenbrandt collected the carbon sample packets, and remained clear of the dye injection areas and avoided contact with contaminated material until after collecting the carbon sample packets.

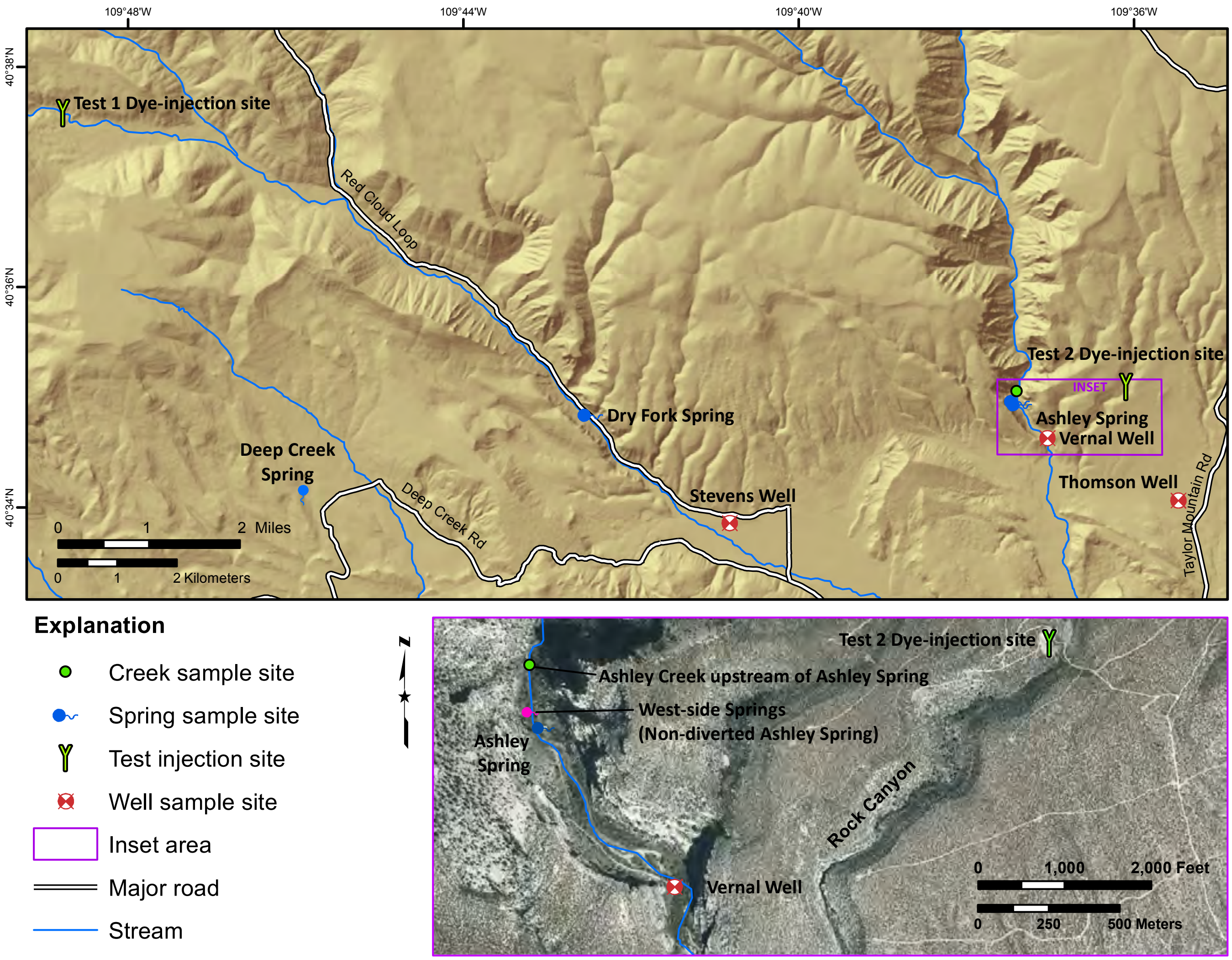


Figure 14. *Locations of dye-injection sites and dye monitoring sample collection sites for dye tracer tests conducted in this study.*

Table 4. *Timeline of significant events for the UGS dye tracer study.*

9/19/2012 11:43	Two carbon packets placed in Ashley Spring box to measure ambient fluorescence (OUL # W1009 and W1010 in appendix A).
9/24/2012 13:26	Three pounds of Rhodamine WT dye poured into Dry Fork at 600347 m E and 4497942 m N (UTM, Zone 12, NAD 1983).
9/24/2012 14:45	Leading edge of dye visible in Dry Fork 750 feet downstream of injection site.
9/24/2012 18:57	Retrieved ambient fluorescence carbon packets (OUL # W1009 and W1010 in appendix A).
9/27/2012 7:56	Carbon packet OUL # W1023 placed in a small spring 250 feet northwest of Ashley Spring box, in the west-side springs, at 616421 m E and 4493093 m N (UTM, Zone 12, NAD 1983).
9/27/2012 16:27	Four pounds of Eosine dye and 4000 gallons of water from a water truck poured at 618255 m E and 4493345 m N (UTM, Zone 12, NAD 1983).
9/28/2012 13:39	Placed carbon packet OUL # W1018 in Ashley Spring.
9/28/2012 21:17	Carbon packet OUL # W1018 collected from Ashley Spring, later showing no measurable Rhodamine WT. Carbon packet OUL # 1019 placed into Ashley Spring box.
9/29/2012 8:00	Carbon packet OUL # W1019 collected from Ashley Spring box, showing positive match for Rhodamine WT dye.
9/29/2012 8:25	Carbon packet OUL # W1023 collected from Ashley Spring box, showing positive match for Rhodamine WT dye.
11/29/2012 14:00	Final carbon packet OUL # W4065 placed in Ashley Spring.
2/12/2013 10:00	Final carbon packet OUL # W4065 collected from Ashley Spring. As of this time, no Eosine was detected in Ashley Spring.

Figure 15. *Melissa Hendrickson injecting the dye for the (A) first and (B) second dye tests. The protective clothing in B was to prevent contamination from windblown powdered dye.*

Analyses

Ozark Underground Laboratory in Missouri analyzed 20 carbon packets and 3 water samples. Melissa Hendrickson analyzed 5 carbon packets and 5 water samples using a filter fluorometer at the U.S. Forest Service station in Vernal, Utah.

We roughly estimated the mass of dye recovered using equation 7 from Mull and others (1988), where the mass recovered is the sum of the products of average dye concentration, average spring discharge, and length of time of sampling. Average dye concentration as calculated is the laboratory concentration divided by the number of days that the carbon packet remained in the spring water (Thomas Aley, Ozark Underground Laboratory, personal communication, April 25, 2013). Using the average dye concentration assumes that the adsorption and retention of the dye is constant (Aley, 2002). In some cases, where organic chemicals may exist in the sample site water, the chemicals can clog the available sorption sites in the bug, reducing the available surface area of the activated carbon, and thereby reducing the adsorption of dye. If the packet is left in the sampling location in the water for long periods of time, the measured dye concentration may be lower than the actual concentration because the rate of dye uptake onto the carbon decreases with time (Aley, 2002). Mull and others (1988) base their determinations on quantitative analysis of water samples, not charcoal, so the results of our approach must be considered tentative. Accurate discharge of Ashley Spring is difficult to determine, and is critical to calculations of mass recoveries (Larry Spangler, USGS, personal communication, November 2013).

Analyses of Previous Tests

To check our results, we compared them to previous results, analyzing the dye traces from Dry Fork conducted by Maxwell and others (1971). Maxwell and others (1971) did not provide direct readings of their fluorometer data, only dye breakthrough graphs, and they omitted details such as the exact amount of dye used from their publication. However, supplementary unpublished documents (Maxwell and Bridges, 1968; Bridges and Maxwell, 1969) add detail to the previous studies, including approximate timing of the dye injection(s) and amount of dye used. We did not apply the quantitative analyses to the UGS data because we did not measure instantaneous dye concentrations, only cumulative dye concentrations—the amount of dye that accumulated in the carbon packets.

We applied relatively recent methods of dye-breakthrough-curve analysis (Mull and others, 1988) to the original Maxwell and others (1971) curves, since these methods were not available at the time of the 1971 study. We first digitized the dye-breakthrough graphs in ArcGIS 10.1 (ESRI, 2012), using a coordinate system with the x coordinate as time and the y coordinate as concentration. We then converted the digitized lines of the breakthrough curves into a series of regularly spaced points along the lines, and exported the coordinates of those points for analysis. For their second test, Maxwell and others (1971) injected dye several miles upstream into the Main Fork of Dry Fork at Blanchett Park. However, they measured dye concentrations near the sinks at Dry Fork. We used the time of the first detection of dye (leading edge of dye) for our calculations.

Mull and others (1988) outlined several techniques for analyzing dye-tracer breakthrough curves based on quantitative analyses of water sample concentrations. Most of their analysis treats the breakthrough curves as distributions, describing the mean time of breakthrough, mean dye velocity, and standard deviation of breakthrough time. First, we normalized the dye concentrations using the Mull and others (1988) formula and dye injection and recovery mass (Maxwell and Bridges, 1968; Maxwell and others, 1971):

$$c_i = \frac{1}{M_{out}} \qquad (1)$$

where:

c_i = standardized concentrations of dye at time i in $(mg/L)/kg$.

M_{out} = mass of dye recovered in kg.

Standardized concentration is used to calculate standardized dye load (Mull and others, 1988):

$$L_i = 28.32 c_i Q_i \quad (2)$$

where:

L_i = normalized dye load at time i in $(mg/L)/kg$.

Q_i = discharge of spring at time i in cubic feet per second (cfs).

Using the results of the above values, mean travel time is calculated using (Mull and others, 1988):

$$t_{avg} = \frac{\sum_{i=1}^{n}(t_i c_i \Delta t_i Q_i)}{\sum_{i=1}^{n}(c_i \Delta t_i Q_i)} \quad (3)$$

where:

t_{avg} = mean travel time (hrs).

t_i = discharge of spring at time i in cubic feet per second (cfs).

From mean travel time, we calculated mean velocity of groundwater flow (Mull and others, 1988):

$$v_{avg} = \frac{d}{3600\, t_{avg}} \quad (4)$$

where:

v_{avg} = mean velocity of groundwater flow in feet per second (ft/s).

d = distance of trace in ft.

The standard deviation of travel time was calculated using (Mull and others, 1988):

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}((t_i - t_{avg})^2 c_i \Delta t_i Q_i)}{\sum_{i=1}^{n}(c_i \Delta t_i Q_i)}} \quad (5)$$

where:

σ = standard deviation of travel time.

Using the dye travel time based on the time of first detection of the dye divided by the linear distance of 10.6 miles (56,000 ft; 17 km) from the USGS gauging station near Dry Fork sinks to Ashley Spring, we plotted the velocities of the two Maxwell and others (1971) tests and the velocity from our test. We did not use the calculated mean velocity of groundwater flow because we could not calculate it for the UGS test. We plotted the velocities as a function of Ashley Spring discharge. We then performed a linear regression on the three points to examine the rough relationship between spring discharge and dye velocity.

Chemistry

Sampling and Analysis

We sampled water at nine sites in the study area in September 2012 (table 5; figure 16) to determine baseline water chemistry and to better understand the groundwater flow paths of the Dry Fork and Ashley Spring hydrologic system. Water from most of the sites was analyzed for general chemistry and nutrients (nitrate, nitrite, ammonia, and phosphorous) by the Utah Division of Epidemiology and Laboratory Services in Salt Lake City. The UGS resampled all sites in May 2013, in addition to Dry Fork Spring (which was dry during autumn 2012). Of the nine sites, water samples from seven were analyzed for oxygen and deuterium isotopes, six for tritium, and two for carbon isotopes.

Data Compilation

We augmented our data with data compiled from the U.S. Environmental Protection Agency (USEPA, 2013), the U.S. Forest Service, the Utah Division of Drinking Water (UDDW, 2013), a consulting firm (Bowen, Collins, and Associates, 2005), and the U.S. Geological Survey (USGS, 2013). To calculate the average concentration of the various chemical constituents for Ashley Spring, we compiled all available chemistry data (including our own), then computed the concentration statistics for each constituent. We conducted a similar compilation for all water wells near the Ashley Creek and Dry Fork watersheds that penetrate the Weber Sandstone (figure 17). Histograms of the concentration data indicate the data are log-normally distributed, making the geometric mean and the median more representative of the middle value of the data than the arithmetic average. Because some of the samples did not include a full suite of the most common anions and cations, we did not screen or discard samples based on charge balance. We also compiled sampling data that included the full suite of the most common anions and cations, allowing a review of charge balance. We rigorously analyzed these data using AquaChem (Schlumberger, 2011) computer software.

We characterized groundwater quality of Ashley Spring by examining how various parameters change over time. We quantified the variability of the common groundwater constituents. We used data provided by the CUWCD for the period 1987 to 2013, based on samples collected from their intake pipe of Ashley Spring. To visualize the data, we plotted it using box and whisker plots and line plots, which show the distribution of the constituents. We also summarized the data into months and seasons, depending on data availability, to describe seasonal variation. We constructed time series plots of data and ran linear regression on the time series to determine any general long-term variations in the data.

Table 5. *Water sources sampled by the Utah Geological Survey for this study.*

Name	Source	UTM (NAD83 Z12) X m	UTM (NAD83 Z12) Y m	Elevation ft	Water Right[1]	Well ID	USGS Station Number
Allen Well	Well	622416	4488830	5706	45-3513	25322	403228109331701
Ashley Creek upstream of Ashley Spring	Stream	616415	4493269	6290			9265500[2]
Vernal Well	Well	616925	4492488	6217	45-4596		
Ashley Spring	Spring	616463	4493048	6270	45-1647		403448109372101, 9266000
Perry Well	Well	613569	4489587	6383	45-3463	33446	
Remember the Maine Well	Well	618677	4486096	5801	45-2072	2931	403101109355202[3]
Stevens Well	Well	611587	4491057	6587	45-5484	10000	
Dry Fork (Test 1 Dye-injection site)	Stream	600366	4497951	8033			9268000[2]
Thomson Well	Well	619131	4491438	6258	45-6150	427454	

[1]Not all water rights listed; see the Utah Division of Water Rights for a complete listing of water rights of each source
[2]Location of sample collection site approximately coincided with these stations, as the stations were not exactly located
[3]Site number was designated for this study and does not exist in the USGS NWIS database (USGS, 2013)

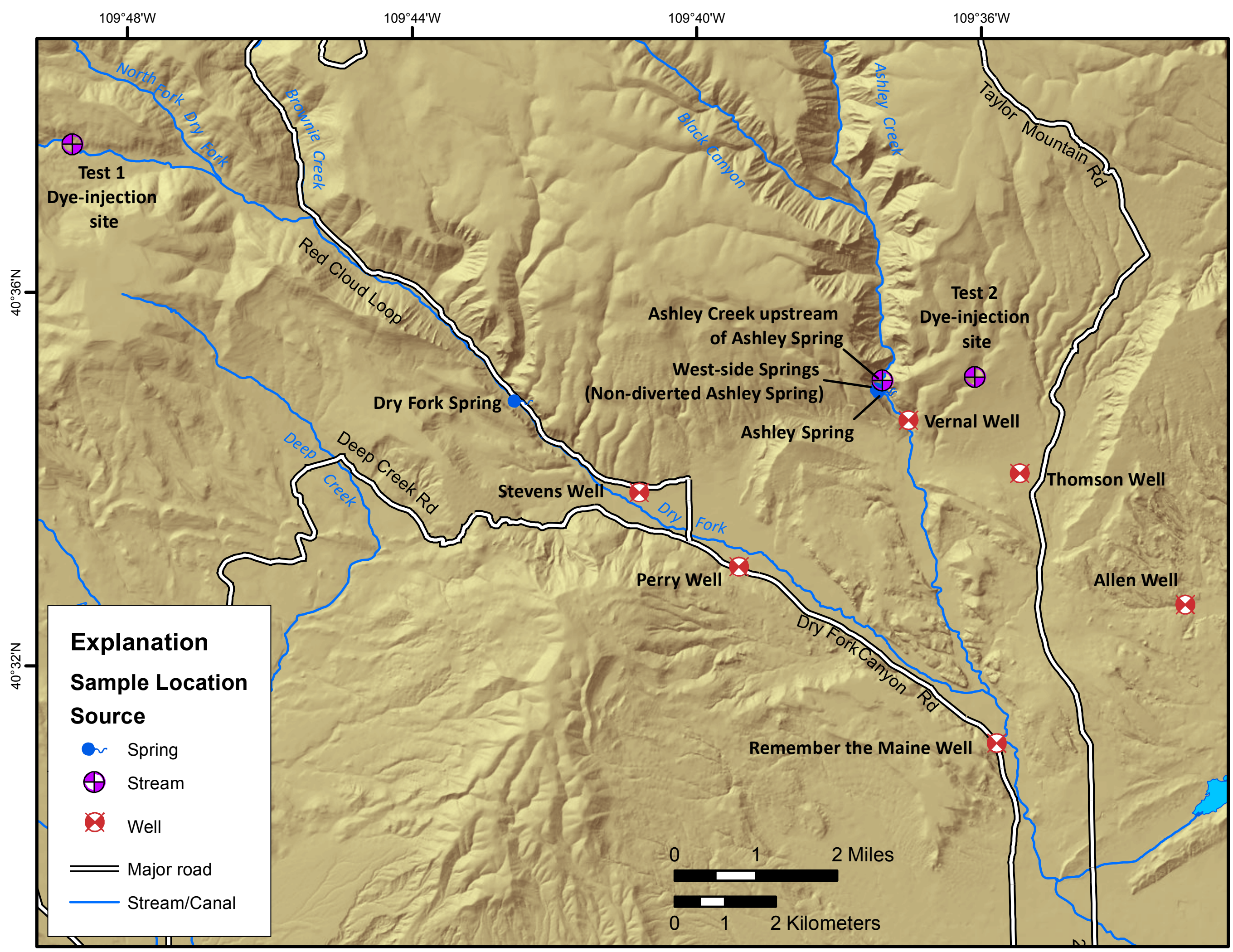


Figure 16. *Water chemistry sample sites for this study.*

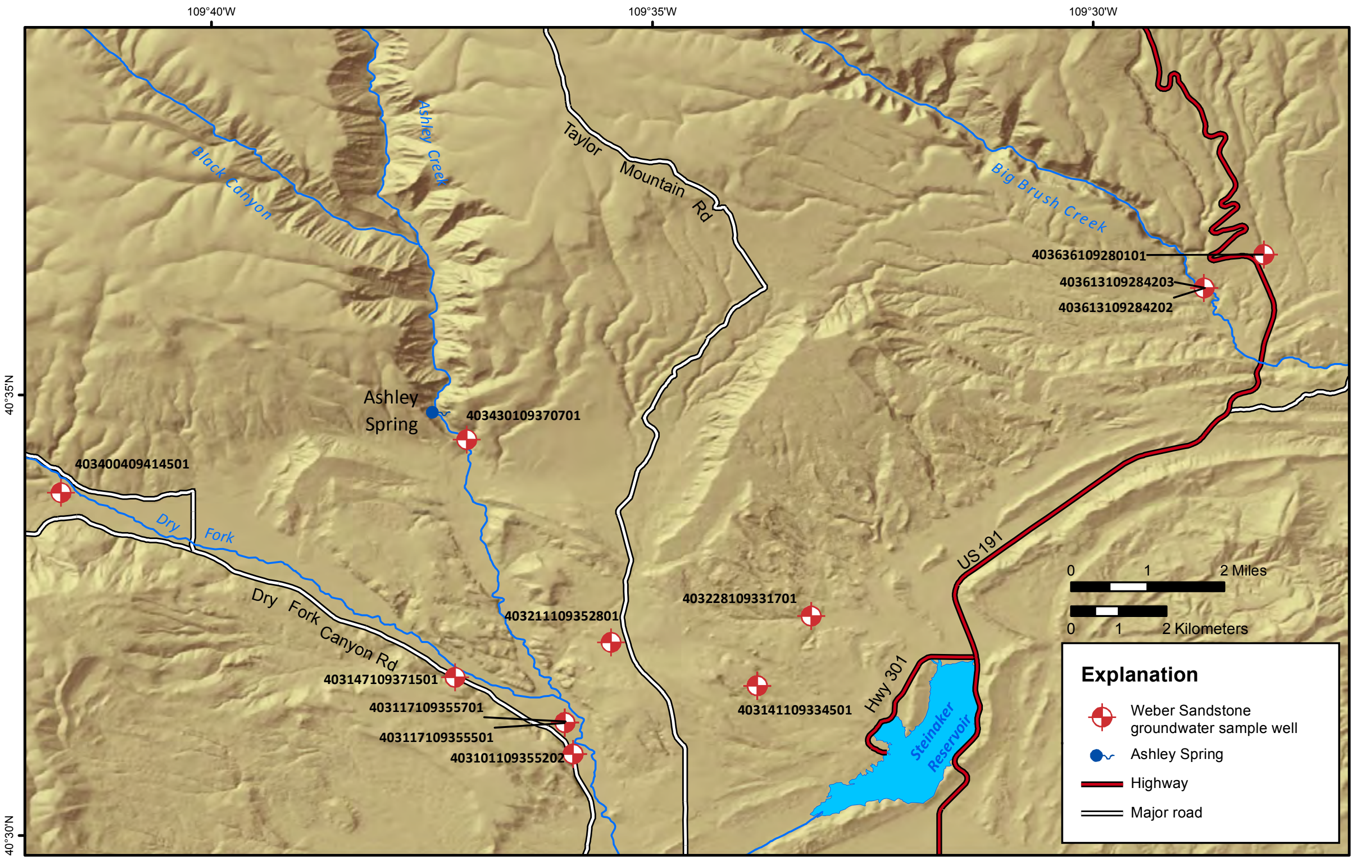


Figure 17. Location of water wells compiled for determining chemical analyses and statistics for groundwater in the Weber Sandstone. Note that Ashley Spring is presented here as a geographic reference and was not used to determine statistics of the Weber Sandstone.

RESULTS

Hydrologic Analyses

Based on our water budget created using USGS gauge data compiled from 1941 to 2013 (figure 13), an average of approximately 13,800 acre-feet (1700 ha-m) of water drains into two different sinks in Dry Fork every year. The tributaries of the North Fork of Dry Fork and Brownie Creek contribute to that drainage. Of the 13,800 acre-feet (1700 ha-m), about 2700 acre-feet (250 ha-m), or 20%, drains into the sinks of Brownie Creek. The watershed of the Main Fork of Dry Fork contributes 72% of the flow to Dry Fork, while the North Fork and Brownie Creek contribute 12% and 16%, respectively. If drainage of water to the sinks in each tributary is proportional to flow, then it is likely that most water flows into sinks in the Main Fork of Dry Fork.

Based on the available compiled data (USGS, 2013; figure 18), the average annual flow of Ashley Spring (9266000) is 19,500 acre-feet (2400 ha-m) (table 6). The flow at this site represented only overflow from the spring and did not include the volume that was diverted for public supply. The average amount of flow gained annually between the gauge on Ashley Creek (9265500) above Ashley Spring and the gauge (9266500) on Ashley Creek below Ashley Spring was 14,500 acre-feet (1800 ha-m) (table 6). The difference between the gauges represents overflow water from the Ashley Spring box and water from the undiverted west-side springs, and does not include water diverted for use. Water-use data (Utah Division of Water Rights, 2013) indicate that an average of 4700 acre-feet (580 ha-m) per year of Ashley Spring water is diverted for use. However, data from gauge 9265500 is limited to 1941–1945, which may have had different amounts of water use than the average water use listed.

Spring discharge data from 1944–1945 and from 1954–1955 indicate that the average peak discharge of Ashley Spring is during the months of May and June, and the lowest values are during January, February, and March (figure 18; table 7). The average peak discharge of Ashley Spring (9266000) is 45 cfs (1.3 cms), whereas the average peak discharge of all springs at Ashley Spring (after water is diverted), including the west-side springs, is 71 cfs (2 cms).

Analysis of discharge recession slopes indicates that flow from the Dry Fork sinks to Ashley Spring is dominantly conduit-based flow based on Taylor and Greene's (2002) conclusion that slopes greater than 0.01 indicate conduit domination. The slope values (α) range from 0.03 to 0.07 (figure 19). This result is only applicable during the time of observation—the

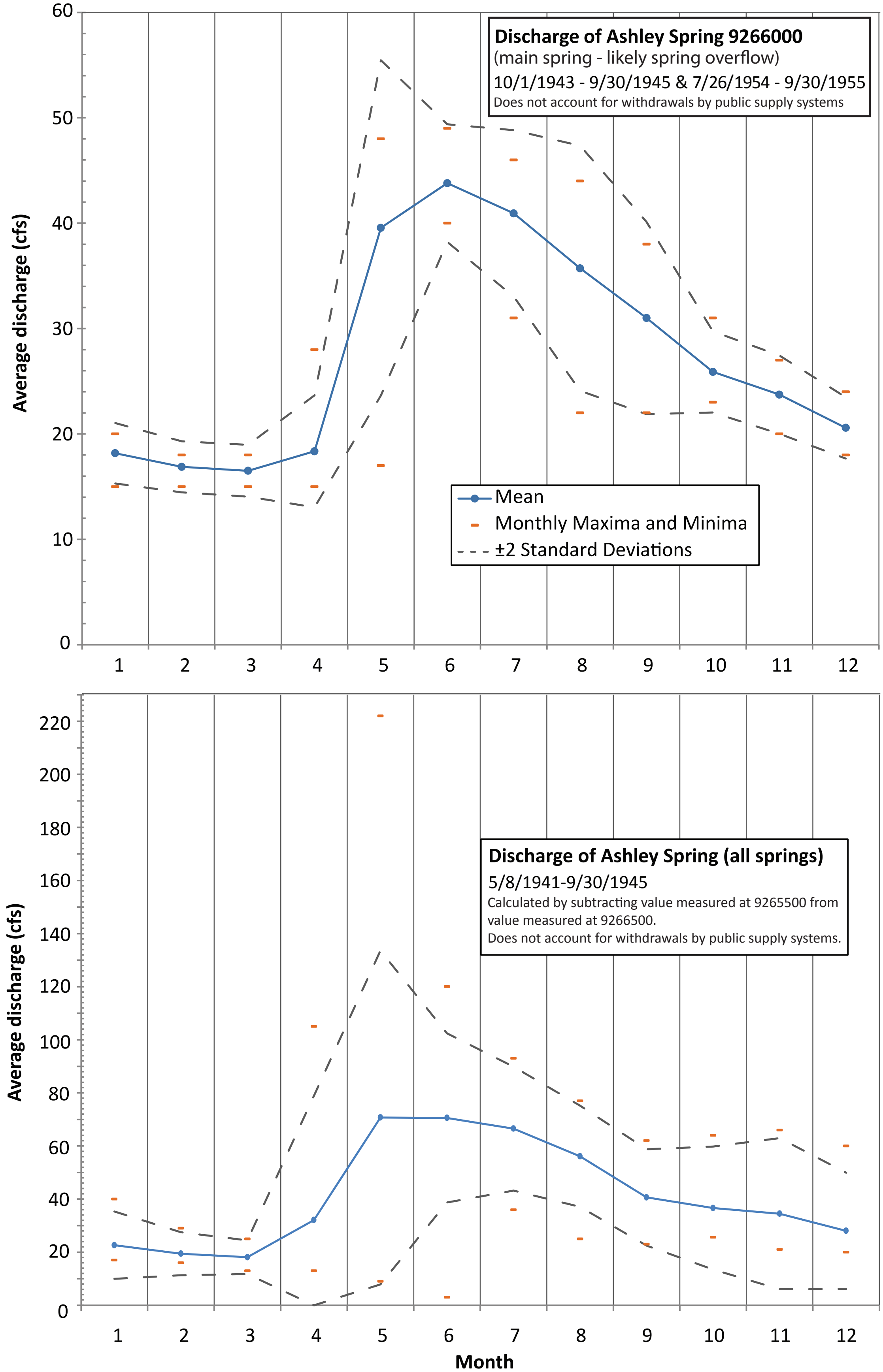


Figure 18. *Average monthly flow of Ashley Spring based on daily discharge measurements (USGS, 2013). These values do not account for withdrawals for public supply.*

Table 6. *Estimates of water flowing into and out of Dry Fork and Ashley Creek.*

	Estimates Using USGS Stations			Estimates Using Climate Data				Comparison	Estimate Using NHDplus[5]	Comparison
	USGS Station Number	Name	Gauge	Watershed (s)[1]	PRISM Precip[2]	NLDAS Evap[3]	Precip Minus Evap[4]	Gauge / (Precip Minus Evap)	Flow	Gauge / Flow
			ac-ft/yr		ac-ft/yr	ac-ft/yr	ac-ft/yr		ac-ft/yr	
Water Lost in Dry Fork Drainage	9269500	Lower Brownie Creek	6800							
	9269000	Middle Brownie Creek	5700							
	9268900	Upper Brownie Creek	9500	8	14,500	6000	8500	112%	8900	107%
		Lost Between Upper and Lower Brownie Creek	2700							
		Lost Between Upper and Middle Brownie Creek	3800							
	9268500	North Fork	4800	2	11,000	4800	6200	77%	8000	60%
	9268000	Upper Dry Fork	26,100							
		Three Forks Above Sinks	40,300	1+2+8	89,700	34,200	55,500	73%	50,100	80%
	9267500	Mosby Canal	4000							
		Total flow from Upper Dry Fork (9267500+9268000)	30,000	1	64,200	23,500	40,700	74%	42,100	71%
	9270000	Dry Fork Below Dry Fork Spring	26,600	1+2+8+3	122,000	52,700	69,300	38%	75,000	35%
		Amount Lost in Sinks of All Forks of Dry Fork (Three Forks Above Sinks - Dry Fork Below Spring)	13,800							
Water Gained by Ashley Spring	9265300	Middle Ashley Creek	48,500	4	77,900	31,700	46,200	105%	49,100	99%
	9265500	Ashley Creek Upstream of Spring	52,700	4+5	122,300	56,400	65,900	80%	70,300	75%
	9266500	Ashley Creek Downstream of Spring	67,200							
		Gain between Middle Ashley Creek and Station below spring (9266500 - 9265300)	18,700							
	9266000	Ashley Spring	19,500							
		Estimated Ashley Spring (9265500 - 9266500); Excludes water for public use	14,500							
		Ashley Spring: Average Reported Use	4700							

[1]See figure 12
[2]PRISM, 2013
[3]NASA, 2013
[4]PRISM Precip data minus NLDAS Evaporation Data
[5]Horizon Systems Corporation, 2013

Table 7. *Monthly discharge statistics of USGS gauge data for Ashley Spring. These values do not account for withdrawals by public supply systems. See figure 18 for a visualization of these values.*

		Discharge								
	Month	Number of Measurements	Average (cfs)	Maximum (cfs)	Minimum (cfs)	Standard Deviation (cfs)	-2 Standard Deviation (cfs)	+2 Standard Deviation (cfs)	Median (cfs)	Geometric Mean (cfs)
9266000 (main spring - likely spring overflow)	1	93	18.2	20	15	1.4	15.3	21.0		
	2	85	16.9	18	15	1.2	14.5	19.3		
	3	93	16.5	18	15	1.2	14.0	19.0		
	4	90	18.4	28	15	2.7	13.0	23.7		
	5	93	39.6	48	17	8.0	23.7	55.5		
	6	90	43.8	49	40	2.8	38.2	49.4		
	7	99	40.9	46	31	3.9	33.0	48.8		
	8	124	35.7	44	22	5.8	24.1	47.3		
	9	120	31.0	38	22	4.6	21.9	40.1		
	10	93	25.9	31	23	1.9	22.0	29.7		
	11	90	23.7	27	20	1.9	20.0	27.5		
	12	93	20.6	24	18	1.5	17.7	23.5		
	All	1163	28.0	49	15	10.3	7.4	48.6	25.0	26.2
9266500-9265500 (difference between up-stream and downstream stream gauges)	1	124	22.6	40	17	6.3	10.0	35.3		
	2	113	19.4	29	16	4.0	11.3	27.5		
	3	124	18.1	25	13	3.2	11.7	24.4		
	4	120	32.1	105	13	23.4	0.0	79.0		
	5	146	70.7	222	9	31.4	7.9	133.6		
	6	150	70.6	120	3	15.9	38.7	102.4		
	7	155	66.5	93	36	11.7	43.2	89.9		
	8	155	56.1	77	25	9.5	37.1	75.2		
	9	150	40.6	62	23	9.1	22.5	58.8		
	10	124	36.6	64	25.6	11.6	13.4	59.8		
	11	120	34.5	66	21	14.2	6.0	63.0		
	12	124	28.0	60	20	11.0	6.1	49.9		
	All	1605	43.2	222	3	24.3	-5.3	91.7	36.0	36.8

fall, when snowmelt is not contributing to the input of the Dry Fork sinks. When snowmelt is contributing to the input of Dry Fork sinks, the trends in the discharge recession slope are masked by the seasonal trend of snowmelt.

Discharge rates of Ashley Creek and Ashley Spring are correlative. Figure 20 (A and B) indicates that Ashley Creek and Ashley Spring(s) discharge rates do not increase proportionately, and that contribution of the flow from Ashley Spring(s) decreases as flow of Ashley Creek increases (figure 20A). Maximum daily discharge observed for Ashley Spring at USGS station 9266000 is 49 cfs (1.4 m^3/s), which is the asymptote approached as spring discharge increases (figure 20B). Regression analysis of the correlation between Ashley Spring and Ashley Creek indicates a strong logarithmic relationship ($r=0.96$) when discharge of Ashley Creek is between 17–140 cfs (0.5–4 m^3/s), and a much weaker relationship above about 140 cfs (4 m^3/s) (figure 21).

Mapping

Most of the results from mapping of the field area are displayed as figures. Structure-contour maps of the Weber Sandstone and Madison Limestone are displayed in figures 22 and 23, showing the elevation of the top of the units and the total depth below ground surface to the top of each unit. Dips for both the Weber Sandstone and the Madison Limestone are to the southeast (figures 22 and 23). The Weber Sandstone structure-contours indicate that a dome is present near the confluence of Dry Fork and Ashley Spring (figure 22). The potentiometric surface map of the Weber Sandstone is shown in figure 24. Figure 25 shows the results of lineament and stream orientation analyses. Mean orientation of stream segments is 128 degrees clockwise from north. Mean orientation of mapped lineaments in aerial photographs is 134 degrees from north, which is coincident with fault trends of the Deep Creek fault zone (figure 11). A rose diagram resulting from the

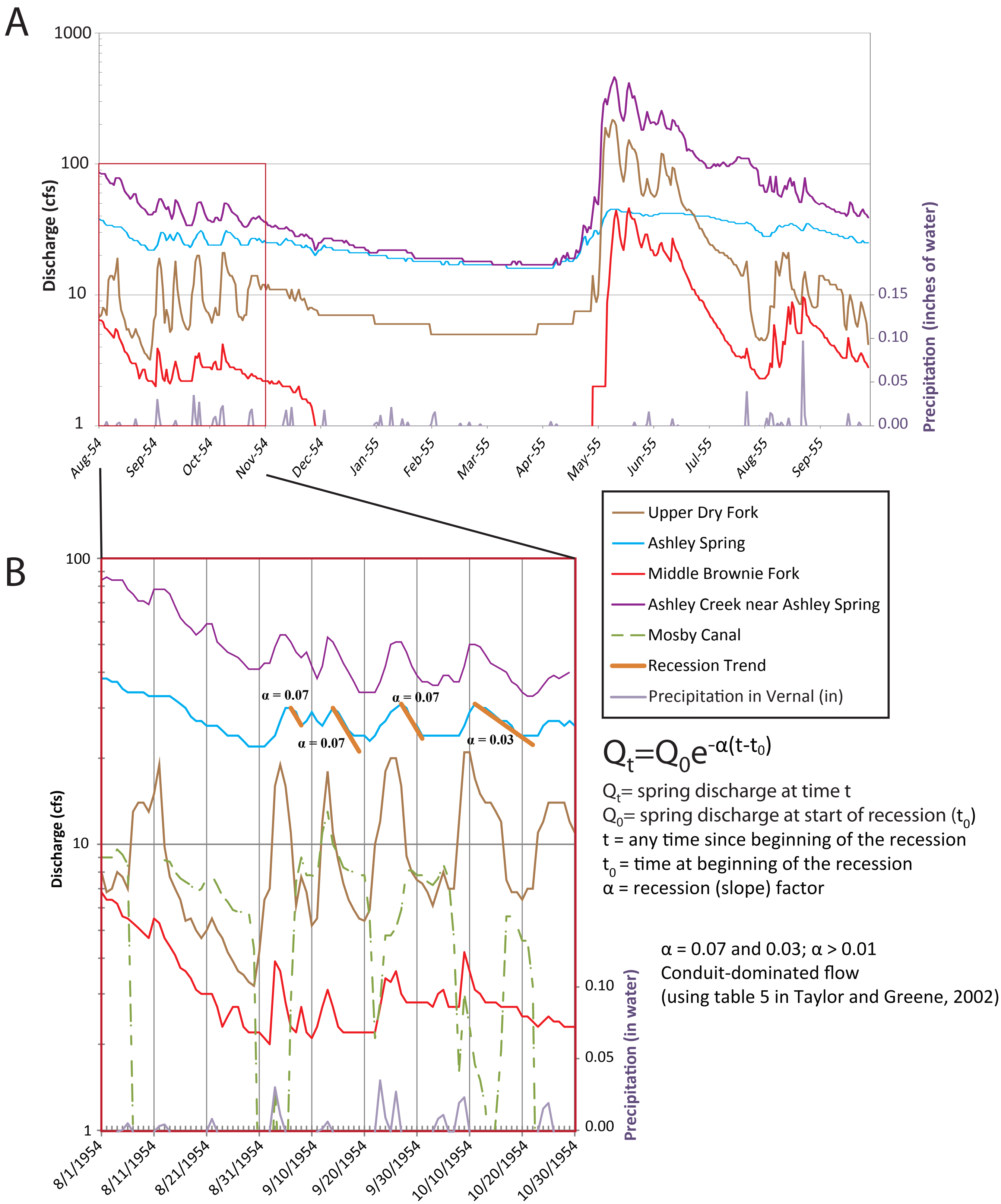
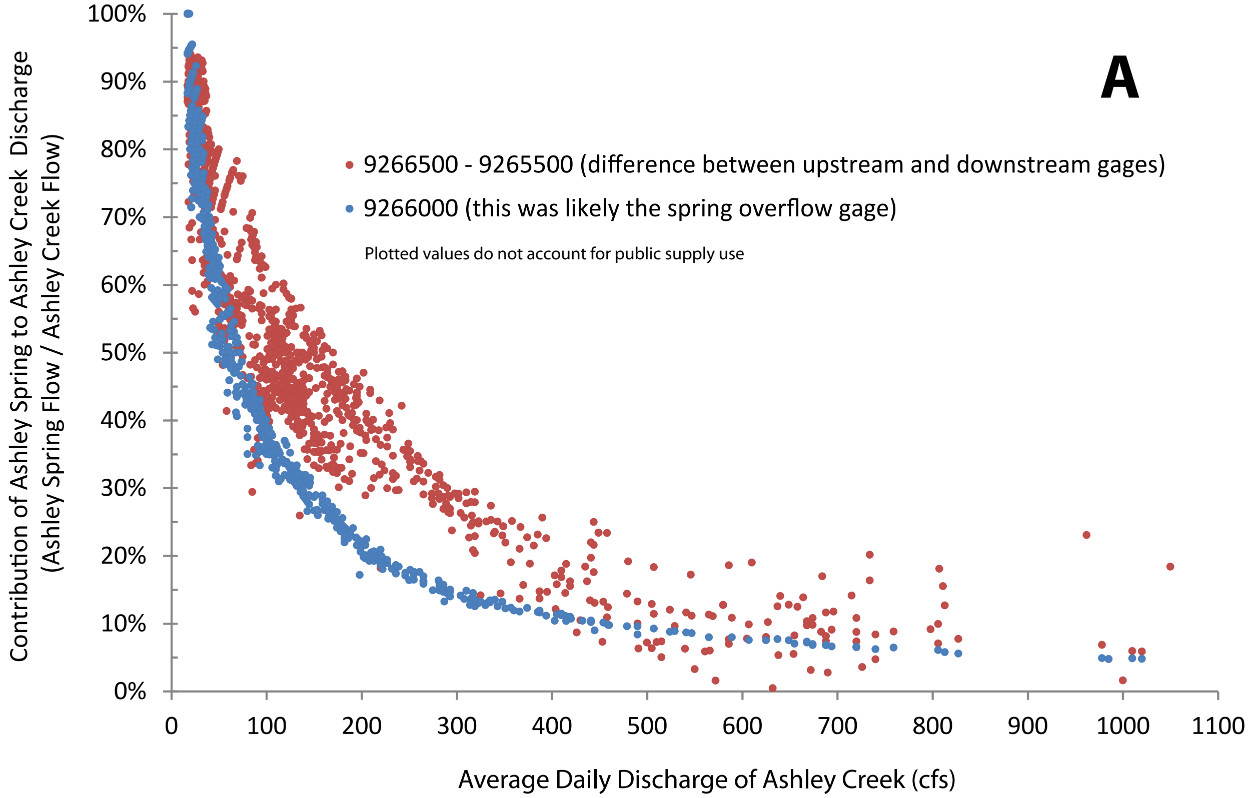


Figure 19. *(A) Discharge data from various gauges (USGS, 2013) in the study area. (B) Slope analysis (Taylor and Greene, 2002) of Ashley Spring discharge recession.*



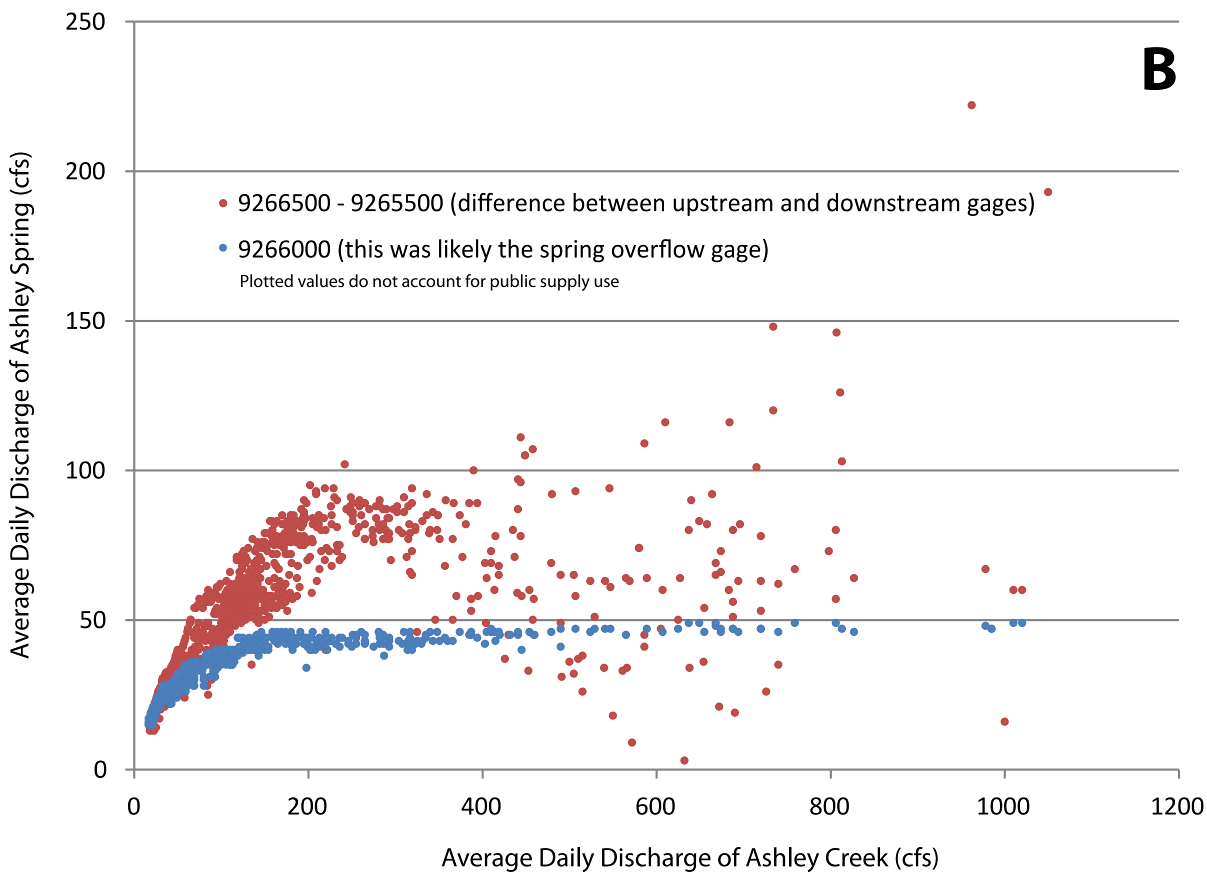


Figure 20. *Relationship of discharge between Ashley Creek and Ashley Spring. (A) Percentage of flow from Ashley Spring that makes up Ashley Creek vs. discharge of Ashley Creek. (B) Average daily discharge of Ashley Spring versus average daily discharge of Ashley Creek.*

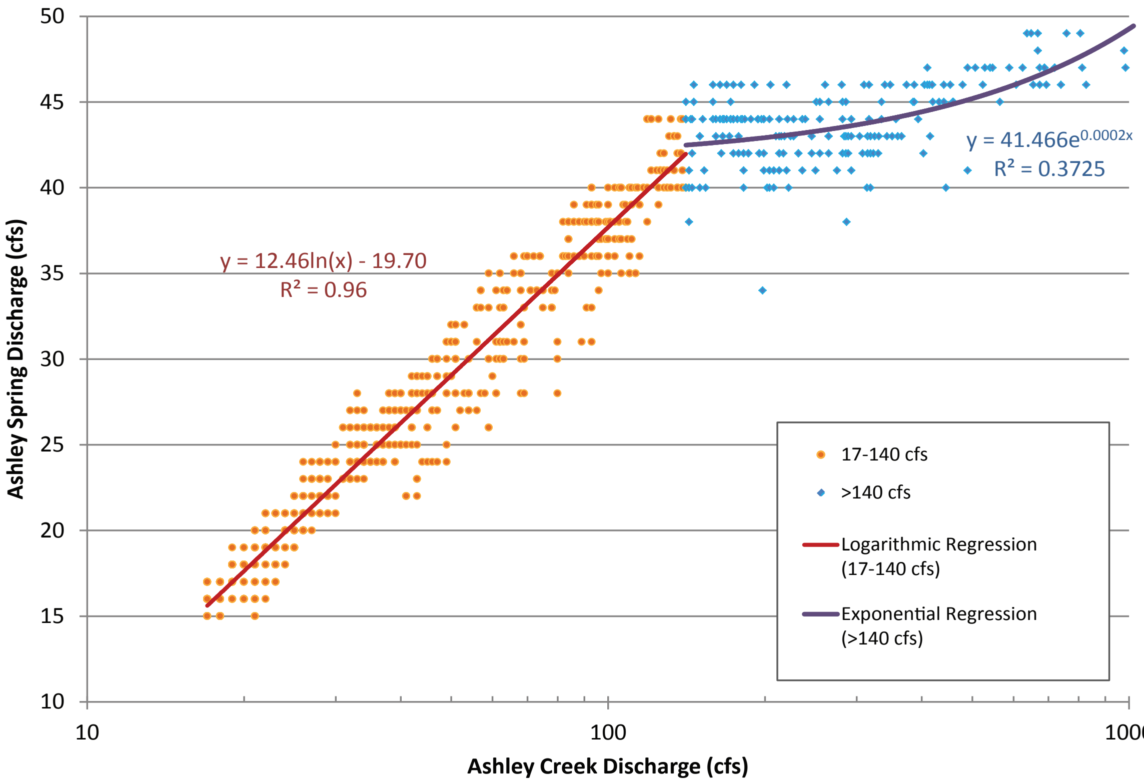


Figure 21. *Relationship between Ashley Creek (USGS station 9266500) discharge and Ashley Spring discharge (USGS station 9266000).*

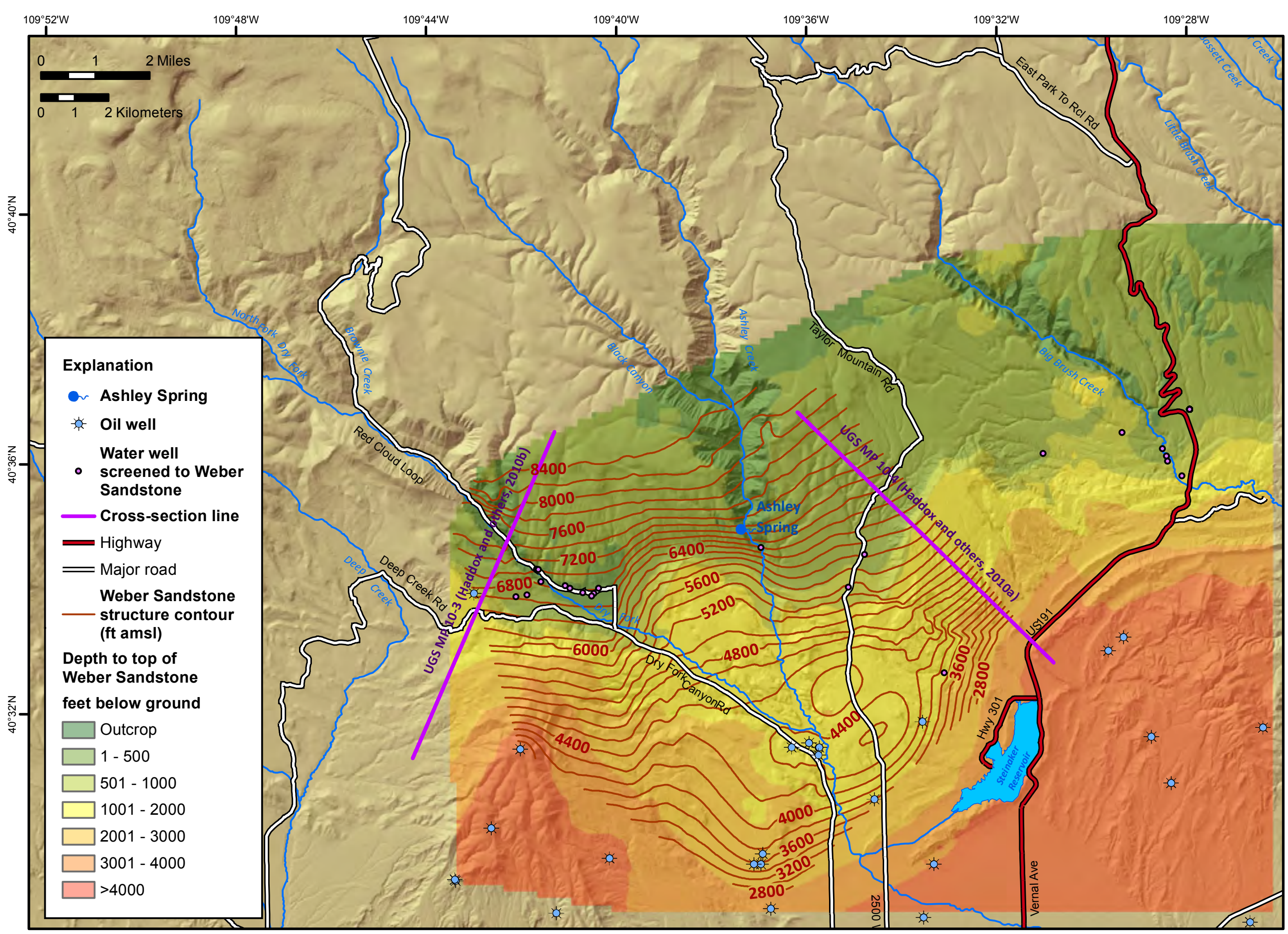


Figure 22. *Structure contours and depth to the top of the Weber Sandstone.*

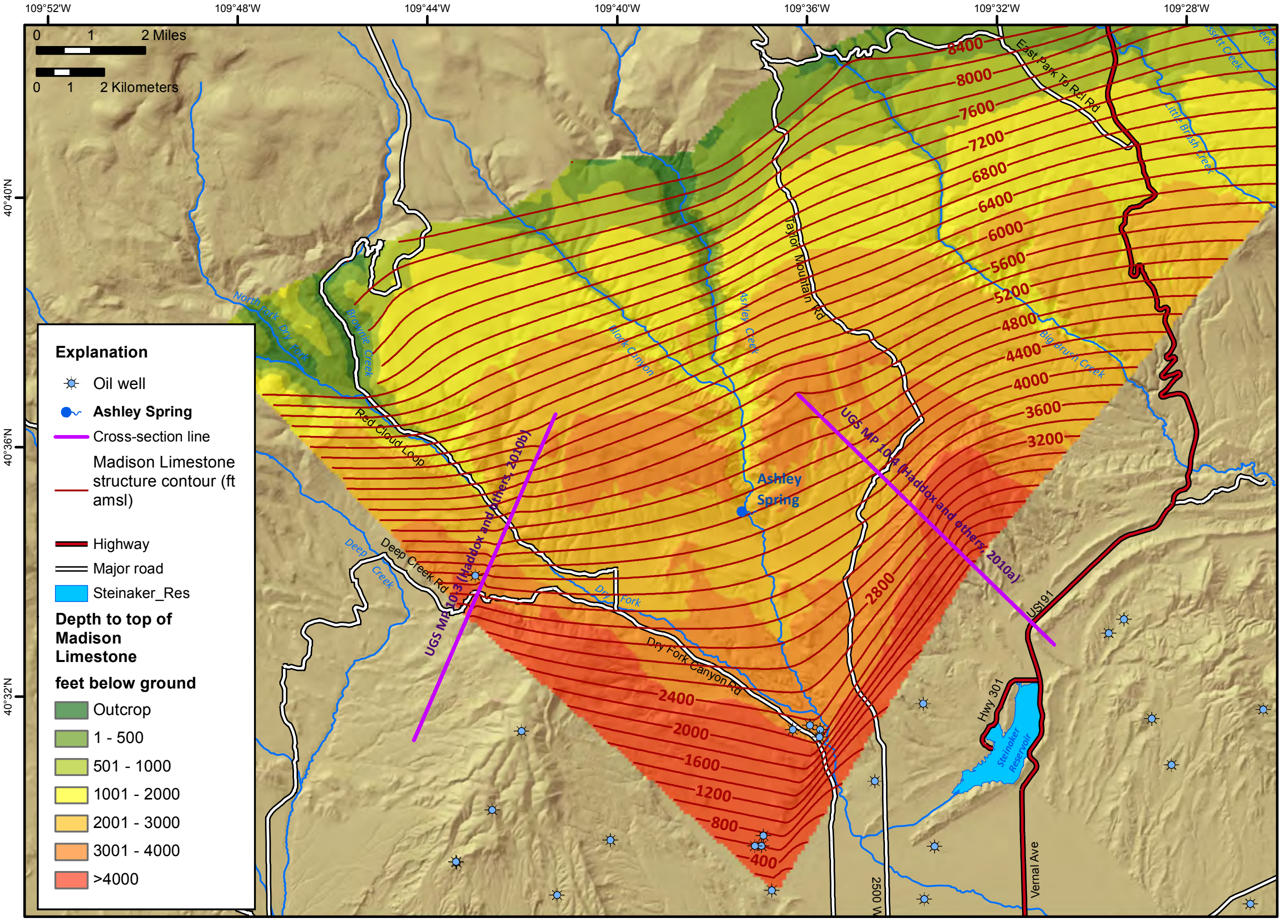


Figure 23. *Structure contours and depth to the top of the Madison Limestone.*

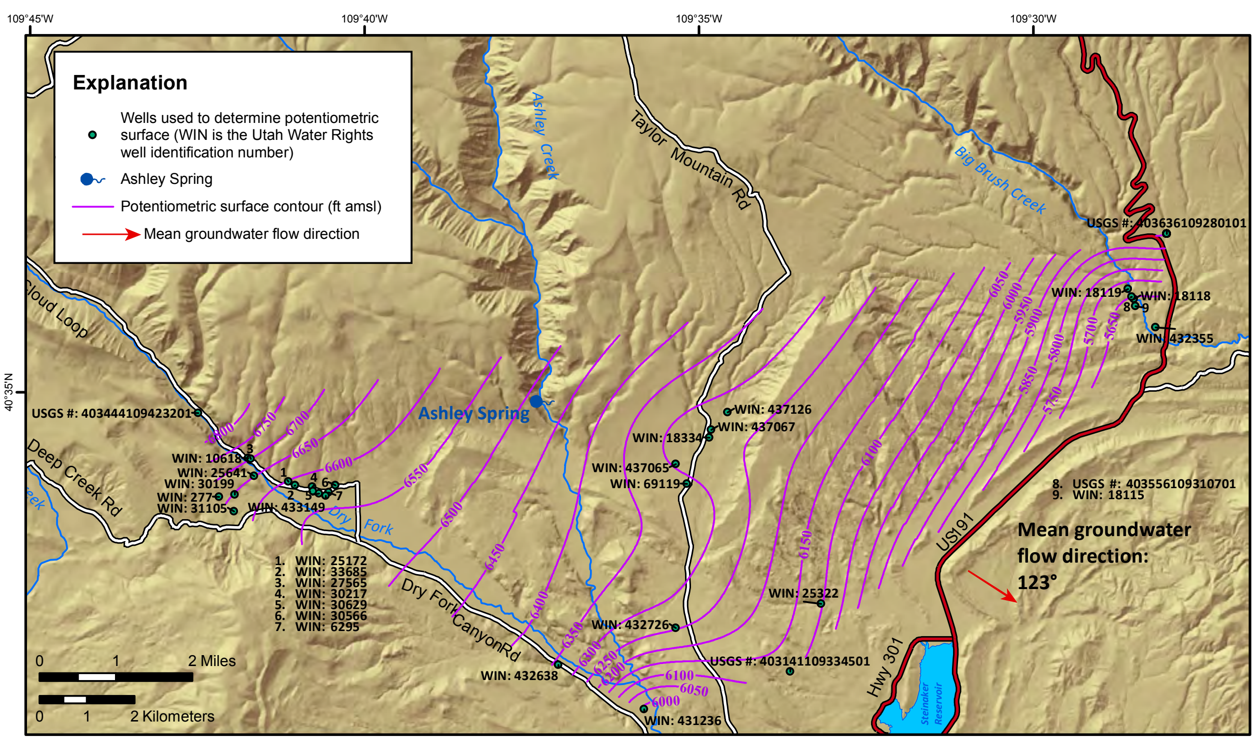


Figure 24. *Potentiometric surface map of the Weber Sandstone aquifer, showing elevation of water levels in wells in feet above mean sea level. The mean flow direction of 123 degrees from north (standard deviation = 19 degrees) is represented by the red arrow. See table 3 for the well water-level data.*

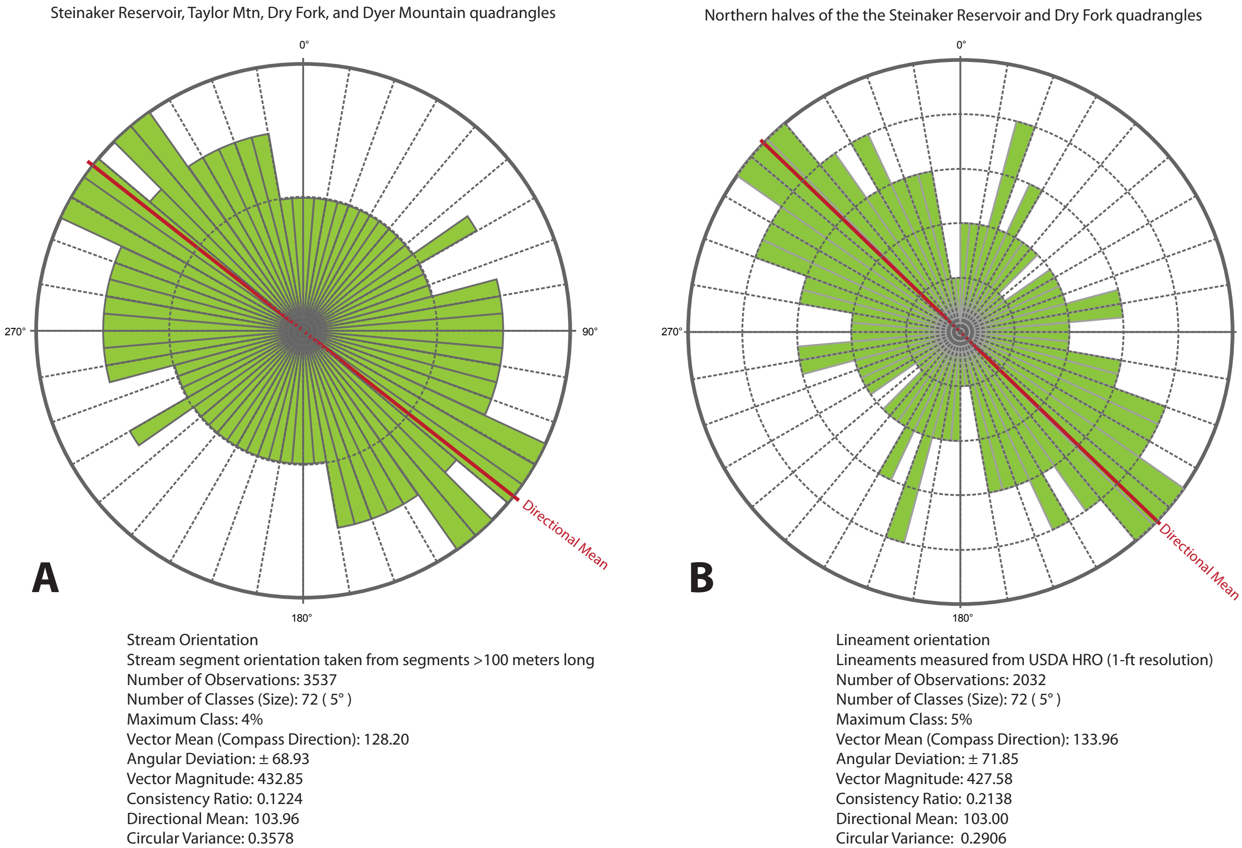


Figure 25. *Statistics of (A) stream orientations and (B) lineaments in the vicinity of Ashley Spring.*

lineament analysis shows a secondary trend at approximately 18 degrees from north (figure 25B). Mapped depressions in the land surface are displayed in figure 26.

Dye Tracing

Of the two dye-tracer studies conducted, only the Dry Fork test resulted in the detection of dye at the dye collection sites (figure 14). Results of the Dry Fork dye analyses are summarized in table 8, figure 27, and appendix A. Rhodamine WT dye injected during the first dye-tracer test appeared in measurable quantities in the Ashley Spring spring box and in the west-side springs immediately upstream of the spring box. Over the duration of the study, dye was not detected in water from the wells or upstream of the springs in Ashley Creek. Eosine dye from the second dye injection, injected into the Weber Sandstone in Rock Canyon on the east lease area (figure 14), was not detected at any of the sample sites over the duration of the study.

For the first dye-tracer test, dye was injected into Dry Fork on September 24, 2012, at 1:26 pm and was first detected by a carbon packet placed in the spring on September 28, 2012, at 9:17 pm. The dye front (leading edge) traveled over the distance of 10.6 miles (17 km) from the Dry Fork injection site to Ashley Spring in at least 103.85 hours (4.3 days) and at most 114.57 hours (4.8 days). This time is bracketed by the times that the first carbon packet that contained a measurable quantity of dye was placed and collected. The minimum travel time of the dye front (based on when dye is first detected) was about 37 hours longer than the travel time of 67 hours calculated by Maxwell and others (1971). Due to potential differences in hydrologic conditions in each test and because the Maxwell test used a more accurate measurement technique, the 37-hour difference may not be significant.

We determined mean travel time of dye for the two Maxwell and others (1971) tests in Dry Fork. Using equations one to five in the Analyses of Previous Tests section of the Methods portion of this report, we calculated the mean and standard deviation of the travel time of the total dye mass from the previous Maxwell and others (1971) tests. The results of these calculations are summarized in table 9. As mentioned in the methods section, we did not analyze the UGS dye trace, as it was only semi-quantitative. Based on the two velocities from Maxwell and others (1971) and the less accurate, semi-quantitative velocity from the UGS test, the velocity of flow increases with increasing spring discharge. However, due to the limited number of available sample points (three) and a high standard deviation, this relationship is poorly defined.

Chemistry

We collected water samples from Ashley Creek and from the Dry Fork drainages, as well as groundwater from various sources, and analyzed the chemical data. We tabulated water chemis-

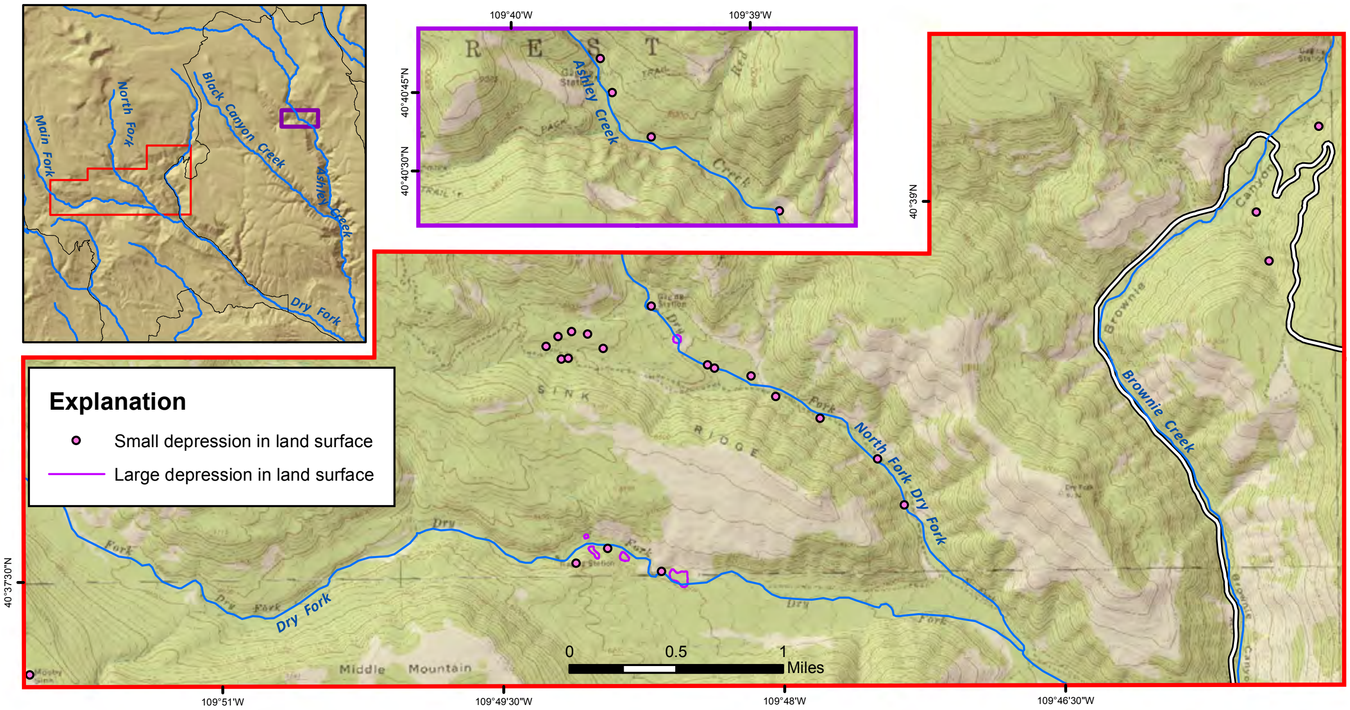


Figure 26. *Mapped land surface depressions in the study area. Depression mapping was focused in areas where Mississippian carbonates were near surface.*

Table 8. *Timeline of dye pour and carbon packet placement and extraction at Ashley Spring for the Dry Fork UGS dye trace.*

Activity	Date-Time	Total Sample Conc.	Duration of Sample (days)	Time After Injection	Average Date-Time	Average Conc.	Average Estimated Spring Discharge*
	mm/dd/yyyy hh:mm	ppb	days	hours		ppm/day	cfs
Pour Dye	9/24/12 13:26						
Place Packet	9/28/12 13:39			96			
Grab Packet	9/28/12 21:17	0	0.32	104	9/28/12 17:28	0.0000	19.4
Place Packet	9/28/12 21:17			104			
Grab Packet	9/29/12 8:00	25	0.45	115	9/29/12 2:38	0.0560	19.4
Place Packet	9/29/12 8:00			115			
Grab Packet	11/29/12 14:00	553	61.25	1585	10/29/12 23:00	0.0090	18.5
Place Packet	11/29/12 14:00			1585			
Grab Packet	2/12/13 10:00	5	74.83	3381	1/6/13 0:00	0.0001	16.7

*Based on measured discharge of Ashley Creek USGS (2013) and the relationship presented in figure 21.

Table 9. *Results of analyses of Maxwell and others (1971) data.*

Test	Statistic	Value	Units
1	travel time of dye front	67	hrs
	mean travel time	105	hrs
	mean flow velocity	0.15	ft/s
	travel time std dev	22 hrs	hrs
2	travel time of dye front	80 hrs	hrs
	mean travel time	93 hrs	hrs
	mean flow velocity	0.17 ft/s	ft/s
	travel time std dev	291 hrs	hrs

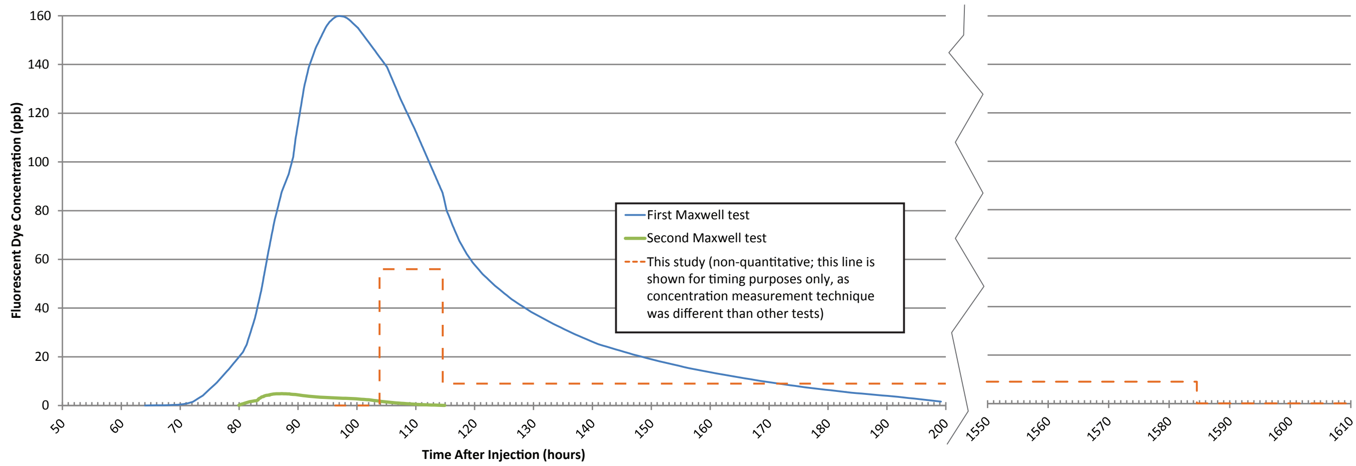


Figure 27. *Comparison of dye breakthrough curves for the first and second dye tracer tests conducted by Maxwell and others (1971) on Dry Fork and the test conducted by the Utah Geological Survey. Note that Maxwell and others (1971) used a continuously recording fluorimeter, allowing for continuous dye concentration measurement, while the UGS used carbon packets, which record approximate cumulative (discrete) dye adsorbed while the carbon packet is in place.*

try statistics for Ashley Spring and the Weber Sandstone (tables 10–12), due to their importance relative to other sources. Box and whisker plots, which graphically summarize the distribution of chemical constituents for Ashley Spring and the Weber Sandstone, are presented in figure 28 A and B, respectively, and figure 29 presents the results in a Piper diagram.

Ashley Spring water chemistry shows significant seasonal variations, but no significant long-term changes. We compiled data from the CUWCD that included records of temperature, specific conductivity, alkalinity, and turbidity (figure 30A–D, respectively), and total dissolved solids (figure 31), all of which are tabulated in table 13. Seasonal variations in water chemistry of Ashley Spring at the spring box from USGS (2013), USEPA (2013), and UGS are displayed in figure 32, but data were not parsed into individual months due to the limited number of samples. Long-term water chemistry is shown in figure 33.

Water chemistry from different locations is shown as a box and whisker plot, as a Piper diagram, and as a Schoeller plot (figures 34 through 36). We generated different plot types to maximize data visualization.

DISCUSSION

Groundwater Flow

The Dry Fork dye-tracer test conducted for this study substantiated the results of earlier studies conducted in the Dry Fork drainage (Maxwell and others, 1971). The peak concentration of the dye at Ashley Spring likely occurred during or soon after September 29, 2012 (table 8). Due to the qualitative nature of the dye-tracer test, exact peak time could not be calculated. However, previous results (Maxwell and others, 1971) indicated that the peak occurred within 27 hours of the appearance of the dye front. Both the Maxwell and others (1971) test and the UGS dye injection were relatively rapid (within 24 hours), which would likely result in tighter, less disperse breakthrough curves. However, we did use a smaller amount of dye than Maxwell and others (1971) and injected directly into the stream as opposed to into a sink, so the dye may have been more dispersed than the Maxwell and others (1971) test. Based on the available concentration data and previous dye-tracer tests, the peak likely occurred between 9/28/2012 21:17 and 9/30/2012 9:17.

Information to calculate the mean travel time of the total dye mass for our test is not available, as the carbon packet dye collection technique that we applied does not allow for exact quantification and display of dye breakthrough curves. However, we observed that the leading edge of the dye took about 37 hours longer to reach Ashley Spring than did the leading edge of both of the Maxwell and others (1971) tests. Although, as stated above, based on examination using Mull and others' (1988) methods we suggest this difference may not be significant, if real it could be due to several causes. One possibility is the lower discharge of Ashley Spring caused the delay, as the discharge is positively correlated (based on only 3 points) to the velocity of the dye. Other possible explanations for the delay are the relative concentrations of dye used (previous tests used much more dye), the location of the injection (stream versus sinks), slight differences in dye pour technique, and the impact of the May 1997 landslide in the Main Fork of Dry Fork.

Despite a slower dye-front travel time in this study relative to previous studies (tables 8 and 9), our first test indicates very rapid groundwater flow relative to flow through typical porous media (Heath, 1982; Cook, 2003; Singhal and Gupta, 2010). Discharge regression slope analysis (figure 19) indicates that conduit flow, versus more diffuse flow, is the dominant flow

Table 10. *Summary statistics of water chemistry from Ashley Spring.*

Parameter	Units	Total Samples	Not Detected	Detected	Geometric Mean	1st Quartile	Median	3rd Quartile	Standard Deviation	Minimum	Maximum	Detection Limit
Alkalinity	mg/L	91		91	67	51	75	92	29	8.4	218	
Aluminum	mg/L	51	32	19	0.11	0.05	0.10	0.30	0.32	0.02	1.30	0.01
Arsenic	mg/L	32	27	5	0.0011					0.00060	0.0020	0.001
Barium	mg/L	30	3	27	0.073	0.060	0.077	0.093	0.022	0.04	0.12	0.002
Bicarbonate	mg/L	101		101	71	57	79	96	33	8.4	218	
Boron	mg/L	5	5									0.01
Cadmium	mg/L	30	30									0.0003
Calcium	mg/L	109		109	17	14	18	23	9.4	2.54	79	
Carbon	mg/L	13		13	3.5	2.3	3.3	5.4	2.0	1.6	8.7	
Carbon Dioxide	mg/L	59	4	55	1.4	1.0	1.0	1.6	3.2	1.00	21	0.2
Carbonate	mg/L	95	87	8	3.0	1.0	1.7	11.6	6.1	1.00	16	0.2
Chloride	mg/L	100	55	45	2.2	1.0	2.7	4.1	4.0	0.20	19	0.2
Chromium	mg/L	30	30									0.001
Copper	mg/L	29	29									0.02
Copper	mg/L	66	62	4	0.004					0.0010	0.02	0.001
Dissolved Oxygen	mg/L	39		39	9.4	8.8	9.2	10.1	1.2	7.4	12	
Fluoride	mg/L	39	15	24	0.079	0.025	0.085	0.196	0.40	0.010	2.0	0.01
Hardness	mg/L	107		107	62	49	69	87	36	1.0	298	
Iron	mg/L	70	17	53	0.08	0.05	0.09	0.13	0.12	0.010	0.56	0.01
Lead	mg/L	66	63	3	0.00021				0.00021	0.00010	0.00050	0.0001
Magnesium	mg/L	109		109	5.0	3.6	5.3	7.8	3.14	0.40	24.7	
Manganese	mg/L	30	22	8	0.00683	0.00539	0.00620	0.00874	0.0021	0.0050	0.0110	0.005
Mercury	mg/L	13	13									0.0002
Nitrate as NO3	mg/L	71		71	0.48	0.18	0.49	2.39	1.53	0.0044	7.53	0.044268
pH		110		110	7.93	7.60	7.94	8.34	0.51	6.35	9.00	
Phosphate	mg/L	99	38	61	0.014	0.008	0.015	0.020	0.20	0.0003	1.34	0.0003
Potassium	mg/L	94	51	43	0.61	0.50	0.62	0.69	0.26	0.27	1.8	0.2
Selenium	mg/L	31	30	1	0.0007							0.0004
Silica	mg/L	47	1	46	2.4	1.3	3.3	5.3	2.6	0.09	10	0.01
Silver	mg/L	30	30									0.01
Sodium	mg/L	102	24	78	1.6	1.0	1.3	1.8	5.31	0.49	33.0	0.2
Specific Conductivity	umho/cm	75		75	122	90	140	180	57	17	262	
Sulfate	mg/L	104	46	58	2.7	2.0	4.0	5.8	5.0	0.01	35	0.01
Temperature	C	98		98	6.6	3.9	7.8	10.8	3.7	1.1	15	
Total Dissolved Solids	mg/L	105		105	84	66	84	120	57	10	372	
Turbidity	NTU	100	10	90	3.2	1.6	3.6	6.7	7.0	0.03	41	0.01
Zinc	mg/L	32	31	1	12.5							

Agency	Total Samples
Utah Division of Drinking Water	20
Utah Geological Survey	1
U.S. Environmental Protection Agency	66
U.S. Forest Service	39
U.S. Geological Survey	6
TOTAL	132

Quarter	Month	Total Samples
1	Jan	5
	Feb	4
	Mar	3
2	Apr	8
	May	18
	Jun	17
3	Jul	18
	Aug	14
	Sep	18
4	Oct	12
	Nov	8
	Dec	7
	TOTAL	132

Table 11. *Results and summary statistics of water chemistry samples from groundwater in the Weber Sandstone. Well locations in figure 17.*

Site number	403101109355202[1]			403117109355501			403117109355501			403117109355701			403141109334501							
Sampled via	DDW		UGS[2]	USGS			USGS			USGS	DDW		USGS							
Sample Date	3/17/88	3/13/01	9/26/12	12/11/47	12/11/51	10/22/57	7/12/58	10/8/58	10/6/64	5/1/73	3/17/88	3/13/01	8/29/29	8/29/29	8/6/30	8/6/30	5/25/34	5/25/34	7/11/67	3/15/72
Alkalinity	182	170	164	98	203	184	180	184		180	175	170	180	187	185	176	160	168	174	
Aluminum			<10																	
Arsenic		2.5	4.17									5.1								
Barium	0.02	0.03	<0.10								0.02	0.02								
Bicarbonate	222	210	200	120	247	224	220	224		220	214	210	230	230	225	215	200	205	210	
Boron	40		<30								20	50								
Cadmium			<0.1																	
Calcium	91	69	75.2	52	88	88	85	95		81	65	110	70	70	70	70	76	75	188	
Carbon Dioxide		160	4	1.9	6.3	18	11	7.2		11		160							8.5	
Carbonate			0			0	0	0		0									1	
Chloride	2		1.89	6	1.8	2	2	3.5	1.1	1.5	1						4	3	7	
Chromium			<2																	
Copper	10	10	1.05								10	9							<20	
Fluoride	1.26	1.1		0.5	0.8		1.3			1.2	1.1	1.2							1.1	0.5
Hardness	179.5	140.5	299.5	240	330	340	340	350		330	135.5	205.5	300	300	300	310	250	310	580	
Iron	760	580	1630	<20						130	720	630							<20	
Lead			<0.1																<2	
Magnesium	30	25	27.2	27	26	29	32	28		31	23	32	31	31	31	33	14	30	28	
Manganese	30	10	13.4							30		10							20	
Mercury			<0.2																	
NH3			<0.03																	
Nitrate	0.13	0.44		<0.04	0.31	0.2	0.4	0.1			0.2	0.4							<0.04	<0.04
NO3-NO2	0.03	0.1	0.026							0.06	0.04	0.1								
pH	7.8		7.56	8	7.8	7.3	7.5	7.7	7.9	7.5	7.8								7.6	
Phosphate	0.07		<0.003							0.03	0.06								0.23	
Potassium	3	3	3.26							3.1	3	3							3	
Selenium			<1																	
Silica				6.4	11	9.1	9.5	10		9.7									7	
Silver			<0.5																	
Sodium	10	4	4.72							6.5	10	7	19	19	9.2	8			6	
Sodium plus Potassium				7.4	11	13	12	9									39	3		
Specific Conductivity		510	565			653	655	654	628	648		720							1000	
Sulfate	186	100	108	124	134	174	175	176	171	170	108	240	140	149	132	145	150	140	418	
Temperature			17.73			17	17	16.5	17	17										
Total Dissolved Solids	435	330	348	332	416	425	448	432			320	520	432	432	428	583	402	397	818	
Turbidity	1	4.7	0.42								0.8	8.6								
Zinc	10	30	<10								10								40	

[1]Site number was designated for this study and does not exist in the USGS NWIS database.

[2]White columns refer to samples collected by the Utah Geological Survey for this study.

[3]BCA refers to the consulting firm Bowen, Collins, and Associates, who contracted Chemtech-Ford Laboratories for analysis; Maeser City provided the consultant's report.

Table 11. *Continued.*

403147109371501[1]	403211109352801[1]	403228109331701		403430109370701	403400409414501[1]	403613109284202	403613109284203		403636109280101		Number of samples n			Statistics							units
BCA[3]	BCA[3]	BCA[3]	UGS[2]	UGS[2]	BCA[3]	USGS	USGS		USGS		Total Samples	Detected	Not Detected	Minimum	Maximum	Geometric Mean	1st Quartile	Median	3rd Quartile	Standard Dev.	
5/22/09	5/21/09	9/9/05	9/26/12	9/25/12	8/30/05	12/11/51	5/16/67	8/31/71	7/18/73	8/16/74											
177		180	166	82	200	172	190	194	146	198	28	28	0	82.0	203	170	168	178	185	27.3	mg/L $CaCO_3$
			12.6	<10							3	1	2	12.6	12.6	12.6					µg/L
		4.00	4.97	1.28	0.7					< 10.0	8	7	1	0.70	5.10	2.66	1.28	4.00	4.97	1.66	µg/L
		0.02	<0.10	<0.10	0.128					<0.01	10	6	4	0.02	0.13	0.03	0.02	0.02	0.04	0.005	mg/L
	283	210	202	100	250	210	232	237	178	242	28	28	0	100	283	210	206	217	230	33.5	mg/L
			<30	<30						< 10	7	3	4	20.0	50.0	34.2				15.3	µg/L
		<0.5	<0.1	<0.1	<0.5						5	0	5								µg/L
65.7	108	81.1	84.1	25.2	73.8	55	51	48	100	71	29	29	0	25.2	188	74.5	67.3	75.0	88.0	29.3	mg/L
			2	2		6.7	6	6	9	12	17	17	0	1.90	160	9.01	4.90	7.20	11.5	50.8	mg/l
<1	<1	<1	0	0	<1	0	0	0	0	0	17	1	16	0.00	1.00	1.00				0.277	mg/L
1	5	<1	1.92	1.58	6	3.6	2.8	4.3	3.1	4	24	23	1	0.00	7.00	2.61	1.80	2.80	4.00	1.74	mg/L
		<5	<2	<2	<5					< 20	6	0	6								µg/L
		<10	6.33	2.56	<10	<20				<20	12	7	5	1.05	10.0	5.50	2.56	9.00	10.0	3.80	µg/L
		1.1			<0.1	0		0.1	0.7	0.32	16	15	1	0.00	1.30	0.74	0.50	1.10	1.20	0.447	mg/L
		328	337	116	255	200	239	230	350	280	27	27	0	116	580	266	230	300	330	94.5	mg/L
		40	1470	<20	<20			<20	20	150	15	10	5	20.0	1630	307	96.8	604	896	566	µg/L
		<1	0.528	0.251	<1					<2	7	2	5	0.25	0.53	0.36				0.196	µg/L
25.5	36.1	30.5	30.8	12.9	17.1	16	27	27	24	25	29	29	0	12.9	36.1	26.2	25.0	28.0	31.0	5.44	mg/L
23	348	<10	16.1	<5	<10			10	100	<10	15	11	4	10.0	348	25.6	10.0	20.0	30.0	28.6	µg/L
		<0.2	<0.2	<0.2	<0.2					<1	6	0	6								µg/L
			<0.03	<0.03							3	0	3								mg/L
<0.4	<0.4	<0.4			2.7	0.31				0.8	17	11	6	0.10	2.70	0.34	0.19	0.31	0.44	0.730	mg/L as NO3
			0.044	0.065				0.08	0.06		10	10	0	0.03	0.10	0.06	0.04	0.06	0.08	0.027	mg/L as N
7.4	8.3	7.21	7.88	7.5	7.09	7.7	7.8	7.8	7.5	7.5	22	22	0	7.09	8.30	7.64	7.50	7.65	7.80	0.186	std units
		<0.01	<0.003	<0.003	<0.01			0.03	0.03	0.02	12	7	5	0.02	0.23	0.05	0.03	0.03	0.07	0.075	mg/L
4	7.1	3.3	3.34	1.38	0.4		2.3	1.1	4	1.3	17	17	0	0.40	7.10	2.49	1.78	3.00	3.32	0.887	mg/L
		<0.5	<1	1.63	3					< 10	6	2	4	1.63	3.00	2.21					µg/L
		8.4			6.5	5.8		9.4	6.3	0.6	13	13	0	0.60	11.0	6.62	6.35	8.40	9.60	2.94	mg/L as SiO_2
		<0.5	<0.5	<0.5	<0.5					16	6	1	5	16.0	16.0	16.0					µg/L
5.3	136	4.8	5.06	2.32	4.1		3.2	3.1	3.2	5.8	21	21	0	2.32	136	6.91	4.05	5.80	9.59	4.97	mg/L
						7.6					8	8	0	3.00	39.0	10.0	7.45	9.95	12.7	11.1	mg/L as Na
		641	620	227	505		423	437	695	640	17	17	0	227	1000	578	507	640	654	170	uS/cm @25C
111	430	143	142	21	35	36	53	44	210	94	30	30	0	21.0	430	123	106	141	174	76.8	mg/L
			13.37	9.7			12	12.5	10	9.5	12	12	0	9.50	17.7	13.7	10.5	14.9	17.0	3.27	deg C
	1020	394	384	108	300	232	253	254	440	442	27	27	0	108	1020	389	330	416	440	133	mg/L
380	390	0.64	2.56	0.146	0.05						11	11	0	0.05	390	2.50	0.42	1.00	8.60	3.08	NTU
		<10	19.2	54.4	0.01					20	10	8	2	0.0	54.4	8.4	10.0	19.6	37.2	16.4	µg/L

Table 12. *Results of analyses conducted on water samples collected for this study.*

Site ID	Site Name	Sample Date	Lab[1]	δO18 ‰	+/- δO18 ‰	δD ‰	+/- δD ‰	C14 (pmC[2])	+/- C14 (pmC[2])	Tritium (TU[3])	+/- Tritium (TU[3])
9	Vernal Well	9/25/12	BYU	-16.86	0.2	-124.4	0.5	27.416	0.104	<0.2	0.2
10	Ashley Spring	9/25/12	BYU	-16.01	0.2	-117.2	0.5	60.972	0.194	3.9	0.2
11	Thomson Well	9/25/12	BYU	-16.04	0.2	-122.1	0.5	–	–	0.7	0.1
12	Perry Well	9/25/12	BYU	–	–	–	–	–	–	–	–
13	Stevens Well	9/25/12	BYU	–	–	–	–	–	–	–	–
14	Maine Well	9/26/12	BYU	-16.33	0.2	-121.2	0.5	–	–	0.9	1
15	Allen Well	9/26/12	BYU	-16.98	0.2	-125.0	0.5	–	–	<0.2	0.2
16	Ashley Stream	9/27/12	BYU	-15.59	0.2	-116.0	0.5	–	–	–	–
17	Dry Fork	9/27/12	BYU	-14.30	0.2	-106.5	0.5	–	–	6.9	0.2
17	Dry Fork	5/12/14	USU	-15.16	0.08	-117.8	3.3	–	–	–	–
10	Ashley Spring	5/12/14	USU	-15.30	0.08	-111.2	3.3	–	–	–	–
9	Vernal Well	4/16/14	USU	-16.24	0.06	-122.8	2.1	–	–	–	–
10	Ashley Spring	4/16/14	USU	-15.59	0.06	-113.9	2.1	–	–	–	–

Site ID	Site Name	Sample Date	Lab[1]	TDS (mg/L)	Field Temp (°C)	Field Cond. (µmhos)	Lab Cond. (µmhos)	pH, Field	pH, Lab	Diss. Oxygen (mg/L)	Susp. Solids (mg/L)	Total Alk (mg/L)	Total Hard (mg/L)	Turb (NTU)
9	Vernal Well	9/25/12	UDH	108	9.7	227	216	7.5	7.98	3.6	<4	82	116	0.15
9	Vernal Well	5/29/13	UDH	112	–	–	216	–	8.19	–	<4	80	117	<0.1
10	Ashley Spring	9/25/12	UDH	74	8.46	185	175.8	7.48	7.76	7.38	37.2	83	105	10.10
10	Ashley Spring	5/29/13	UDH	60	–	–	95.8	–	7.02	–	7.6	43	54	8.30
11	Thomson Well	9/25/12	UDH	486	10.65	679	638	7.75	7.74	4.65	<4	238	360	0.28
11	Thomson Well	5/29/13	UDH	378	–	–	636	–	7.96	–	<4	236	359	0.12
12	Perry Well	9/25/12	UDH	1024	10.63	1439	1357	7.4	7.61	5.63	<4	308	818	0.51
13	Stevens Well	9/25/12	UDH	220	10.85	430	404	8.08	7.94	5.1	<4	195	235	1.95
14	Maine Well	9/26/12	UDH	348	17.73	565	534	7.56	7.93	1.74	<4	164	300	0.42
15	Allen well	9/26/12	UDH	384	13.37	620	592	7.88	8.17	6.16	<4	166	337	2.56
16	Ashley Creek	9/27/12	UDH	164	9	270	321	7.9	8.41	–	<4	156	183	0.50
17	Dry Fork	9/27/12	UDH	10	9.1	1	29.61	7.9	6.27	–	<4	12	–	1.49
17	Dry Fork	5/29/13	UDH	20	–	–	18.28	–	5.68	–	6	4	10	2.64
18	Dry Fork Spring	5/29/13	UDH	56	–	–	90.33	–	6.70	–	10.4	40	51	9.39

Site ID	Site Name	Sample Date	Lab[1]	Cr (µg/L)	Hg (µg/L)	Zn (µg/L)	Se (µg/L)	Ag (µg/L)	Cu (µg/L)	Fe (µg/L)	Pb (µg/L)	Al (µg/L)	As (µg/L)	Ba (µg/L)	Cd (µg/L)	B (mg/L)	Mn (µg/L)
9	Vernal Well	9/25/12	UDH	<2	<0.2	54.4	1.63	<0.5	2.6	<20	0.25	<10	1.28	<100	<0.1	<30	<5
9	Vernal Well	5/29/13	UDH	–	–	–	–	–	–	–	–	–	1.02	–	–	–	–
10	Ashley Spring	9/25/12	UDH	<2	<0.2	12.5	<1	<0.5	1.2	29	0.20	21	1.27	109	<0.1	<30	<5
10	Ashley Spring	5/29/13	UDH	<2	<0.2	<10	<1	<0.5	1.1	59	<0.1	85.3	<1	<100	<0.1	<30	<5
11	Thomson Well	9/25/12	UDH	<2	<0.2	18.7	3.69	<0.5	1.2	<20	0.22	<10	<1	<100	<0.1	47.3	12.5
12	Perry Well	9/25/12	UDH	<2	<0.2	39.5	6.04	<0.5	3.6	96	0.47	<10	1.29	<100	<0.1	86.7	<5
13	Stevens Well	9/25/12	UDH	<2	<0.2	18.4	<1	<0.5	2.1	22	0.13	<10	<1	114	<0.1	<30	<5
14	Maine Well	9/26/12	UDH	<2	<0.2	<10	<1	<0.5	1.1	1630	<0.1	<10	4.17	<100	<0.1	<30	13.4
15	Allen well	9/26/12	UDH	<2	<0.2	19.2	<1	<0.5	6.3	1470	0.53	12.6	4.97	<100	<0.1	<30	16.1
16	Ashley Creek	9/27/12	UDH	<2	<0.2	<10	1.04	<0.5	<1	<20	<0.1	<10	<1	182	<0.1	<30	<5
17	Dry Fork	5/29/13	UDH	<2	<0.2	<10	<1	<0.5	<1	108	<0.1	122	<1	<100	<0.1	<30	<5
18	Dry Fork Spring	5/29/13	UDH	<2	<0.2	<10	<1	<0.5	1.0	53	<0.1	77.1	<1	<100	<0.1	<30	<5

[1]USU = Utah State University; BYU = Brigham Young University; UDH = Utah Department of Health
[2]pmC = percent modern carbon
[3]TU = Tritium Units

Table 12. *Continued.*

Site ID	Site Name	Sample Date	Lab[1]	PO^4 (mg/L)	NH^4 (mg/L)	NO^2 + NO^3 - N (mg/L)	SO^4 (mg/L)	Na (mg/L)	Mg (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	CO^3 Solids (mg/L)	CO^2 (mg/L)	CO^3 (mg/L)	HCO^3 (mg/L)
9	Vernal Well	9/25/12	UDH	<0.003	<0.03	0.065	21	2.32	12.9	1.38	25.2	1.6	49	2	0	100
9	Vernal Well	5/29/13	UDH	0.004	<0.046	0.0761	18	2.21	13.1	1.4	25.3	0.9	48	1	0	97
10	Ashley Spring	9/25/12	UDH	0.02	<0.03	0.24	7	1.48	8.7	<1	27.6	1.5	50	3	0	101
10	Ashley Spring	5/29/13	UDH	0.012	<0.046	0.12	<2.44	<1	3.58	<1	15.7	0.9	26	8	0	53
11	Thomson Well	9/25/12	UDH	0.009	<0.03	0.117	89	10.9	37.8	1.26	82	6.5	143	8	0	290
11	Thomson Well	5/29/13	UDH	0.008	<0.046	0.125	84	11.3	38	1.44	81.1	4.9	142	5	0	288
12	Perry Well	9/25/12	UDH	0.011	<0.03	3.21	395	19.3	66.7	2.44	218	17.7	185	15	0	376
13	Stevens Well	9/25/12	UDH	0.011	<0.03	0.342	13	2.63	17.1	<1	65.9	3.9	117	4	0	238
14	Maine Well	9/26/12	UDH	<0.003	<0.03	0.026	108	4.72	27.2	3.26	75.2	1.9	98	4	0	200
15	Allen well	9/26/12	UDH	<0.003	<0.03	0.044	142	5.06	30.8	3.34	84.1	1.9	99	2	0	202
16	Ashley Creek	9/27/12	UDH	0.004	<0.03	0.274	12	2.42	15.6	1.1	47.8	2.3	94	1	4	183
17	Dry Fork	9/27/12	UDH	0.008	<0.03	0.05	<2.44	0.72	0.78	0.03	3.17	0.7	7	13	0	15
17	Dry Fork	5/29/13	UDH	0.007	<0.046	0.075	<2.44	<1	<1	<1	2.53	0.8	2	15	0	5
18	Dry Fork Spring	5/29/13	UDH	0.011	<0.046	0.111	<2.44	<1	3.2	<1	15	0.9	24	16	0	49

[1]USU = Utah State University; BYU = Brigham Young University; UDH = Utah Department of Health

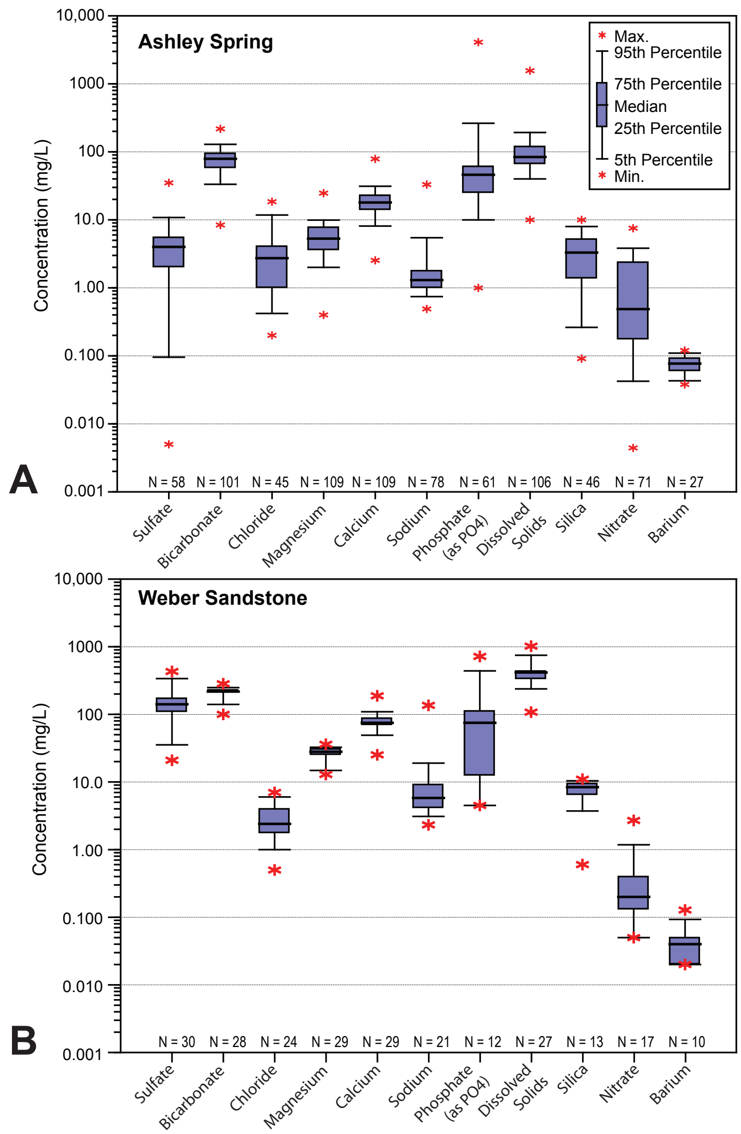


Figure 28. *Distribution of concentrations of major chemical constituents in (A) Ashley Spring and (B) Weber Standstone groundwater.*

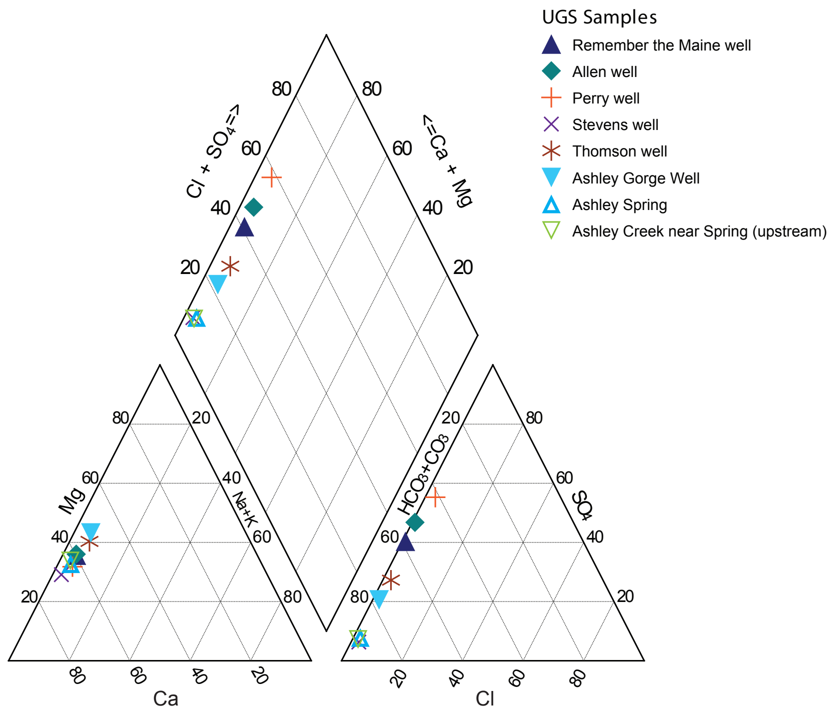


***Figure 29.** Piper diagram showing general solute chemistry for sites sampled in the study area during September 2012.*

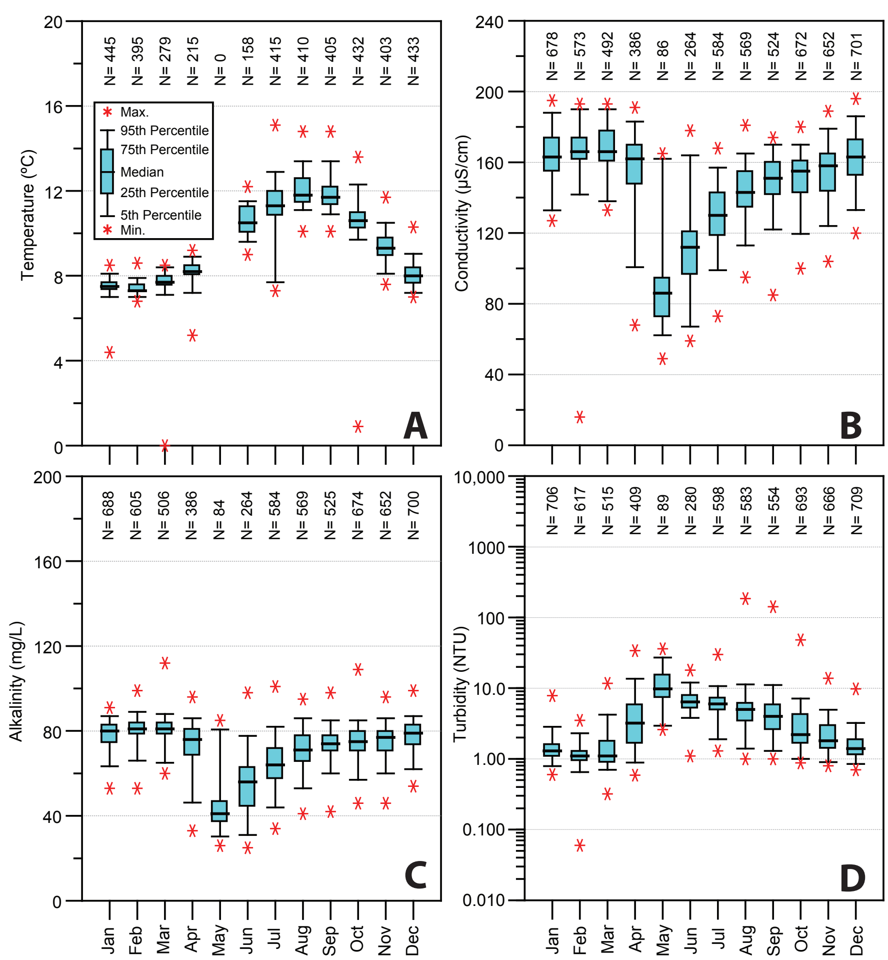


***Figure 30.** Monthly statistics of daily (A) temperature, (B) conductivity, (C) alkalinity, and (D) turbidity data for water from Ashley Spring at the Central Utah Water Conservancy District (CUWCD) treatment plant, 1987 to 2013. Relatively few samples exist for May because the CUWCD used Red Fleet Reservoir as an alternative water source during this time. Turbidity is reported in Nephelometric Turbidity Units (NTU).*

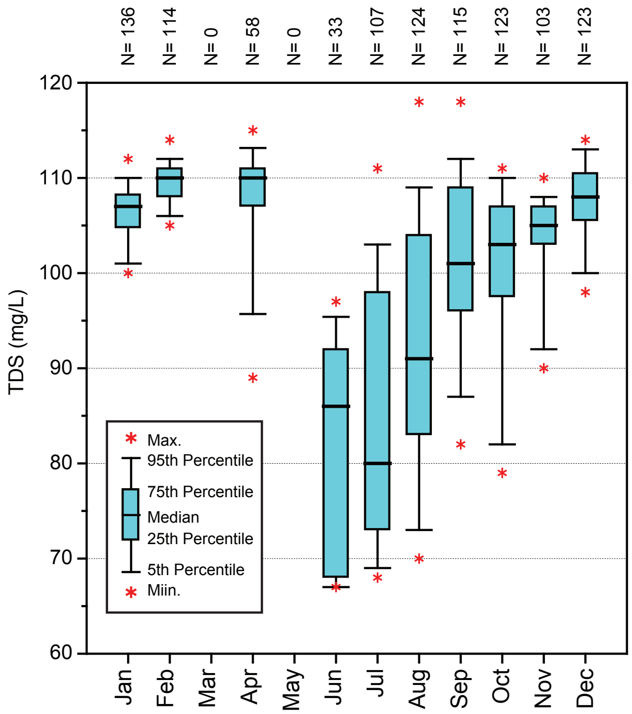


Figure 31. *Monthly statistics of daily total dissolved solids (TDS) for water from Ashley Spring at the Central Utah Water Conservancy District treatment plant, 2009 to 2013. No samples were collected during March and May because the water treatment plant used Red Fleet Reservoir as an alternative water source during this time.*

regime for Ashley Spring. Dye travel times and available hydrographs (figures 18–19) indicate that Ashley Spring receives water from a karst conduit system.

On May 17, 1997, the Mosby Canal failed, triggering a large landslide that deposited thousands of cubic feet of red sediment into the Dry Fork drainage and the karst network (Fallon, 1997; Wallis, 1997). Subsurface flow continued between the sinks of Dry Fork and Ashley Spring. Because there have been no direct measurements of Ashley Spring flow since 1955 (figure 13, USGS, 2013), we cannot say with certainty if the washout from the canal failure impacted the flow of the spring. Based on mineralogical sediment analysis, Godfrey (1985) concluded that suspended sediment and turbidity observed in Ashley Spring was from the karst network, and not contributed by the sediment in the Dry Fork catchment. However, the appearance of red, highly turbid water for several weeks following the canal failure indicated that sediment can be transported from Dry Fork to Ashley Spring. While the source of some sediment in Ashley Spring may be detrital grains released from the dissolving limestone matrix of the karst network, Dry Fork is likely contributing sediment.

We compiled a map showing karst flow paths based on all available tracer data (figure 37), using our data and information provided by Godfrey (1985) and Spangler (2005). The map is a visualization of dominant direction of flow and approximate hydraulic gradient of the karst network, showing the sources known to contribute to Ashley Spring. Some of the flow paths, such as Dry Fork sink to Dry Fork Spring and to Brush Creek Spring, appear to be seasonal and depend on the available discharge of the karst system Godfrey (1985). The flow direction in the karst system is dominantly southeast, and there is no evidence of flow to Ashley Spring from basins to the east. Surface water flow (figure 25A), lineaments (figure 25B), and joints in the area (Haddox and others, 2005) all have a similar dominant northwest/southeast trend. The trend coincides with that of faults in the Deep Creek fault zone (figure 11). Karst development preferentially occurs along existing fractures, meaning that karst systems generally follow fracture orientations (Bakalowicz, 2006). Limited depression mapping data (figure 26) and unpublished cave maps (Green, 1957) also support that the karst system follows trends similar to that of the regional faulting.

Discharge from Ashley Spring (both the diverted spring water and non-diverted west side springs) varies seasonally and correlates with snowmelt. While periodic precipitation does influence spring discharge (figure 19), melting snowpack is dominant. Based on flow measurements from 1944–1945 and 1954–1955 of Ashley Spring (USGS station 9266000) and Ashley Creek (USGS station 9266500), the maximum flow of Ashley Spring, occurring from May to June during snowmelt (Spangler, 2005), typically does not exceed 50 cfs, and minimum flow, from January to March, generally does not drop below 12 cfs (0.33 cms) (figures 18–21). Maximum flow of Ashley Spring (including west-side springs and neglecting diverted water) based on the difference between the upstream (USGS station 9265500) and downstream (9266500) gauges, was 220 cfs (6.2 cms); the average maximum discharge is about 70 cfs (2 cms) (figure 18). Mundorf (1971) reported a range of discharge of 15 to 90 cfs (0.4–2.5 cms).

The relative proportion of discharge that Ashley Spring contributes to Ashley Creek decreases as flow of Ashley Creek increases (figure 20A). Contributions from Ashley Spring make up most of the discharge of Ashley Creek at discharges below about 50 cfs (1.4 cms). When the discharge of Ashley Creek approaches 1000 cfs (28 cms), the contribution from spring water is less than 10% of the total creek discharge. This is likely because the karst system accommodates a finite amount of discharge, while the volume in the Ashley Creek channel is derived from snowmelt runoff over a large high- altitude area. When high discharge occurs, the karst network reaches capacity, but Ashley Creek discharge continues to increase. When the karst system between Dry Fork and Ashley Spring is at capacity, the overflow goes down the surface channel and also resurges at Dry Fork Spring (Spangler, 2005). Dry Fork Spring is at a higher elevation than Ashley Spring and is dry except during the spring and summer, both of which are consistent with the overflow hypothesis.

Flow trends in Ashley Creek and Ashley Spring change as discharge increases. When the discharge of Ashley Spring (USGS station 9266000) approaches 50 cfs (1.4 cms), and discharge

Table 13. Monthly statistics of daily Ashley Spring water chemistry measured by the Central Utah Water Conservancy District.

	Month	ALL	January	February	March	April	May	June	July	August	September	October	November	December
Turbidity (NTU)	range	185	7.2	3.4	11	33	33	17	29	184	141	47	13	9.1
	maximum	185	7.8	3.5	12	34	36	18	30	185	142	48	14	9.8
	minimum	0.06	0.6	0.06	0.3	0.6	2.6	1.1	1.3	1	1	0.9	0.8	0.7
	average	3.6	1.5	1.2	1.7	4.8	12	7.0	6.2	6.2	5.6	3.4	2.4	1.7
	standard deviation	5.4	0.7	0.5	1.5	4.9	7.5	2.8	2.9	11	10	3.8	1.7	1.2
	1st quartile	1.3	1.0	0.9	0.9	1.6	6.9	5.0	4.7	3.3	2.5	1.6	1.4	1.1
	median	2	1.3	1.1	1.1	3.2	9.8	6.4	6	5	4	2.2	1.8	1.4
	3rd quartile	4.9	1.6	1.3	1.8	6.0	16	8.0	7.4	6.2	5.9	4.3	3.0	1.9
	count	6419	706	617	515	409	89	280	598	583	554	693	666	709
Hardness (mg/L)	range	134	83	93	116	110	49	101	71	73	118	93	66	73
	maximum	138	115	117	120	117	56	129	111	115	138	113	106	113
	minimum	4	32	24	4	7	7	28	40	42	20	20	40	40
	average	82	87	89	85	79	37	63	74	80	86	84	85	87
	standard deviation	17	13	17	24	24	12	18	13	11	10	9	9	11
	1st quartile	77	83	85	86	76	30	53	67	75	81	80	81	82
	median	85	89	91	92	86	36	64	75	81	85	85	84	87
	3rd quartile	92	96	98	96	92	46	71	82	87	91	91	92	94
	count	5850	644	563	474	359	66	259	554	538	499	617	608	669
Alkalinity (mg/L)	range	87	38	46	52	63	59	73	67	54	56	63	50	45
	maximum	112	91	99	112	96	85	98	101	95	98	109	96	99
	minimum	25	53	53	60	33	26	25	34	41	42	46	46	54
	average	73	78	80	80	73	45	55	64	71	73	74	75	77
	standard deviation	11	7	6	6	11	14	15	11	10	8	8	8	8
	1st quartile	68	74	78	78	68	36	44	57	65	70	70	70	73
	median	76	80	81	81	76	41	56	64	71	74	75	77	79
	3rd quartile	81	83	84	84	81	47	63	72	78	78	80	80	83
	count	6239	688	605	506	386	84	264	586	569	525	674	652	700
Conductivity (µS/cm)	range	147	68	65	60	123	116	119	95	86	89	80	85	76
	maximum	196	195	193	193	191	165	178	168	181	174	180	189	196
	minimum	49	127	128	133	68	49	59	73	95	85	100	104	120
	average	151	162	166	167	155	91	111	130	143	149	150	154	162
	standard deviation	23	16	13	15	24	28	26	18	16	15	16	17	16
	1st quartile	139	154	161	160	147	72	96	118	134	141	142	143	152
	median	156	163	166	166	162	86	112	130	143	151	155	158	163
	3rd quartile	166	174	174	178	170	95	121	143	155	160.75	161	165	173
	count	6183	678	573	492	386	86	264	586	569	524	672	652	701
Temperature (Celcius)	range	15.1	4.1	1.8	8.5	4	–	3.2	7.8	4.7	4.7	12.7	4.1	3.3
	maximum	15.1	8.5	8.6	8.5	9.2	–	12.2	15.1	14.8	14.8	13.6	11.7	10.3
	minimum	0	4.4	6.8	0	5.2	–	9	7.3	10.1	10.1	0.9	7.6	7
	average	9.5	7.5	7.4	7.7	8.2	–	10.6	11.2	12.0	11.8	10.7	9.3	8.1
	standard deviation	1.9	0.4	0.3	0.7	0.5	–	0.7	1.3	0.7	0.7	1.0	0.8	0.6
	1st quartile	7.7	7.2	7.2	7.5	8	–	10	10.8	11.4	11.3	10.2	8.9	7.6
	median	9.3	7.5	7.3	7.7	8.2	–	10.5	11.3	11.8	11.7	10.6	9.3	8
	3rd quartile	11.3	7.7	7.6	8	8.5	–	11.3	12	12.6	12.2	11	9.8	8.4
	count	4003	446	396	279	215	–	158	415	410	415	432	404	433
Total Dissolved Solids (mg/L)	range	51	12	9	–	26	–	30	43	48	36	32	20	16
	maximum	118	112	114	–	115	–	97	111	118	118	111	110	114
	minimum	67	100	105	–	89	–	67	68	70	82	79	90	98
	average	101	106	110	–	108	–	81	84	92	101	100	103	108
	standard deviation	11.5	2.7	1.9	–	5.5	–	12	12	12	8	9	5	4
	1st quartile	96	104	108	–	107	–	68	73	83	96	97	103	105
	median	105	107	110	–	110	–	86	80	91	101	103	105	108
	3rd quartile	109	109	111	–	111	–	92	98	104	109	107	107	111
	count	1036	136	114	–	58	–	33	107	124	115	123	103	123

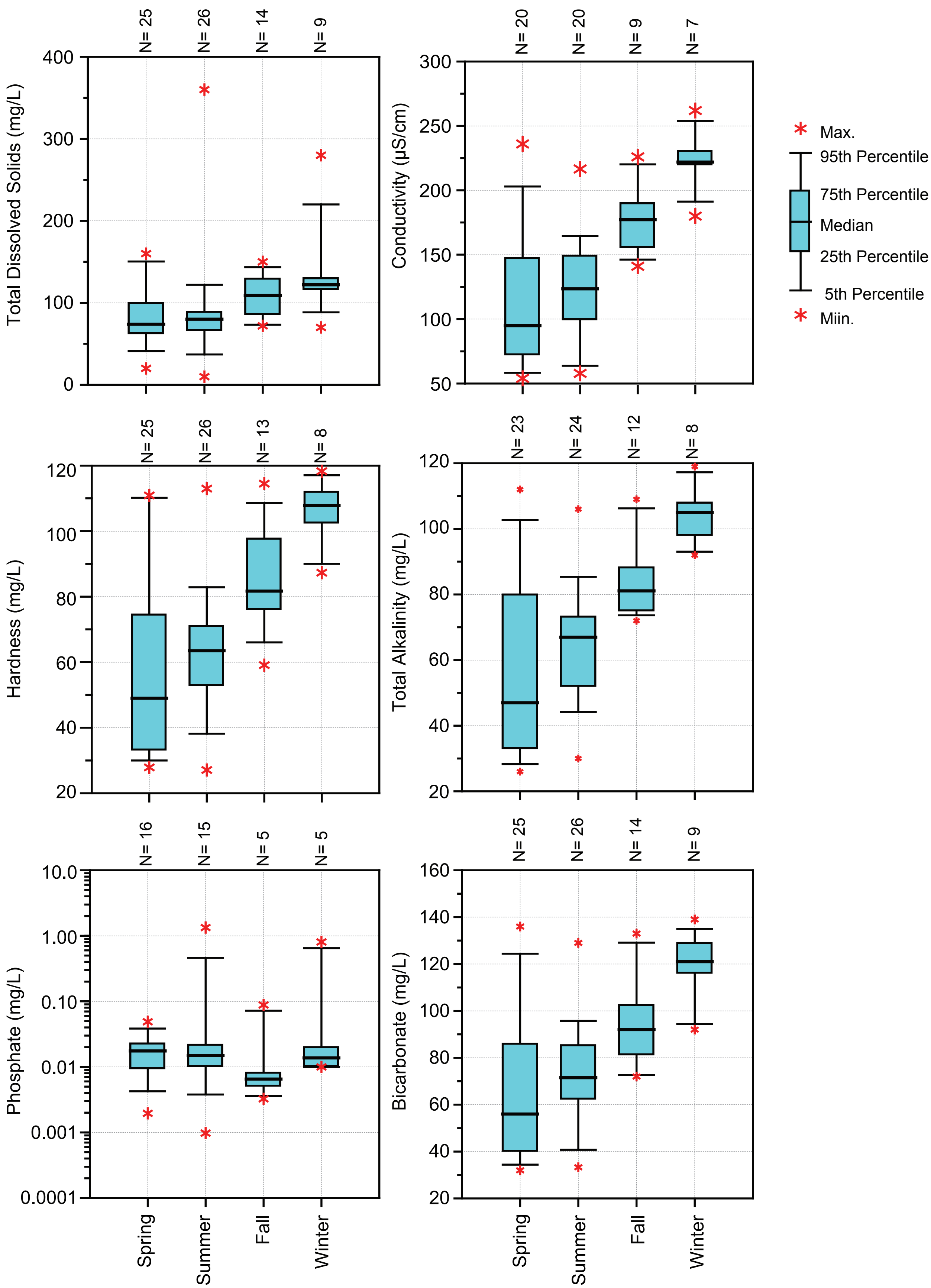


Figure 32. *Seasonal variations in Ashley Spring water chemistry compiled from UGS, USGS (2013), and EPA (2013) data.*

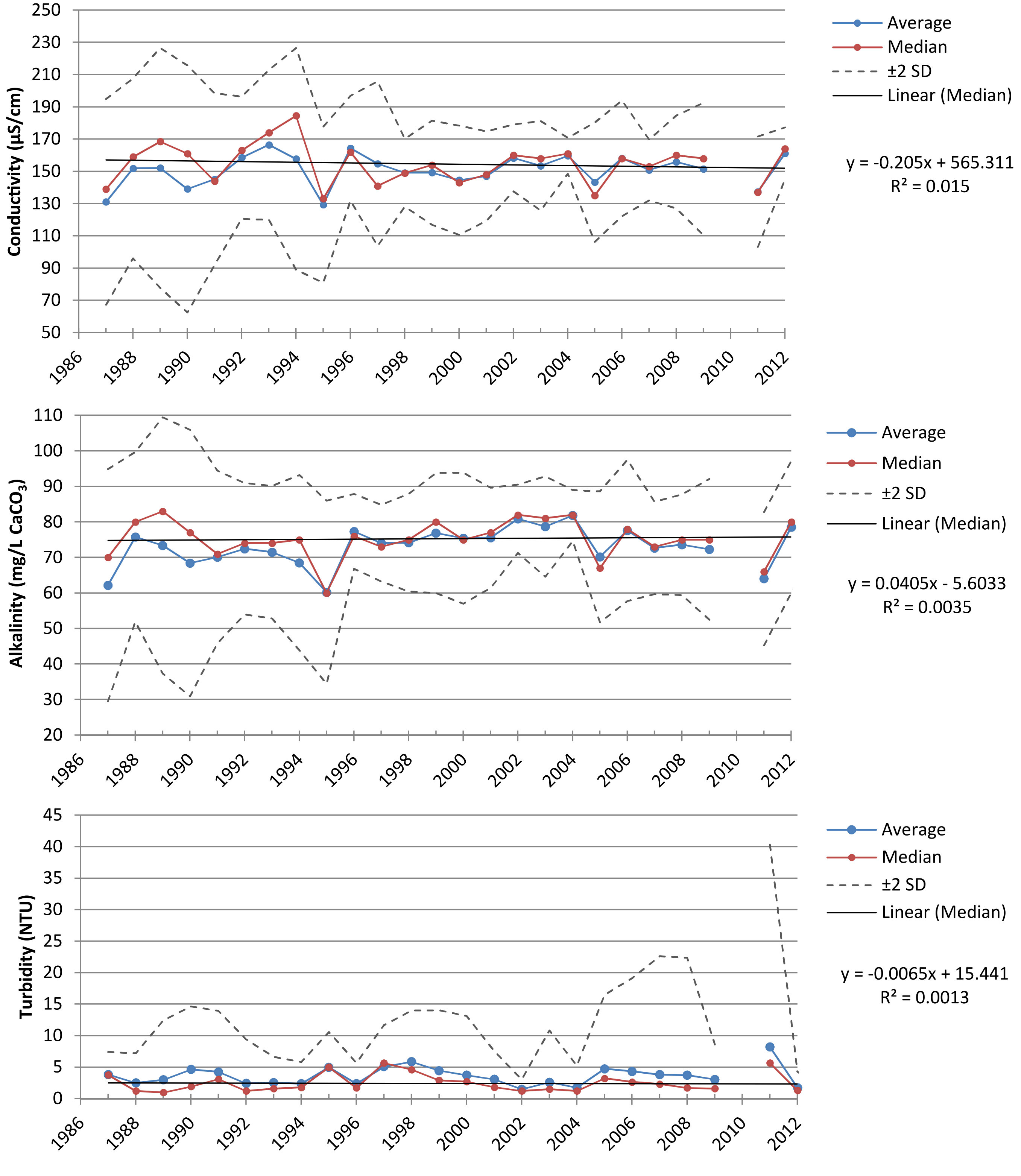


Figure 33. *Yearly statistics of daily water chemistry data for water from Ashley Spring at the Central Utah Water Conservancy District treatment plant, 1987 to 2013. No data were available for 2010. Turbidity is reported in Nephelometric Turbidity Units (NTU).*

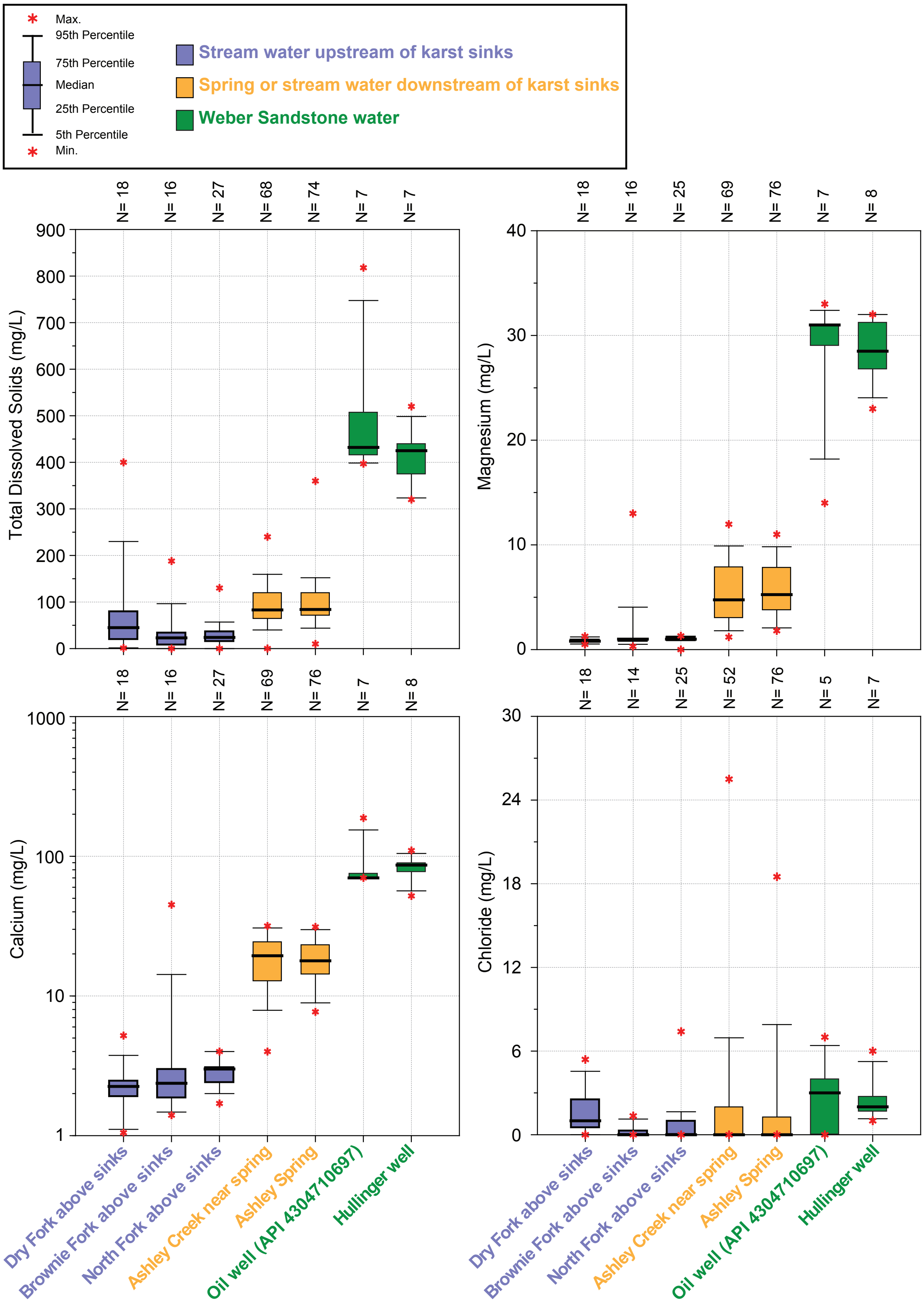


Figure 34. *Distribution of concentrations of chemical constituents in water compiled from various sources in the study area.*

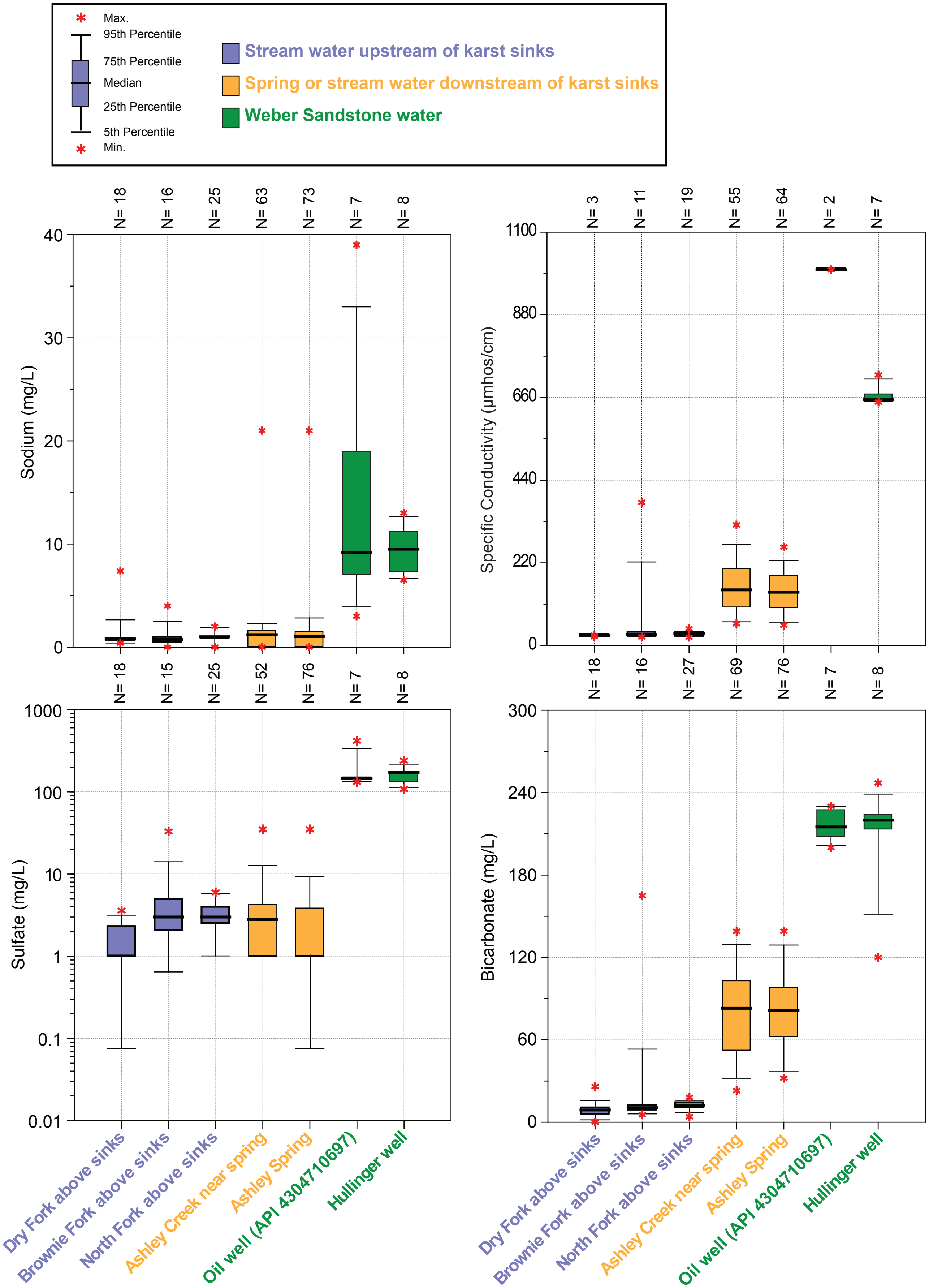


Figure 34. Continued.

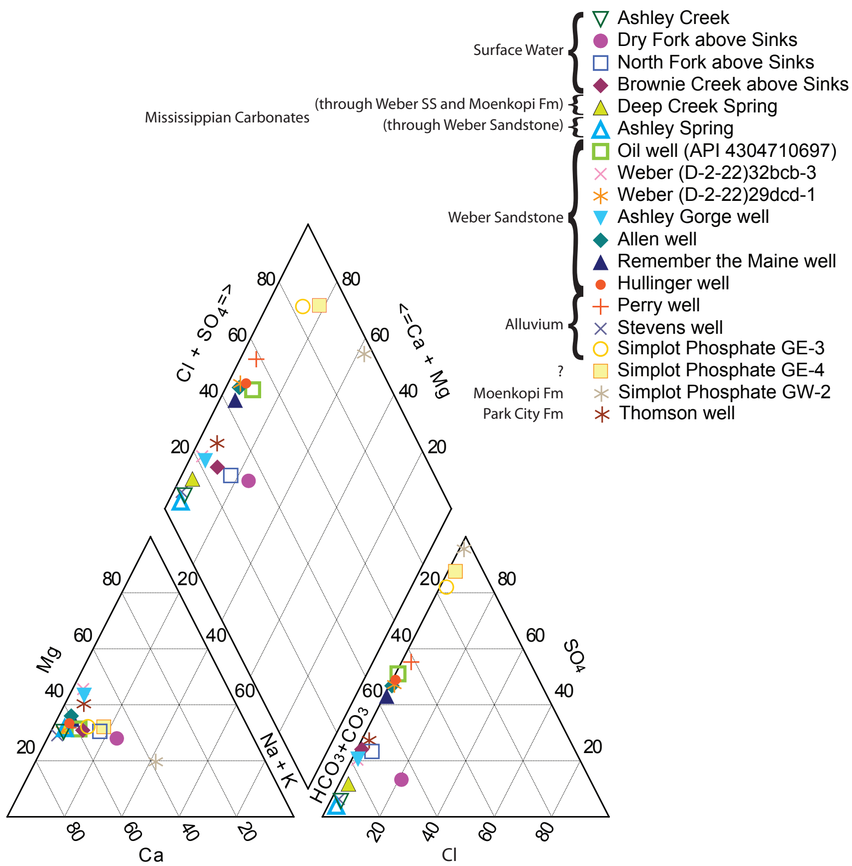


Figure 35. *Piper diagram showing general solute chemistry for aggregated samples from various compiled sources. The Simplot Phosphate wells are wells monitored by the Simplot Phosphate mine east of the study area.*

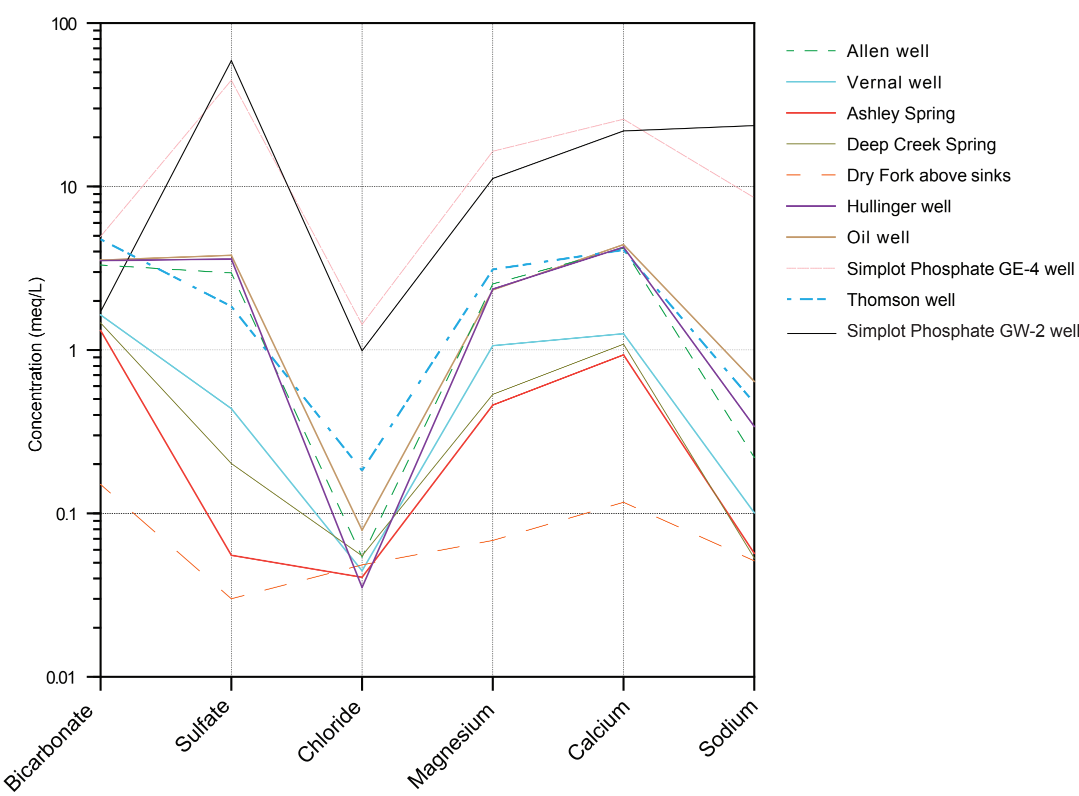


Figure 36. *Relative average concentrations of major ions in water from various locations in the study area. The Simplot Phosphate wells are wells monitored by the Simplot Phosphate mine east of the study area.*

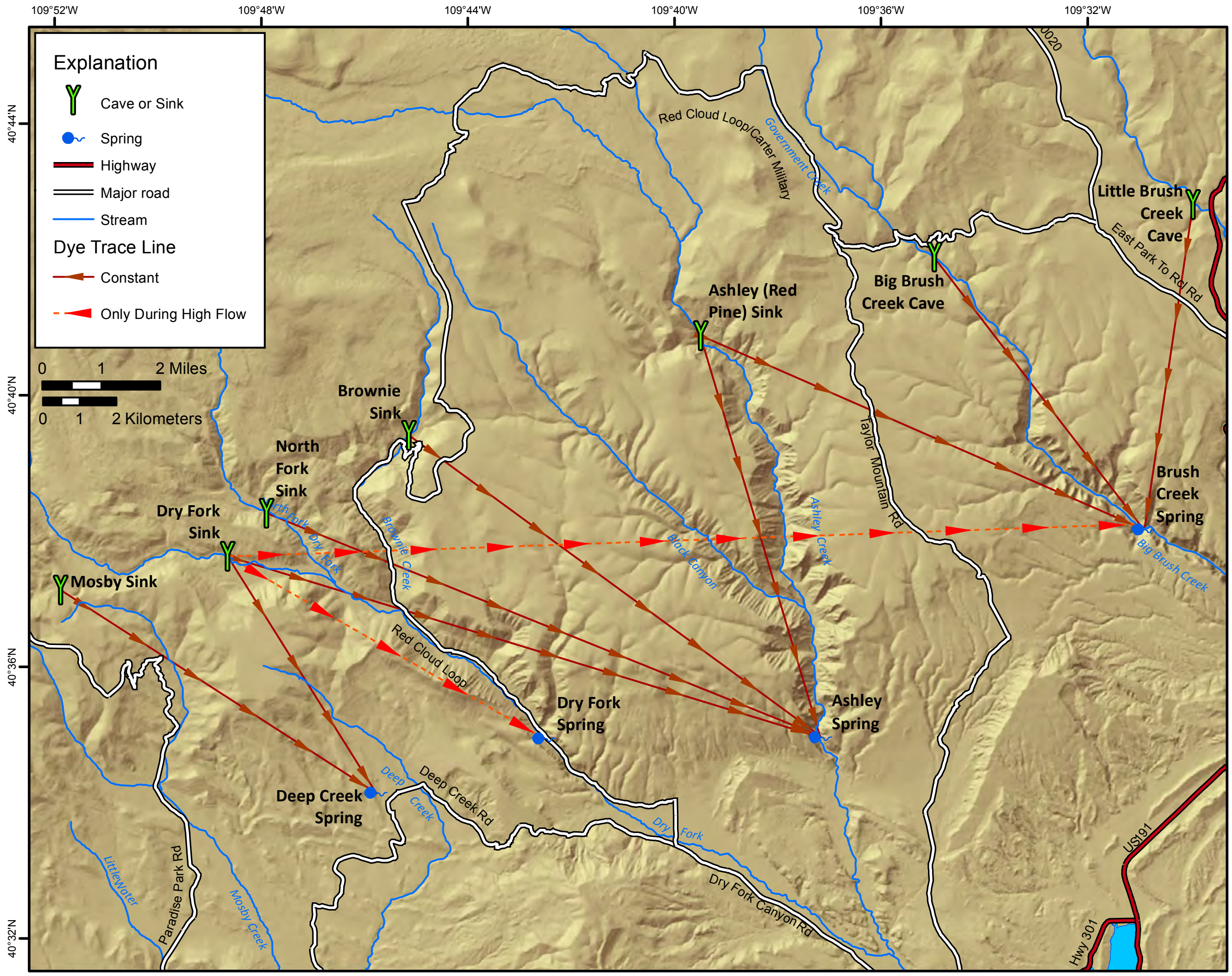


Figure 37. *Compilation of dye trace lines for the Deep Creek, Dry Fork, Ashley, and Brush Creek Spring basins (modified from Godfrey, 1985).*

of Ashley Creek exceeds 140 cfs (4 cms), the relationship between Ashley Spring discharge and Ashley Creek discharge changes. Also, the discharge relationship changes when Ashley Creek discharge exceeds about 250 cfs (7 cms) (figure 20B). This could be due to limitations of the equipment measuring the discharge (the flow of the spring may be difficult to resolve when Ashley Creek flow is high) or possible flow through the alluvium and surface flow bypass around gauges (and possibly to the spring). However, the change in trend is fairly abrupt, indicating the springflow may have reached a threshold. One possible explanation is that the flow of Ashley Spring is at maximum capacity near 50 cfs (1.4 cms). This could be due to Dry Fork Spring serving as an overflow for Ashley Spring, thus limiting discharge from the main spring. Another factor that could affect peak flow includes increasing flow from the west-side springs when the main spring peaks.

The Weber Sandstone groundwater potentiometric surface gradient, lineament and stream orientation, and karst conduit flow all follow a general northwest to southeast trend (figures 24–25, 37), although the flow in the Weber Sandstone is more north-south in some localized areas. The similar trends imply that fractures related to the Deep Creek fault zone and possibly the deformation associated with local and regional structural folds in the area have some control on the direction and magnitude of groundwater flow (figures 10 and 11; Spangler, 2005; Haddox and others, 2005). Fracture patterns also likely influence vertical flow through the aquifer. High permeability fracture systems likely exist in other locations influenced by the Deep Creek fault zone, creating conduits across assumed confining layers to and/or from aquifer units.

Water lost along the Dry Fork drainage most likely follows the dip of Mississippian carbonates as it travels to Ashley Spring, as opposed to traveling laterally across dipping bedding planes (Spangler, 2005). Dye trace results indicate that the water flowing from Dry Fork to Ashley Spring is moving at a velocity appropriate for conduit flow. Karst passages and large fractures are most conducive to conduit flow. The Mississippian carbonates are the only units in the area noted as having karst, and the Humbug Formation, Doughnut Shale, and the Morgan Formation are all siliciclastic units that could potentially hinder conduit flow. However, fractures in the area may be connected and open enough for conduit flow across siliciclastic units and through carbonate units, as is proposed for the vertical flow from the Mississippian carbonates to Ashley Spring. A karst system feeding into a well-connected vertical fracture system near the axis of an anticline seems more probable than a series of well-connected lateral fractures that are sufficiently open to allow for lateral flow.

For the water to travel from the Madison Limestone exposed in Dry Fork to the base of the Weber Sandstone along Ashley Creek, it must travel 10.6 miles (17 km) horizontally, then vertically through about 1500 to 2900 feet (460–900 m) of rock (figures 7, 22, and 23). The most likely conduit of travel through the vertical section is fractures, which must have a relatively high vertical hydraulic conductivity to create the observed dye transport times. We calculated the maximum vertical hydraulic gradient can be as high as 0.1 (in this case, the positive value indicates the gradient is up), by assuming that groundwater head from the Weber Sandstone rises, at most, 100 feet (32 m) above land surface (figure 24) over the minimum possible thickness separating Ashley Spring from the Madison Limestone (1500 ft; 460 m). Assuming the maximum value (0.1) of gradient and the velocity calculated from the dye trace (0.15 ft/s; 0.05 m/s), the minimum estimated bulk vertical hydraulic conductivity for the fractures would be about 1.15 feet per second (100,000 ft/day; 0.35 m/s), which is around the range of hydraulic conductivity for cavernous limestone (Heath, 1982). This estimate is based on Darcy's Law (Singhal and Gupta, 2010), which assumes linear flow and is not typically applicable at velocities this high. However, based on calculated velocities, we can assume groundwater flow through this system is essentially unrestricted, or at least is through fractures having apertures greater than 0.04 inch (1 mm) (Singhal and Gupta, 2010).

No dye from the tracer tests was detected at the Vernal well (figure 14), which is open to the Weber Sandstone (Lund, 1981). Lund (1981) noted that although the driller likely drilled to the bottom of the Weber Sandstone, no significant water-bearing fractures were encountered. Lack of connecting high-permeability fractures between the well and Ashley Spring could explain the differences in groundwater age (table 12) and lack of dye recovery. The well is likely developed in a considerably tighter part of the Weber Sandstone matrix where groundwater flow is considerably slower, and thus, older.

Based on observations at the Vernal well and results from the second dye-tracer test (no dye detected), flow through the Weber Sandstone appears to be highly dependent on the connectivity of fractures and the horizontal and vertical hydraulic gradients. Dye injected for the second tracer test was not detected in either Ashley Spring or the Vernal well (figure 14) during the extent of this study. Based on limited potentiometric surface data (figure 24) and because the dye-laden water was injected into the top of the Weber Sandstone at a higher elevation than Ashley Spring, we can assume the hydraulic gradient is primarily to the south. The dye did not reach the collection sites likely due to either a lack of connectivity between fracture sets and/or a disparity in the hydraulic gradient. The absence of dye could also be due to dispersion within the matrix and a very long travel time well beyond the length of the study. Flow within the matrix could also be moving downdip and into the subsurface along the flank of the mountain.

Springs above Ashley Spring could indicate discharge zones of the Weber Sandstone or could represent perched zones above the Weber Sandstone. U.S. Geological Survey topographic maps show several springs north of and topographically higher than Ashley Spring. Some of the springs, such as Lind Spring, Beck Spring, Middle Spring, Bear Spring, and Three Trough Spring (figure 38) are near the contact of the Park City Formation and the underlying Weber Sandstone. Of these springs, we visited Lind Spring, which was not flowing in either October 2012 or May 2013, and the U.S. Forest Service examined several (table 14). These springs could represent localized perched conditions where water periodically moves from the top of the hill (above the springs) and discharges a short distance downhill at the spring (hypocrene or hillslope springs).

Chemistry

The groundwater chemistry of Ashley Spring varies seasonally, but has not changed significantly from year to year in recent decades. During the study, water temperature increased from April to August (figure 30), peaking at about 13°C (55°F) in August, and decreasing to about 7°C (45°F) in February. The temperatures in figure 30 may be higher than water temperatures at the spring, as the CUWCD recorded them at the water treatment plant, 6 miles (10 km) to the southeast of the spring. Alkalinity, conductivity, and total dissolved solids are inversely correlated with annual flow (figures 18, 30, and 31). Variability of alkalinity and conductivity is highest in the spring and lowest in the winter (figure 32). Lower concentrations of these constituents are likely functions of a faster rate of flow through the system, limiting residence time and subsequent reaction rates, or a function of a higher proportion of surface water runoff versus groundwater flow in the spring discharge. The variability observed in conductivity and temperature is comparable to the variability observed in other alpine karst springs (Despain, 2006). Phosphate concentrations (figure 32) did not appear to vary seasonally, but the number of samples per season was low (<16). The coefficient of variation (standard deviation divided by the mean) of hardness of Ashley Spring was 20%, which is another indication of conduit flow (Shuster and White, 1971). The water chemistry of Ashley Spring has not changed significantly over the past three decades, and there are no major discernible long-term trends in the compiled water chemistry data (figure 33).

Comparing surface water chemistry to water from different aquifer systems may indicate the potential path(s) of water in the region. We measured field specific conductance of wa-

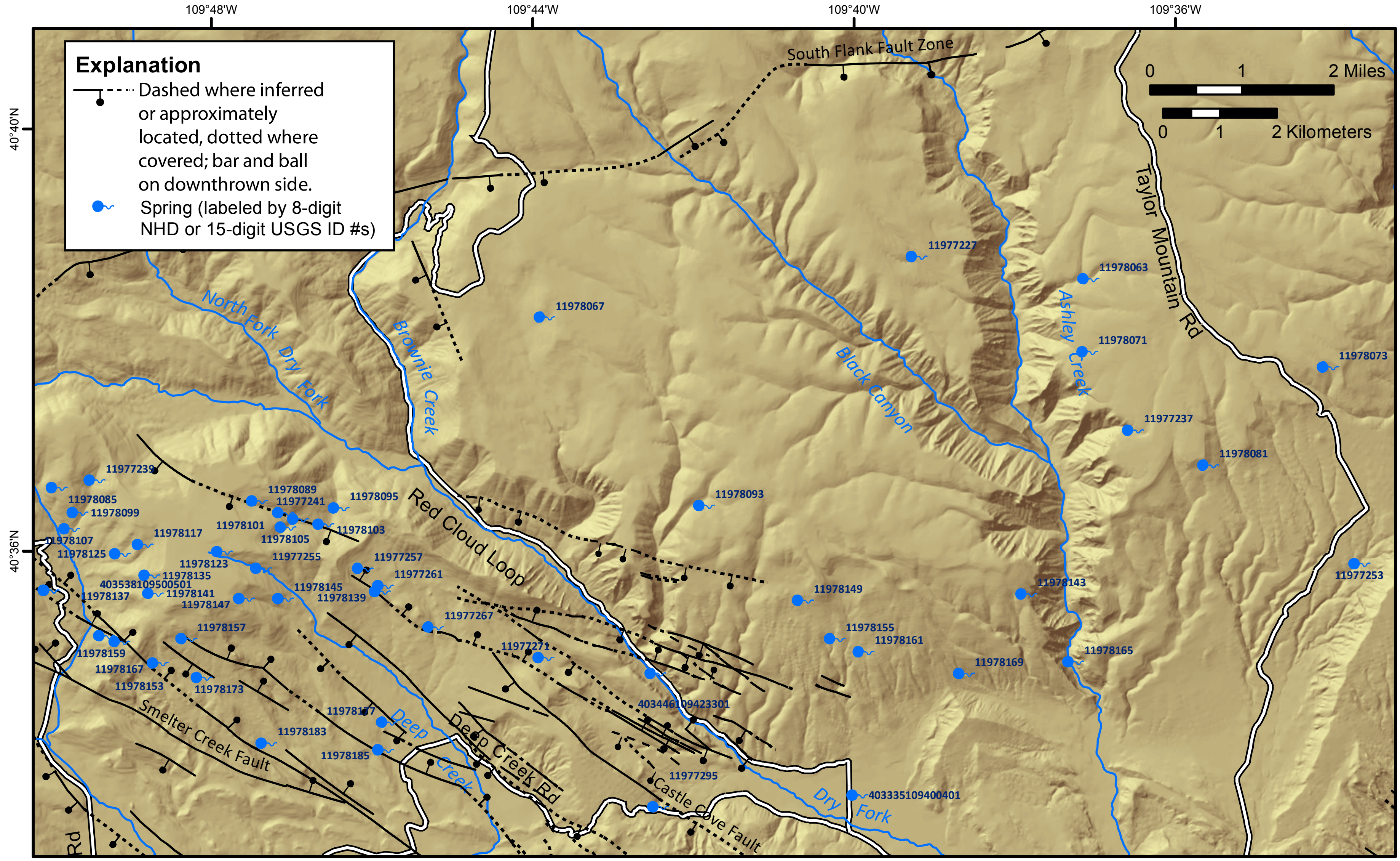


Figure 38. Distribution of springs and their relation to faults in the south-central portions of the Dry Fork and Ashley Creek drainages. Springs are labeled by either their 8-digit National Hydrography Dataset (NHD) identification number or their 15-digit U.S. Geological Survey number.

Table 14. *Summary of spring data collected by the U.S. Forest Service in 2013.*

Spring Name	NHD ID[1]	Comments	Type	Geology	Flow	Temp	pH	Cond.	ORP[2]
					L/min	C		µS/cm	mV
Single Trough Spring	11978081	diffuse flow almost dry	hillslope/hypocrene		–	18	8.4	590	92
Walkup Spring	11978123	diffuse flow	hillslope	colluvium quartzite	–	9	7.8	520	133
Lake Canyon Spring	11977255	diffuse flow; almost dry	rheocrene	colluvium quartzite	–	14	7.8	360	127
Flat Spring	11977257		rheocrene	colluvium quartzite	5	12	7.5	350	-18
Lower Flat Spring	11977261		rheocrene	colluvium quartzite	1.6	15	7.8	570	-29
Three Trough Spring 1st	11978063	two different distinct areas	hillslope/hypocrene	colluvium quartzite	2	13.5	7.8	530	146
Three Trough Spring 2nd	11978063	two different distinct areas	hillslope/hypocrene	colluvium quartzite	6.4	8	7.4	480	195
Bodily Spring	11978067	too diffuse flow to measure	hypocrene/hillslope	colluvium quartzite	–	21	6.9	260	88
Bear Spring	11978071	maybe a former hypocrene meadow; dry at least 2 years			–	–	–	–	–
Mud Spring	11978093	too diffuse for flow	hypocrene/hillslope	colluvium quartzite	–	22	7.2	420	65
Squaw Spring	11978125	dry	hypocrene/hillslope	colluvium quartzite	–	–	–	–	–
Shelmadine Spring	11978073	no facultative veg. = dry for many years	hillslope	colluvium quartzite	–	–	–	–	–
Buckhorn Spring	11978101		rheocrene/hillslope	colluvium quartzite	10.9	8	7.5	390	150
Gull Lake Spring	11978089	dry	helocrene	colluvium quartzite	–	–	–	–	–

[1]NHD ID = The National Hydrography Dataset (NHD) Identification Number; see figure 38 for the location of these springs.
[2]ORP = Oxidation-Reduction Potential

ter in Dry Fork, Brownie Creek, and North Fork above the sinks to be 30 µS/cm or lower, and found relatively low concentrations of major ions in Dry Fork water (figures 34 and 36), whereas Ashley Spring has an average conductivity of 140 µS/cm and concentrations of major ions almost an order of magnitude higher than in water in Dry Fork. Water from wells completed in the Weber Sandstone has higher concentrations of major ions than Ashley Spring (figures 34 and 36), especially sulfate. Water from wells monitored by Simplot Phosphate, 8 miles (13 km) east of the study area, and screened through alluvium or the Moenkopi Formation, has higher concentrations of major ions relative to wells screened within the Weber Sandstone and Ashley Spring. Higher concentrations in the Weber relative to the streams and Ashley Spring could indicate a longer residence time of water, allowing for prolonged chemical interaction of the water with the aquifer material. The surface water upstream of karst sinks has the lowest dissolved constituents, while the water coming out of karst springs and water downstream of the sinks has a higher concentration of dissolved constituents. The significant differences in general chemistry could indicate a disconnect between water in the pores of Weber Sandstone and water traveling through fracture systems connected to the Mississippian carbonates. The path the stream water follows to get to the downstream destinations can explain the minor chemical concentration differences between the stream water upstream of the karst sinks and the spring water and water downstream of the karst sinks. As the water travels along the stream bed and through the karst conduits and fractures, it picks up the dissolved load that makes up the differences observed in the chemical concentrations (figures 34 and 36).

We used tritium and Carbon-14 (^{14}C) to bracket the relative ages of water from the Weber Sandstone and water from Ashley Spring. Tritium values are a qualitative measure of groundwater age, providing the relative time recharge of the groundwater. Tritium is a radioactive isotope of hydrogen (H^3), having a half-life of 12.3 years. While cosmic rays produce naturally occurring tritium in the atmosphere, above-ground nuclear testing from 1952 to 1969 added significant concentrations of tritium to the atmosphere and precipitation. Atmospheric concentrations of tritium from weapons testing peaked in the first half of the 1960s and have been declining since. Modern water (very recently recharged), typically has concentrations of tritium between 20 and 50 tritium units (TU). Groundwater recharge that occurred prior to 1952 contains no detectable tritium. Carbon-14 is a radioactive isotope having a half-life of 5730 years (Clark and Fritz, 1997). Carbon-14 is generally reported as percent modern carbon (pmC). Clark and Fritz (1997) explain tritium and Carbon-14 in great detail and outline parameters required to estimate absolute ages.

Based on carbon dating and tritium values (table 12), and the dye-tracer tests, all (or most) of the water discharging from Ashley Spring is young, modern water, and carbon dating and tritium data also indicate that as least some of the water in the Weber Sandstone is older than water from Ashley Spring. Tritium was not detected or detected in low concentrations in wells open to the Weber Sandstone, meaning that much of the water in the Weber Sandstone predates atomic testing of the 1950s and 1960s (Clark and Fritz, 1997). Water from Ashley Spring had concentration of tritium of 3.9 tritium units (table 12), indicating a more recent exposure to the atmosphere. These results are substantiated by the ^{14}C data, showing that the Vernal well has a percent modern carbon (pmC) value that is half of that of values measured in Ashley Spring, indicating decay of ^{14}C over time since the groundwater was last exposed to the atmosphere. Relatively higher values of pmC indicate relatively younger ages of groundwater (Clark and Fritz, 1997). Because dilution factors and initial ^{14}C values are not well constrained for this area, we cannot provide an exact age of the water. Results of dye tracing indicate that most of the groundwater discharging at Ashley Spring from the Dry Fork karst system entered the system less than a week prior to the time of discharge. An increase in solute concentrations between Dry Fork and Ashley Spring can occur within the travel time of the water. Martinez and White (1999) have shown empirically that calcium and magnesium can dissolve to concentrations much higher than the concentrations measured at Ashley Spring in less than 60 hours (albeit in warmer water) (figure 39). The analysis of slopes in the hydrographs offers no evidence to support an older component of groundwater contributing to the water discharging from Ashley Spring. Mixing models using stable isotope data from Dry Fork, Ashley Spring, and the Vernal well are inconclusive, and isotope values appear to vary seasonally (figure 40).

Carbon and tritium analyses from samples collected for this study (table 12), as well as results of the dye-tracer tests (see above), indicate that groundwater from the Vernal well (figure 14) does not have the same travel path as water from Ashley Spring. Groundwater sampled from the Vernal well is much older (about 2000–6000 years) than water collected from Ashley Spring. Based on information from the Vernal well chemistry, water from Ashley Spring has a specific flow path in a specific fracture zone of the Weber Sandstone, which the Vernal well does not penetrate. This helps explain the absence of dye in the Vernal Ashley Gorge well.

CONCLUSIONS

Using information from both the chemical analyses and the fracture and structure interpretations, we propose a hypothetical conceptual model for the area. This model roughly follows that proposed by Chidsey and Sprinkel (2005) (figure 41A). Snowmelt and rainwater infiltrate into recharge zones, which include the tributaries of Dry Fork and Ashley Creek, extending all the way up to the high Uinta Mountains in the northernmost part of the study area. These tributaries and creeks then lose water when flowing over regions where Madison Limestone is near the ground surface. Most of these tributaries are perennial streams, fed by extensive high-elevation

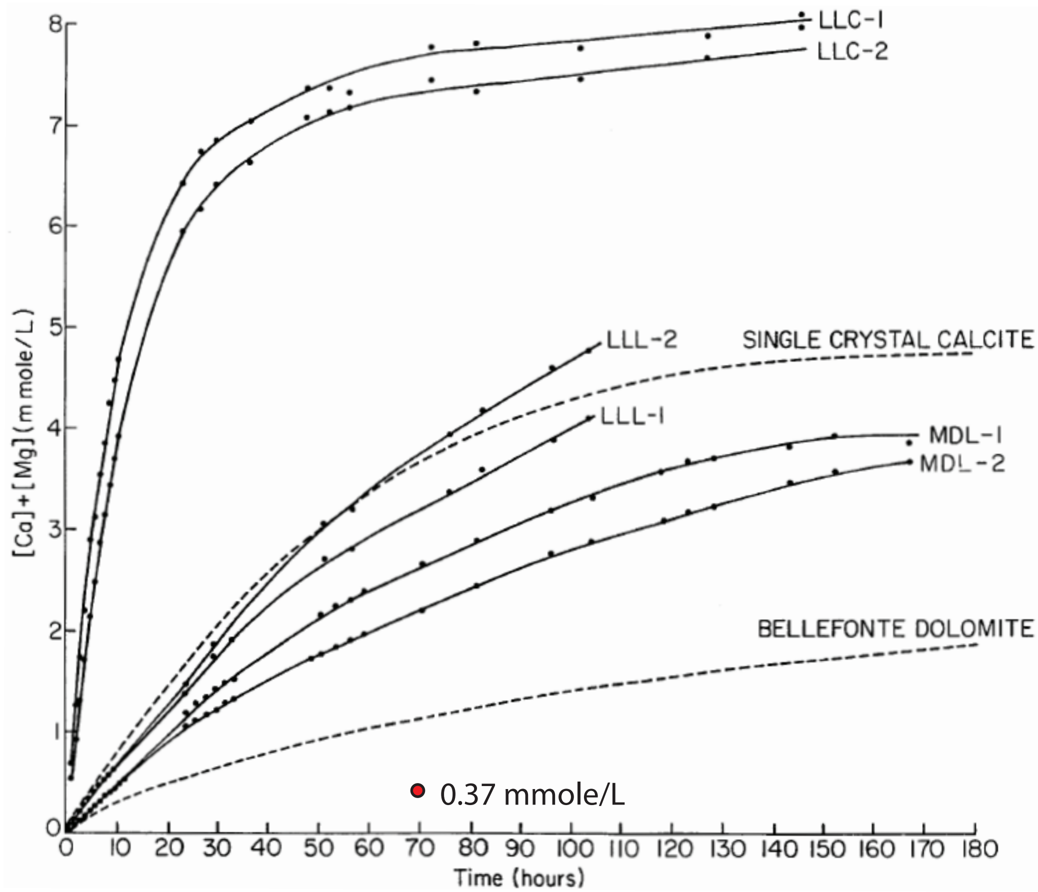


Figure 39. *Concentration of calcium and magnesium ions as a function of time that various limestone and dolomite samples are exposed to turbulent water with* P_{CO2} *of 0.93 and temperature at 25 degrees Celsius (from Martinez and White, 1999). The average concentration of calcium and magnesium in water from Ashley Spring has been added for comparison.*

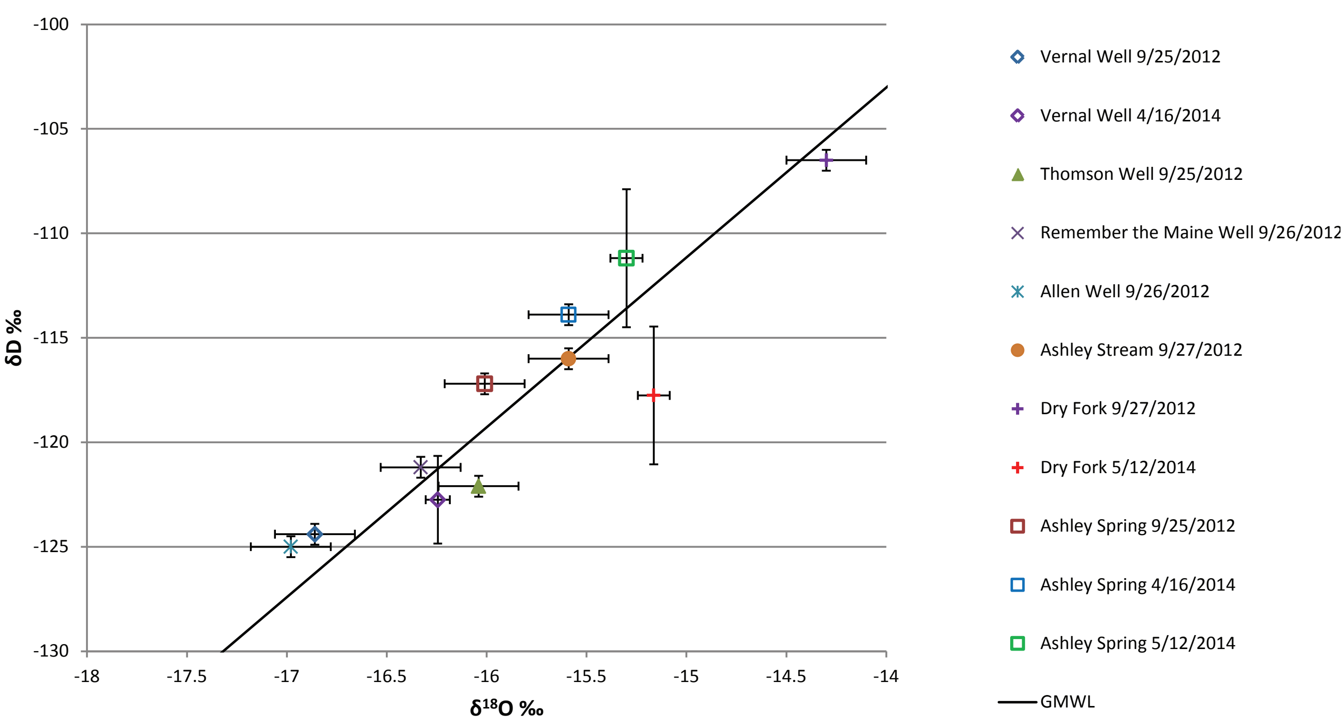


Figure 40. *Results of stable isotope analyses plotted against the Global Meteoric Water Line (GMWL) (Craig, 1961).*

snowpacks, as well as some baseflow from groundwater storage in the Bishop Conglomerate and Quaternary deposits that are upgradient of and overlie the carbonates (figures 6 and 7). The updated hypothetical model (figure 41B) shows the Weber Sandstone and Madison Limestone as more hydraulically separated than implied by the Chidsey and Sprinkel (2005) model (figure 41A).

The recharge zones vary depending on the aquifer system. The Madison Limestone and Weber Sandstone are recharged to the south of the south flank fault zone where the units are exposed or near ground surface (figures 6 and 42), or where fractures connect the surface to the underlying units and the hydrologic gradient allows. Water in the Weber Sandstone has evidence of slower flow paths, and water moving through this unit is likely a combination of fracture flow with a minor amount of porous media flow. To the south of Ashley Spring, the Weber Sandstone aquifer is confined by overlying units, particularly the Moenkopi and Chinle Formations, in the basin downgradient from the flank of the mountains (figures 6 and 7). Based on the available potentiometric surface and dye trace data (figure 24), most water in the Madison Limestone and Weber Sandstone flows from northwest to southeast generally following topography and fracture patterns. However, the well data are very limited, for both the Madison and the Weber. Flow in the Weber Sandstone could be down dip (southerly) in some areas and into the Uinta Basin.

While hydraulic connections between the Madison and the Weber exist in some areas, flow between these units could be significantly different depending on geographic location. Fractures related to the Deep Creek fault system connect the units in localized regions where the fractures penetrate through both units. Porous media flow dominates in the Weber Sandstone where there are no fractures.

Water chemistry is an important indicator of changes in an aquifer system. Water in Ashley Spring is generally of Pristine quality (Class IA; Utah Division of Water Quality, 2013), although, due to the limited and fast travel path, the water is considered a groundwater source heavily influenced by surface water (appendix B). Ashley Spring is especially vulnerable to bacteriological influence, and is treated to accommodate for this type of contamination. Water chemistry has remained relatively stable over the past few decades, as no major discernible long-term trends in the compiled water chemistry data exist. However, water chemistry does fluctuate seasonally, mostly in response to annual precipitation and snowmelt patterns.

Ashley Spring is a high quality and high quantity water supply, which is irreplaceable and important to surrounding communities. Ashley Spring is supplied by a poorly-mapped fracture system, with an unknown extent. Although we have some idea of the regional hydraulic gradient, the vertical and horizontal hydraulic gradients between the top of the Weber Sandstone, the Mississippian carbonate aquifer, and Ashley Spring have not been determined or well described. Based on these observations and the information gained from this study, we proposed source protection zones presented in appendix B (figure 42), which outlines the methods and justification of source protection zone delineation. While the area in immediate proximity to the source should be protected, the most important areas to protect are where water is entering the karst system, specifically the Dry Fork (including tributaries) and Ashley Creek sinks. The delineation should be refined as more information is gained on the aquifer systems.

ACKNOWLEDGMENTS

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REFERENCES

Aley, T., 2002, Groundwater tracing handbook: Protem, Missouri, Ozark Underground Laboratory, 44 p.

Bakalowicz, M., 2006, Importance of regional study site conditions in elaborating concepts and approaches in karst science, *in* Harmon, R.S., Wicks, C.M., Ford, D.C., and White, W.B., editors, Perspectives on karst geomorphology, hydrology, and geochemistry—A tribute volume to Derek C. Ford and William B. White: Geological Society of America Special Paper 404, p. 15–22.

Bowen, Collins, and Associates, 2005, Chemical analyses for exploratory boreholes: Unpublished consultant's report pre-

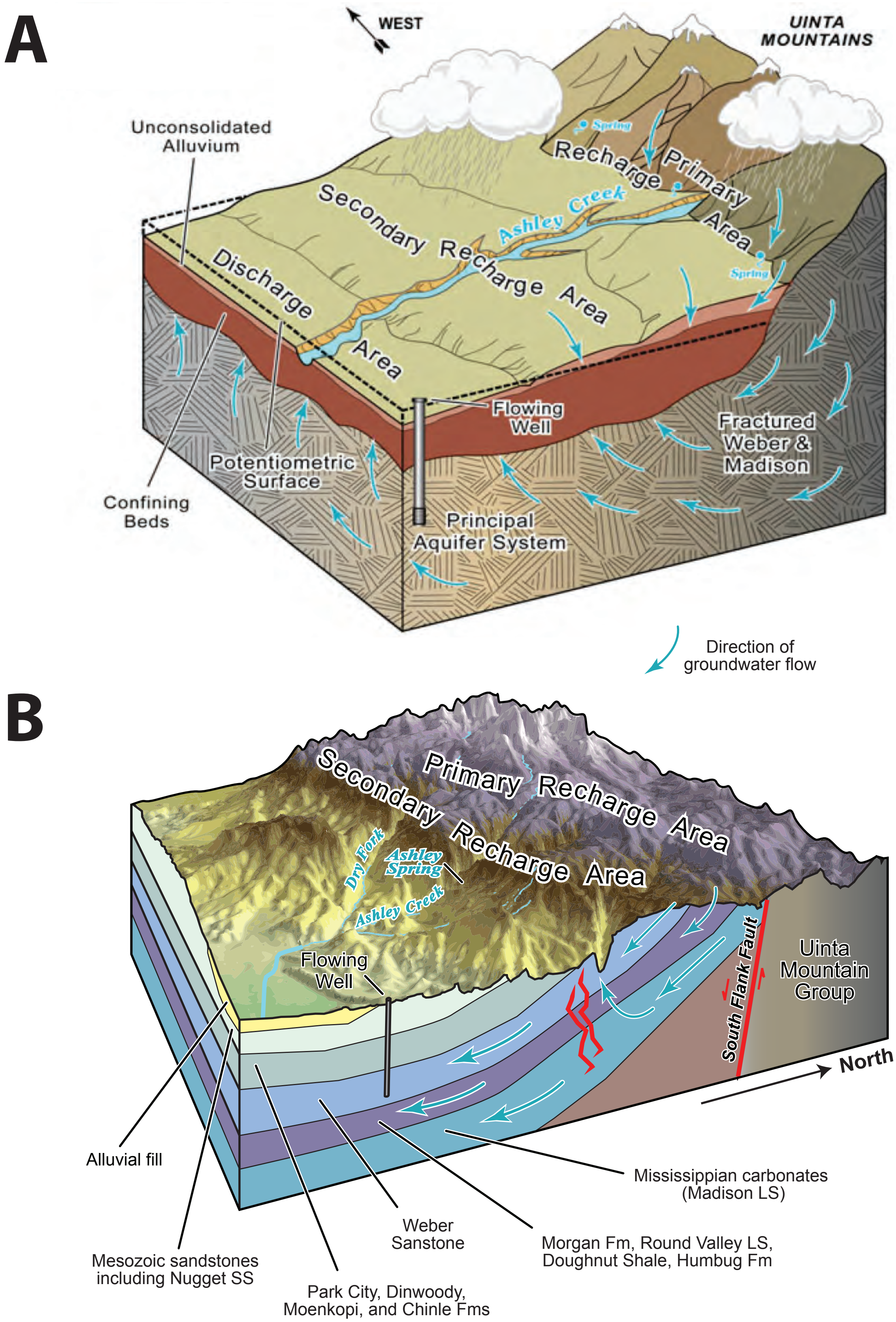

Figure 41. *Conceptual block diagram of regional groundwater flow by (A) Chidsey and Sprinkel (2005) and (B) proposed by this study.*

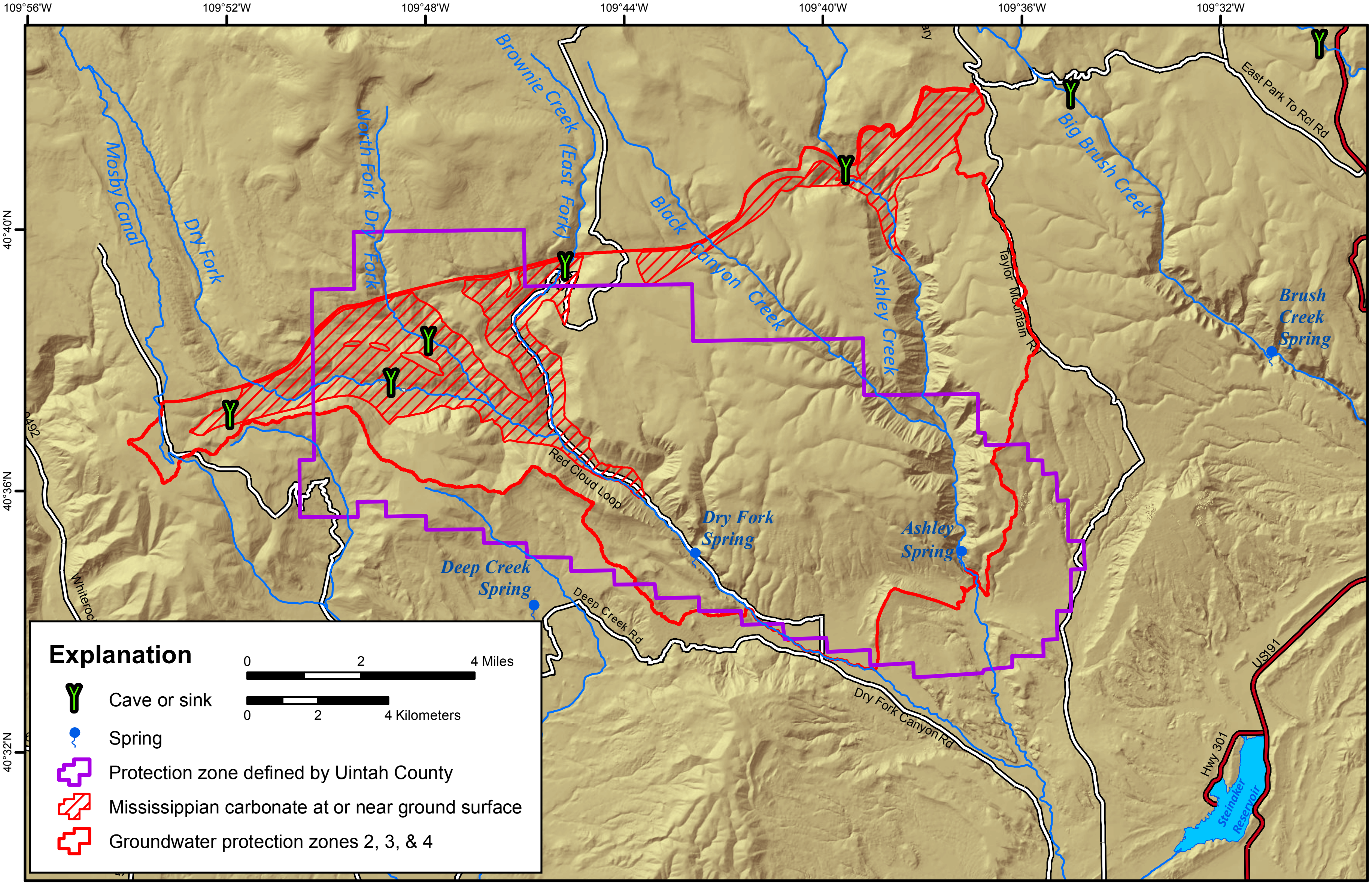

Figure 42. *Source protection areas and areas where Mississippian carbonate is near ground surface (vulnerable recharge zones) for Ashley Spring.*

pared for Maeser Water Improvement District, Utah, 13 p.

Bridges, B.L., and Maxwell, J.D., 1969, Inter-relationship of surface and groundwater in Ashley and Brush Creek basins, Utah: Unpublished U.S. Soil Conservation Service Report, 7 p.

Chidsey, T.C., Jr., and Sprinkel, D.A., 2005, Petroleum geology of Ashley Valley oil field and hydrocarbon potential of the surrounding area, Uintah County, Utah, *in* Dehler, C.M., Pederson, J.L., Sprinkel, D.A., and Kowallis, B.J., editors, Uinta Mountain geology: Utah Geological Association Publication 33, p. 347–421.

Christenson, G.E., 1997, Investigation of erosional ravines in Dry Fork Canyon, Uintah County, Utah: unpublished report by the Utah Geological Survey for the Utah Division of Comprehensive Emergency Management, Job no. 97-09, RS 234 HB 280, 9 p.

Clark, I., and Fritz, P., 1997, Environmental isotopes in hydrogeology: New York, Lewis Publishers, 328 p.

Cook, P.G., 2003, A guide to regional groundwater flow in fractured rock aquifers: Henley Beach, South Australia, CSIRO Land and Water, 115 p.

Craig, H., 1961, Standard for reporting concentrations of deuterium and oxygen-18 in natural waters: Science, v. 133, p. 1833–1834.

Despain, J.D., 2006, Hydrochemistry in an alpine karst system, Sequoia and Kings Canyon National Parks, California: Bowling Green, Kentucky, Western Kentucky University, unpublished M.S. thesis, 104 p.

ESRI, 2012, ArcGIS - Release 10.1: Redlands, California, Environmental Systems Research Institute computer software.

Fallon, D., 1997, Ashley National Forest earth flow: Bridger-Teton National Forest Bridger-East Ecological Unit unpublished report, 4 p.

Gesch, D.B., 2007, The National Elevation Dataset, *in* Maune, D., editor, Digital elevation model technologies and applications—The DEM users manual, 2nd edition: Bethesda, Maryland, American Society for Photogrammetry and Remote Sensing, p. 99–118.

Gesch, D.B., Oimoen, M., Greenlee, S., Nelson, C., Steuck, M., and Tyler, D., 2002, The national elevation dataset: Photogrammetric Engineering and Remote Sensing, v. 68, no. 1, p. 5–11.

Godfrey, A.E., 1985, Karst hydrology of the south slope of the Uinta Mountains, Utah, *in* Picard, M.D., editor, Geology and energy resources, Uinta Basin of Utah: Utah Geological Association 12, p. 277–293.

Green, D.J., 1957, The Dry Fork cave system, Uintah County, Utah: National Speleological Society Salt Lake Grotto Technical Note 3, 8 p.

Haddox, D.A., 2005, Mapping and kinematic structural analysis of the Deep Creek fault zone, south flank of the Uinta Mountains, near Vernal, Utah: Provo, Utah, Brigham Young University, unpublished M.S. Thesis, 144 p.

Haddox, D.A., Kowallis, B.J., and Shakespeare, J.D., 2005, Mapping and kinematic analysis of the Deep Creek fault zone, south flank of the Uinta Mountains, Utah, *in* Dehler, C.M., Pederson, J.L., Sprinkel, D.A., and Kowallis, B.J., editors, Uinta Mountain geology: Utah Geological Association Publication 33, p. 205–214.

Haddox, D.A., Kowallis, B.J., and Sprinkel, D.A., 2010a, Geologic map of the Steinaker Reservoir quadrangle, Uintah County, Utah: Utah Geological Survey Miscellaneous Publication 10-4, 2 plates, scale 1:24,000.

Haddox, D.A., Kowallis, B.J., and Sprinkel, D.A., 2010b, Geologic map of the Dry Fork quadrangle, Uintah County, Utah: Utah Geological Survey Miscellaneous Publication 10-3, 2 plates, scale 1:24,000.

Heath, R.C., 1982, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 84 p.

Hintze, L.F., 1988, Geologic history of Utah: Brigham Young University Geologic Studies Special Publication 7, 202 p.

Hood, J.W., 1976, Characteristics of aquifers in the northern Uinta Basin area, Utah and Colorado: Utah Department of Natural Resources Technical Publication 53, 71 p., 3 plates.

Horizon Systems Corporation, 2013, National Hydrography Dataset Version 2 (NHDPlusV2): Online, http://www.horizon-systems.com/NHDPlus/NHDPlusV2_home.php, accessed March 2013.

Kinney, D.M., 1955, Geology of the Uinta River–Brush Creek area, Duchesne and Uintah Counties, Utah: U.S. Geological Survey Bulletin 1007, 194 p.

Lund, W.R., 1981, Summary report on the drilling and pump testing of a proposed water well in the bedrock Weber Sandstone aquifer, Uintah County, Utah: Utah Geological Survey Report of Investigation No. 161, 11 p.

Martinez, M.I., and White, W.B., 1999, A laboratory investigation of the relative dissolution rates of the Lirio Limestone and the Isla de Mona Dolomite and implications for cave and karst development on Isla de Mona: Journal of Cave and Karst Studies v. 61(1), p. 7–12.

Maxwell, J.D., and Bridges, B.L., 1968, Dry Fork watershed groundwater tracer studies—Dry Fork Creek and Brush Creeks: Unpublished U.S. Soil Conservation Service Report, 7 p.

Maxwell, J.D., Bridges, B.L., Barker, D.A., and Moore, L.G., 1971, Hydrogeology of the eastern portion of the south slopes of the Uinta Mountains, Utah: Utah Department of Natural Resources Information Bulletin Number 21, 58 p.

McFadden, T., 1979, A cultural resource evaluation of the Dry Fork historic flume: U.S. Department of Agriculture Forest Service Region Tour Guide, 12 p.

Mull, D.S., Liebermann, T.D., Smoot, J.L., and Woosley, L.H., 1988, Application of dye-tracing techniques for determining solute-transport characteristics of ground water in karst terranes: U.S. Environmental Protection Agency Document Number EPA904/6-88-001, 117 p.

Mundorff, J.C., 1971, Nonthermal springs of Utah: Utah Geological and Mineralogical Survey Water Resources Bulletin 16, 78 p.

NASA, 2013, NLDAS-2 monthly NOAH LSM 0.125 x 0.125 degree data: Goddard Earth Sciences Data and Information Services Center, online: ftp://hydro1.sci.gsfc.nasa.gov/data/s4pa/NLDAS/NLDAS_NOAH0125_M.002/, accessed May 2013.

PRISM, 2013, U.S. precipitation data: Oregon State University, online http://www.prismclimate.org, accessed May 2013.

Schlumberger, 2011, AquaChem 2011.1: Tucson, Arizona, Schlumberger Water Services computer software, http://www.swstechnology.com/groundwater-software/water-quality-analysis/aquachem.

Shuster, E.T., and White, W.B., 1971, Seasonal fluctuations in the chemistry of limestone springs—a possible means for characterizing carbonate aquifers: Journal of Hydrology, v. 14, p. 93–128.

Singhal, B.B.S., and Gupta, R.P., 2010, Applied hydrogeology of fractured rocks, 2nd edition: Springer, London, 429 p.

Spangler, L.E., 2005, Geology and karst hydrology of the eastern Uinta Mountains—an overview, *in* Dehler, C.M., Pederson, J.L., Sprinkel, D.A., and Kowallis, B.J., editors, Uinta Mountain geology: Utah Geological Association Publication 33, p. 205–214.

Sprinkel, D.A., 2006, Interim geologic map of the Dutch John 30′ x 60′ quadrangle, Daggett and Uintah counties, Utah, Moffat county, Colorado, and Sweetwater county, Wyoming: Utah Geological Survey Open-File Report 491DM, 3 plates, scale 1:100,000.

Taylor, C.J., and Greene, E.A., 2002, Hydrogeologic characterization and methods used in the investigation of karst hydrology, *in* Rosenberry, D.O., and LaBaugh, J.W., editors, Field techniques for estimating water fluxes between surface water and ground water: U.S. Geological Survey Techniques and Methods 4-D2, p. 75–114.

U.S. Department of Agriculture (USDA), 2013a, Twelve-digit watershed boundary dataset: Online, http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/water/watersheds/dataset/ , accessed March 2013.

U.S. Department of Agriculture (USDA), 2013b, National Agriculture Imagery Program (NAIP) 1-meter resolution aerial imagery: Online, http://www.fsa.usda.gov/FSA/apfoapp?area=home&subject=prog&topic=nai, accessed March 2013.

U.S. Environmental Protection Agency (USEPA), 2013, STORET water chemistry data: Online, http://www.epa.gov/storet/, accessed March 2013.

U.S. Forest Service (USFS), 2014, Dry Fork flume: Online, http://www.fs.usda.gov/detail/ashley/learning/history-culture/?cid=fsm9_002394, accessed March 2014.

U.S. Geological Survey (USGS), 2013, National Water Information System (NWIS): Online, http://waterdata.usgs.gov/nwis, accessed March 2013.

Utah Division of Drinking Water (UDDW), 2013, Safe Drinking Water Information System (SDWIS) Database: downloaded upon request from the Utah Division of Drinking Water, March 2013.

Utah Division of Oil, Gas, and Mining (UDOGM), 2013, Oil and gas well file search: Online, http://oilgas.ogm.utah.gov/Data_Center/LiveData_Search/wellfile_data_lookup.cfm, accessed March 2013.

Utah Division of Water Quality, 2013, Utah Ground Water Quality Protection Program: Online, http://www.waterquality.utah.gov/GroundWater/gwclasses.htm, accessed March 2013.

Utah Division of Water Rights, 2013, Public water suppliers water use data: Online, http://www.waterrights.utah.gov/distinfo/wuse.asp, accessed March 2013.

Wallis, S., 1997, Red water causes emergency: Vernal, Utah, Vernal Express newspaper, printed May 21, 1997.

Watson, D., 1992, Contouring—A guide to the analysis and display of spatial data: London, England, Pergamon Press, 340 p.

Ozark UNDERGROUND LABORATORY 1572 Aley Lane • Protem, MO 65733 • (417) 785-4289 • fax (417) 785-4290 • contact@ozarkundergroundlab.com

Certificate of Analysis

Date of certificate: October 15, 2012
Client: Utah Geological Survey
Project name: Ashley Springs, Utah
Contact person: PaulInkenbrandt@utah.gov
Mailing address: 1594 W. North Temple, Suite 3110
Salt Lake City, Utah 84114-6100

Samples collected by: Paul Inkenbrandt
Date samples shipped: October 2, 2012
Date samples rec'd at OUL: October 4, 2012
Date analyzed by OUL: October 10 and 11, 2012
Included with certificate of analysis:
Table of results, copies of sample collection data sheets

Results for charcoal and water samples analyzed for the presence of eosine and rhodamine WT (RWT) dyes.
Peak wavelengths are reported in nanometers (nm); dye concentrations are reported in parts per billion (ppb).
All results are for charcoal unless otherwise noted.

OUL Number	Station Number	Station Name	Date/Time Placed	Date/Time Recovered	Eosine		RWT	
					Peak nm	Conc. ppb	Peak nm	Conc. ppb
W1009	001	Background Ashley Spring	9/19/12 1143	9/24/12 1857	ND		ND	
W1010	002	Background Ashley Spring (DUP)	9/19/12 1143	9/24/12 1857	ND		ND	
W1011	100	Ashley Spring	9/24/12 1857	9/27/12 0740	ND		ND	
W1012	101	Ashley Spring	9/27/12 0740	9/27/12 1226	ND		ND	
W1013	102	Ashley Spring	9/27/12 1226	9/27/12 1736	ND		ND	
W1014	103	Ashley Spring	9/27/12 1736	9/27/12 2215	ND		ND	
W1015	104	Ashley Spring	9/27/12 2215	9/28/12 0330	ND		ND	
W1016	105	Ashley Spring	9/28/12 0330	9/28/12 0839	ND		ND	
W1017	106	Ashley Spring	9/28/12 0839	9/28/12 1339	ND		ND	
W1018	107	Ashley Spring	9/28/12 1339	9/28/12 2117	ND		ND	
W1019	108	Ashley Spring	9/28/12 2117	9/29/12 0800	ND		568.5	25.0
W1020	Laboratory control charcoal blank							
W1021	201	Ashley Creek	9/28/12 0824	9/29/12 0820	ND		ND	
W1022	000	No Name Spring	9/28/12 0745	9/29/12 0800	ND		ND	
W1023	401	Spring Streamlet	9/27/12 0756	9/29/12 0825	ND		568.7	26.9

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OUL Number	Station Number	Station Name	Date/Time Placed	Date/Time Recovered	Eosine		RWT	
					Peak nm	Conc. ppb	Peak nm	Conc. ppb
W1024	301	Vernal Gorge Well	9/28/12 0854	9/29/12 0927	ND		ND	
W1025	701	Wayne Well	**Water**	9/28/12 1018	ND		ND	
W1026	601	Thompson Well	**Water**	9/29/12 1000	ND		ND	
W1027	801	Russ Well	**Water**	9/28/12 1036	ND		ND	

Note: Dye concentrations are based upon standards used at the OUL. The standard concentrations are based upon the as sold weight of the dye that the OUL uses. If the client is not using OUL dyes, the client should provide the OUL with a sample of the dye to compare to the OUL dyes.

Footnotes:

ND = No dye detected

Thomas J. Aley, PHG and RG

Thomas J. Aley

f:\docs\coa\UtahGeoSur_AshleySprings_01.xls

OZARK UNDERGROUND LABORATORY, INC.

1572 Aley Lane Protem, MO 65733 (417) 785-4289 fax (417) 785-4290 email: oul@tri-lakes.net

SAMPLE COLLECTION DATA SHEET for FLUORESCENCE ANALYSIS

Project: ASHLEY SPRINGS UTAH Week No: 1 Samples Collected By: PAUL INKENBRANDT

Samples Shipped By: REBECCA MEDINA Samples Received By: Rebecca [illegible]/OUL

Date Samples Shipped: 10/2/2012 Date Samples Received: 10/4/12 Time Samples Received: 13:30 Return Cooler? Yes____ No X

Bill to: UTAH GEOLOGICAL SURVEY Send Results to: PAUL INKENBRANDT

Analyze for: Fluorescein____ Eosine X Rhodamine WT X Other________ Ship cooler to:________

Please indicate stations where dye was visible in the field
for field technician use - use black ink only

OUL use only: # CHAR REC'D	OUL use only: LAB NUMBER Charcoal	STATION NUMBER 1-4 Numbers	STATION NAME	PLACED DATE	PLACED TIME	COLLECTED DATE	COLLECTED TIME	OUL use only: # WATER REC'D
1	W1009	001	BACKGROUND ASHLEY SPRING	9/19/12	11:43	9/24/12	18:57	0
1	W1010	002	BACKGROUND ASHLEY SPRING (DUP)	9/19/12	11:43	9/24/12	18:57	0
1	W1011	100	ASHLEY SPRING	9/24/12	18:57	9/27/12	7:40	0
1	W1012	101	ASHLEY SPRING	9/27/12	7:40	9/27/12	12:26	0
1	W1013	102	" " " "	9/27/12	12:26	9/27/12	17:36	0
1	W1014	103	" " " "	9/27/12	17:36	9/27/12	22:15	0
1	W1015	104	" " " "	9/27/12	22:15	9/28/12	3:30 *	0
1	W1016	105	" " " "	9/28	3:30	9/28	8:39	0
1	W1017	106	" " " "	9/28	8:39	9/28	13:39	0
1	W1018	107	" " " "	9/28	13:39	9/28	21:17	0
1	W1019	108	" " " "	9/28	21:17	9/29	8:00 *	0
1	W1021	201	ASHLEY CREEK	9/28	8:24	9/29	8:20	0
1	W1022	000	NO NAME SPRING	9/28	7:45	9/29	8:00 *	0
1	W1023	401	SPRING STREAMLET	9/27	7:56	9/29	8:25	0
1	W1024	301	VERNAL GORGE WELL	9/28	8:54	9/29	9:27	0

analyzed 10/10/12 by WE

Analyzed 10/11/12 by WE

COMMENTS: THESE ARE THE CARBON PACKETS (BUGS) W1020- OUL Charcoal blank.
Analyzed 10/10/12 + 10/11/12 by WE/OUL OUL Project 1209 *AM noted on ziplock bag. LG/OUL

This sheet filled out by OUL staff? Yes________ No X Charts for samples on this page proofed by OUL: [illegible] 10-12-12

f:\shared\forms\coc.doc, Rev. 8/99

OZARK UNDERGROUND LABORATORY, INC.

1572 Aley Lane Protem, MO 65733 (417) 785-4289 fax (417) 785-4290 email: oul@tri-lakes.net

SAMPLE COLLECTION DATA SHEET for FLUORESCENCE ANALYSIS

Project: ASHLEY SPRINGS UTAH **Week No:** 1 **Samples Collected By:** PAUL INKENBRANDT

Samples Shipped By: REBECCA MEDINA **Samples Received By:** Rebecca Scott/RL

Date Samples Shipped: 10/2/2012 **Date Samples Received:** 10/4/12 **Time Samples Received:** 13:30 **Return Cooler? Yes** ___ **No** x

Bill to: UTAH GEOLOGICAL SURVEY **Send Results to:** PAUL INKENBRANDT

Analyze for: Fluorescein ___ **Eosine** ___ **Rhodamine WT** ___ **Other** ___ **Ship cooler to:** ___

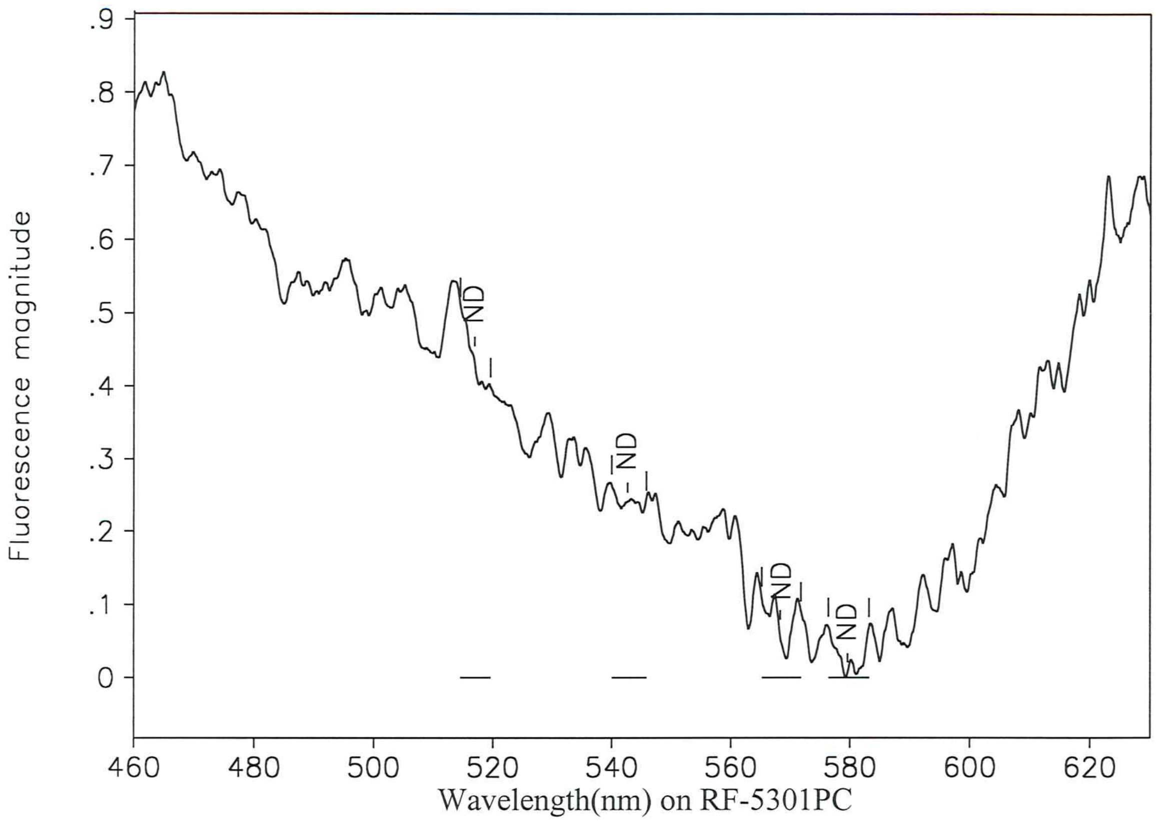
OUL use only		***Please indicate stations where dye was visible in the field*** *for field technician use - use black ink only*						OUL use only
# CHAR REC'D	LAB NUMBER Water	STATION NUMBER 1-4 Numbers	STATION NAME	PLACED DATE	PLACED TIME	COLLECTED DATE	COLLECTED TIME	# WATER REC'D
0	W1025	701	WAYNE WELL	9/28/12	10:18			1
0	W1026	601	THOMPSON WELL	9/29/12	10:00			1
0	W1027	801	RUSS WELL	9/28/12	10:36			1

COMMENTS: analyzed by mclone 10/11/12

This sheet filled out by OUL staff? Yes ___ **No** x **Charts for samples on this page proofed by OUL:** Ca/DM

Page 2 of 2 RL

Ozark Underground Laboratory



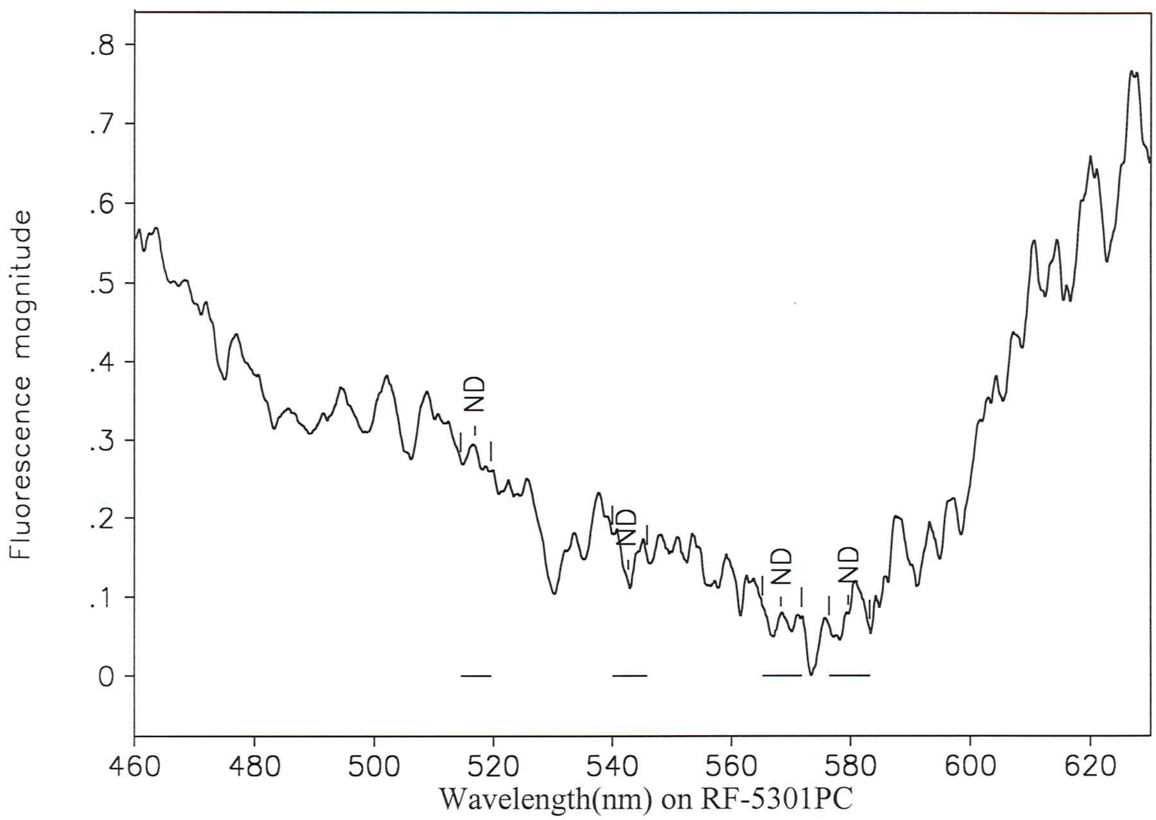
Station 001: Background Ashley Spring
OUL number: W1009 Analyzed: 10/10/12
Matrix: Elutant
Placed: 09/19/12 1143 Collected: 09/24/12 1857

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.9	514.5	519.6	0.00	0.00	0.00	ND
542.7	540.0	545.8	0.00	0.00	0.00	ND
568.3	565.2	571.8	0.00	0.00	0.00	ND
579.6	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



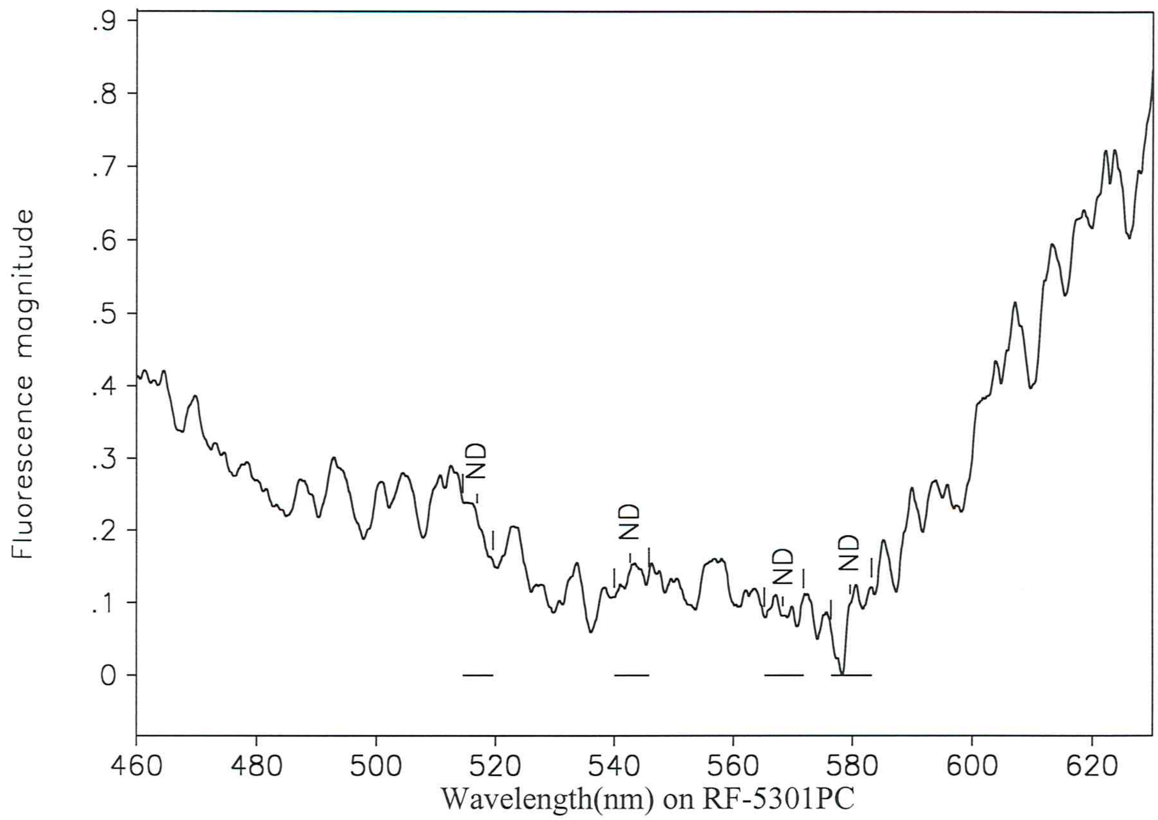
Station 002: Background Ashley Spring (DUP)
OUL number: W1010 Analyzed: 10/10/12
Matrix: Elutant
Placed: 09/19/12 1143 Collected: 09/24/12 1857

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.9	514.5	519.6	0.00	0.00	0.00	ND
542.7	540.0	545.8	0.00	0.00	0.00	ND
568.3	565.2	571.8	0.00	0.00	0.00	ND
579.6	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



Station 100: Ashley Spring
OUL number: W1011
Matrix: Elutant
Placed: 09/24/12 1857

Analyzed: 10/10/12

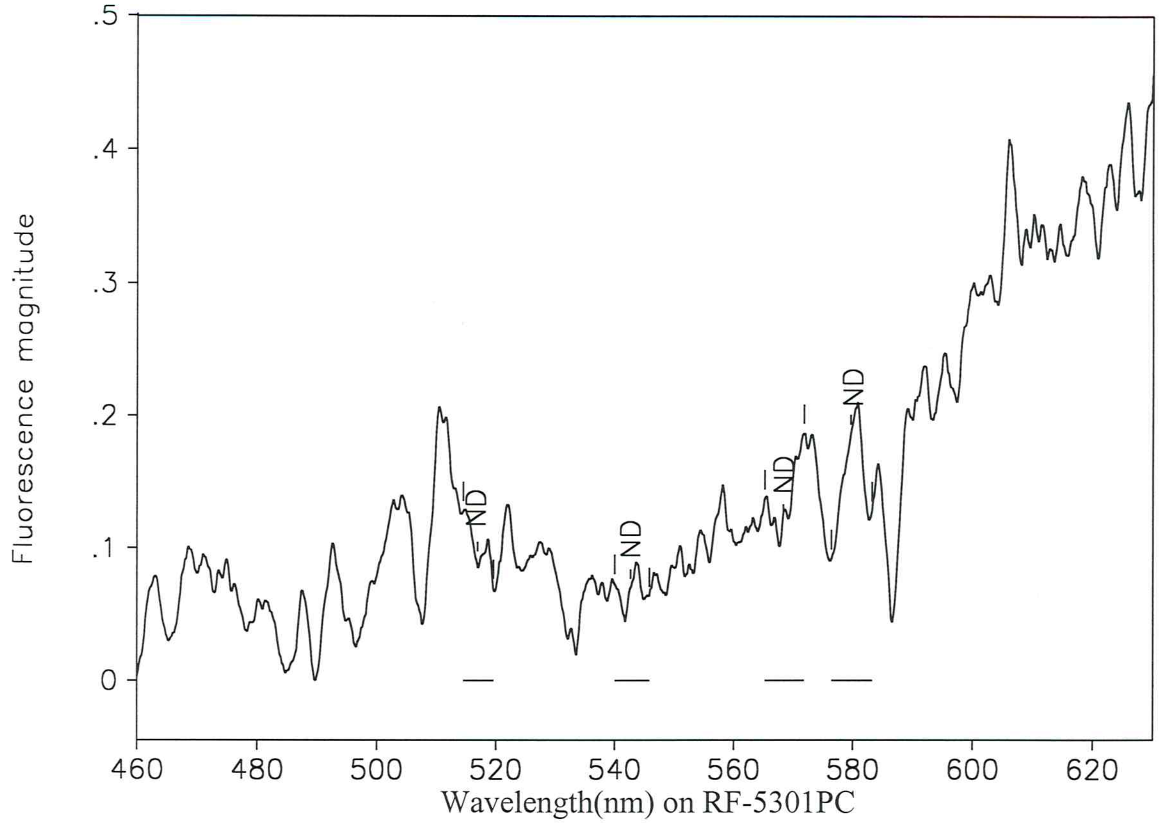
Collected: 09/27/12 0740

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.9	514.5	519.6	0.00	0.00	0.00	ND
542.7	540.0	545.8	0.00	0.00	0.00	ND
568.3	565.2	571.8	0.00	0.00	0.00	ND
579.6	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



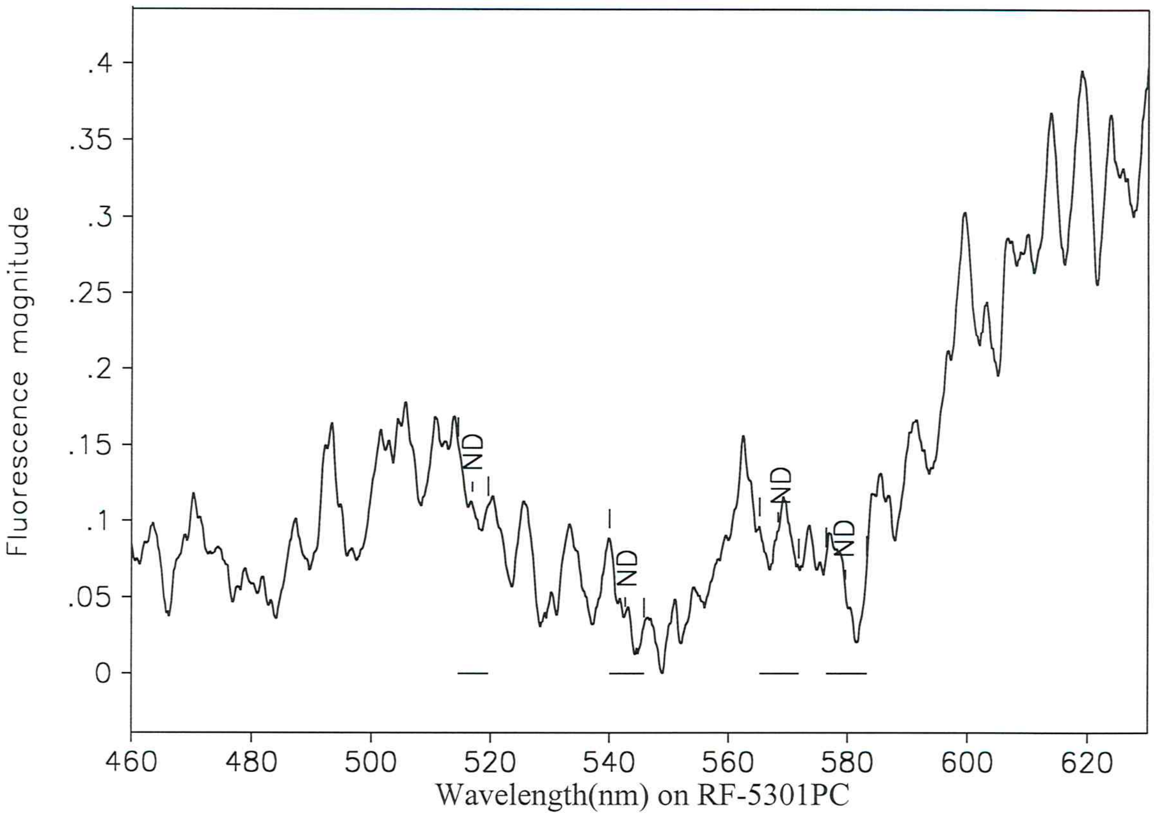
Station 101: Ashley Spring
OUL number: W1012 Analyzed: 10/11/12
Matrix: Elutant
Placed: 09/27/12 0740 Collected: 09/27/12 1226

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.9	514.5	519.6	0.00	0.00	0.00	ND
542.7	540.0	545.8	0.00	0.00	0.00	ND
568.3	565.2	571.8	0.00	0.00	0.00	ND
579.6	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



Station 102: Ashley Spring
OUL number: W1013
Matrix: Elutant
Placed: 09/27/12 1226

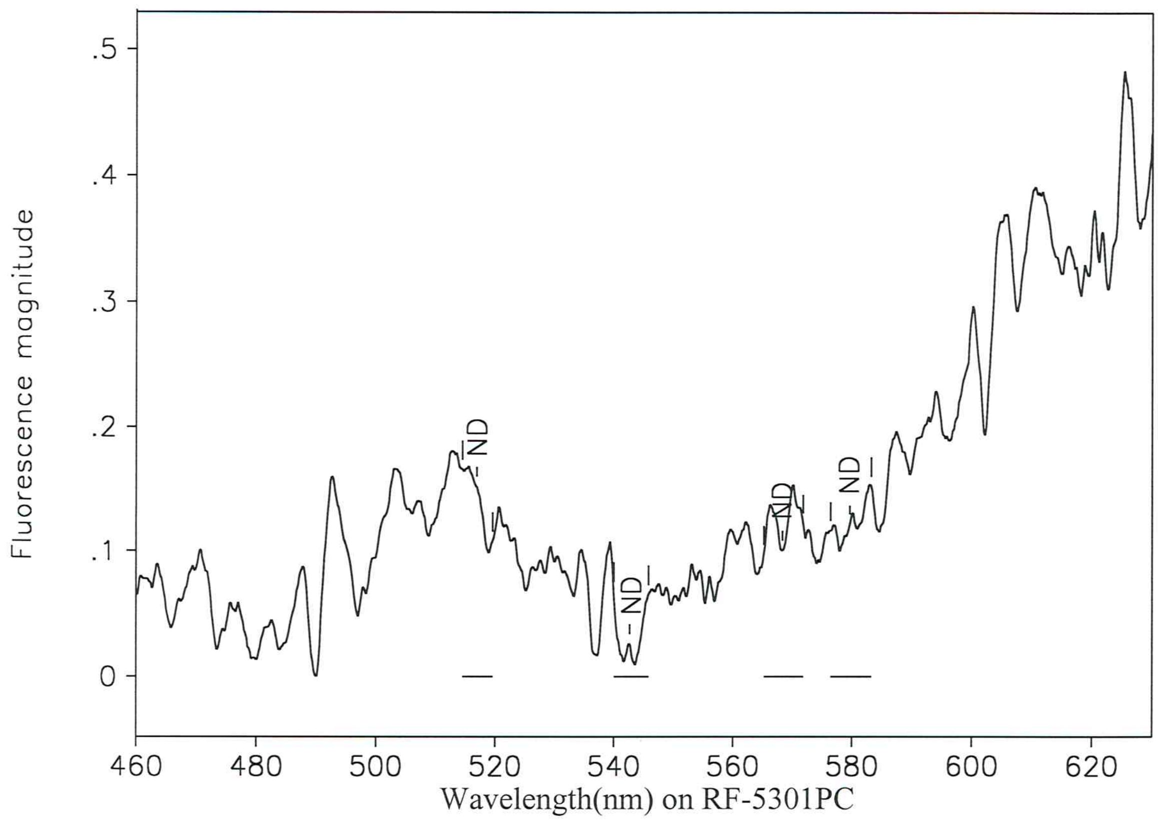
Analyzed: 10/11/12
Collected: 09/27/12 1736

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.9	514.5	519.6	0.00	0.00	0.00	ND
542.7	540.0	545.8	0.00	0.00	0.00	ND
568.3	565.2	571.8	0.00	0.00	0.00	ND
579.6	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



Station 103: Ashley Spring
OUL number: W1014
Matrix: Elutant
Placed: 09/27/12 1736

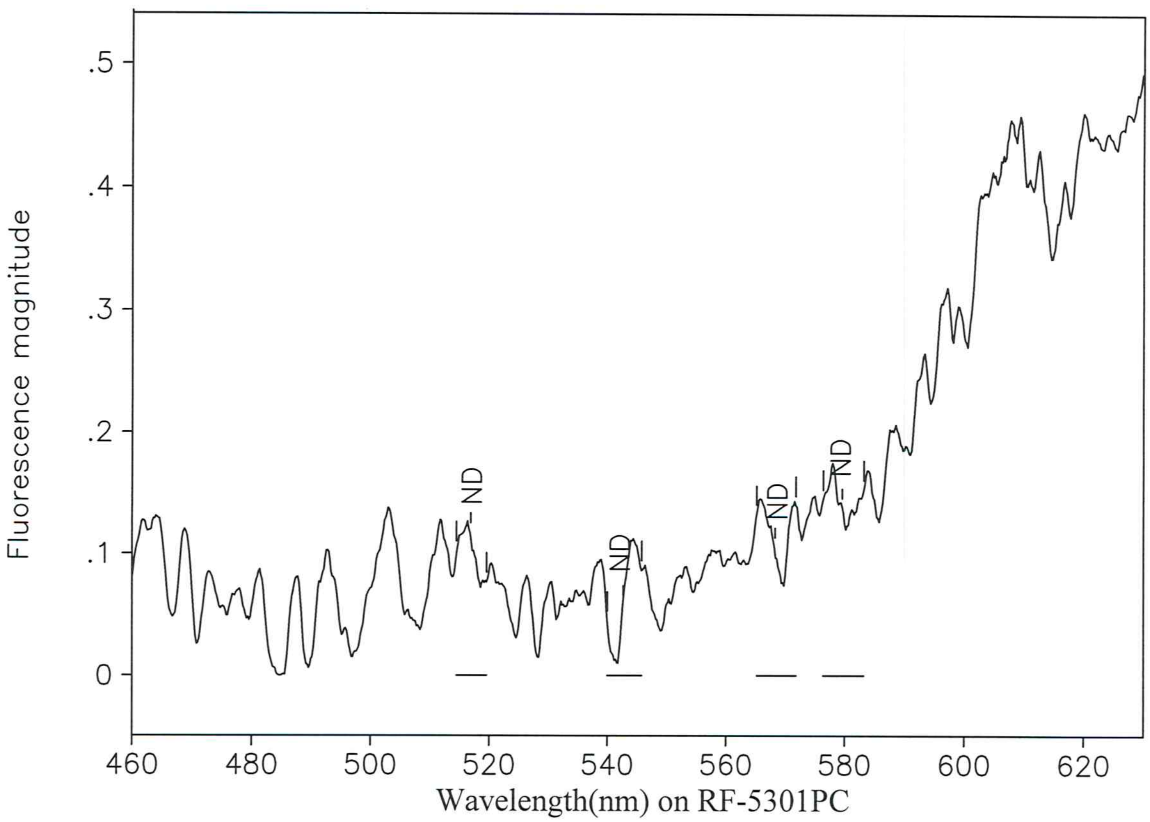
Analyzed: 10/11/12
Collected: 09/27/12 2215

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.9	514.5	519.6	0.00	0.00	0.00	ND
542.7	540.0	545.8	0.00	0.00	0.00	ND
568.3	565.2	571.8	0.00	0.00	0.00	ND
579.6	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



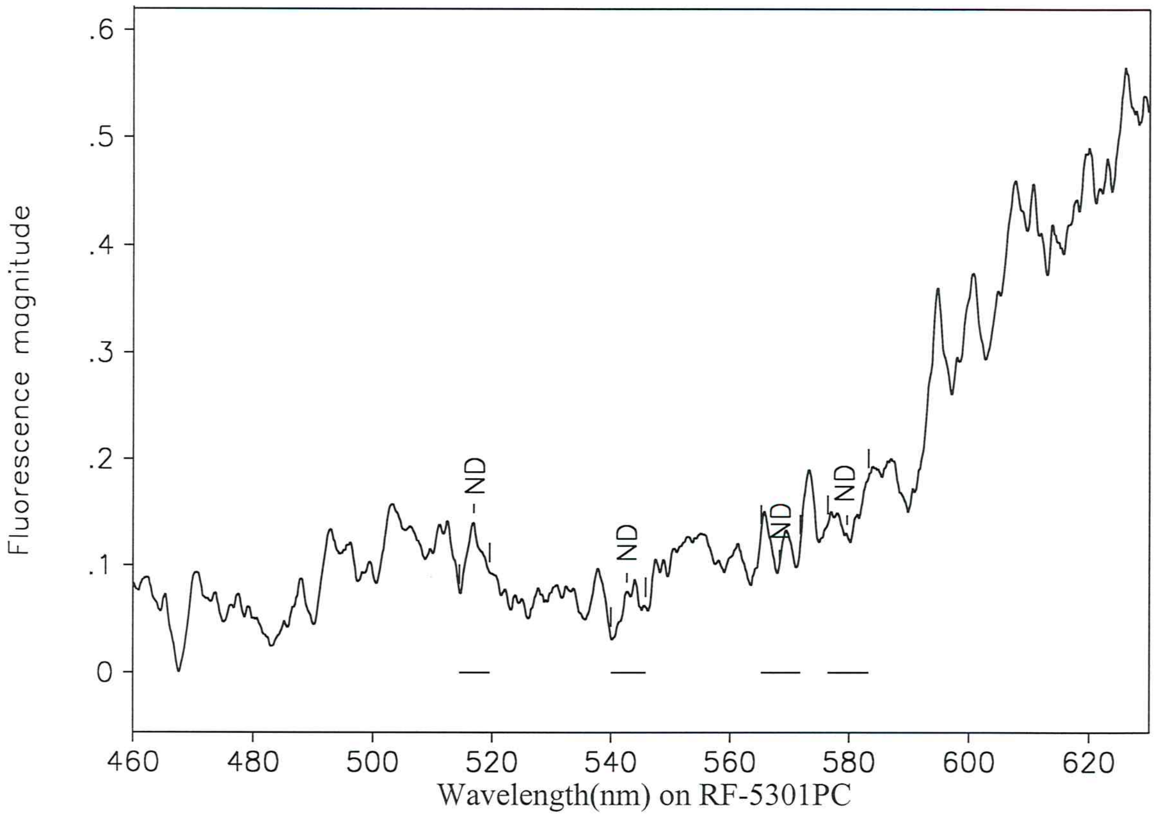
Station 104: Ashley Spring
OUL number: W1015 | Analyzed: 10/11/12
Matrix: Elutant
Placed: 09/27/12 2215 | Collected: 09/28/12 0330

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.9	514.5	519.6	0.00	0.00	0.00	ND
542.7	540.0	545.8	0.00	0.00	0.00	ND
568.3	565.2	571.8	0.00	0.00	0.00	ND
579.6	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



Station 105: Ashley Spring
OUL number: W1016
Matrix: Elutant
Placed: 09/28/12 0330

Analyzed: 10/11/12

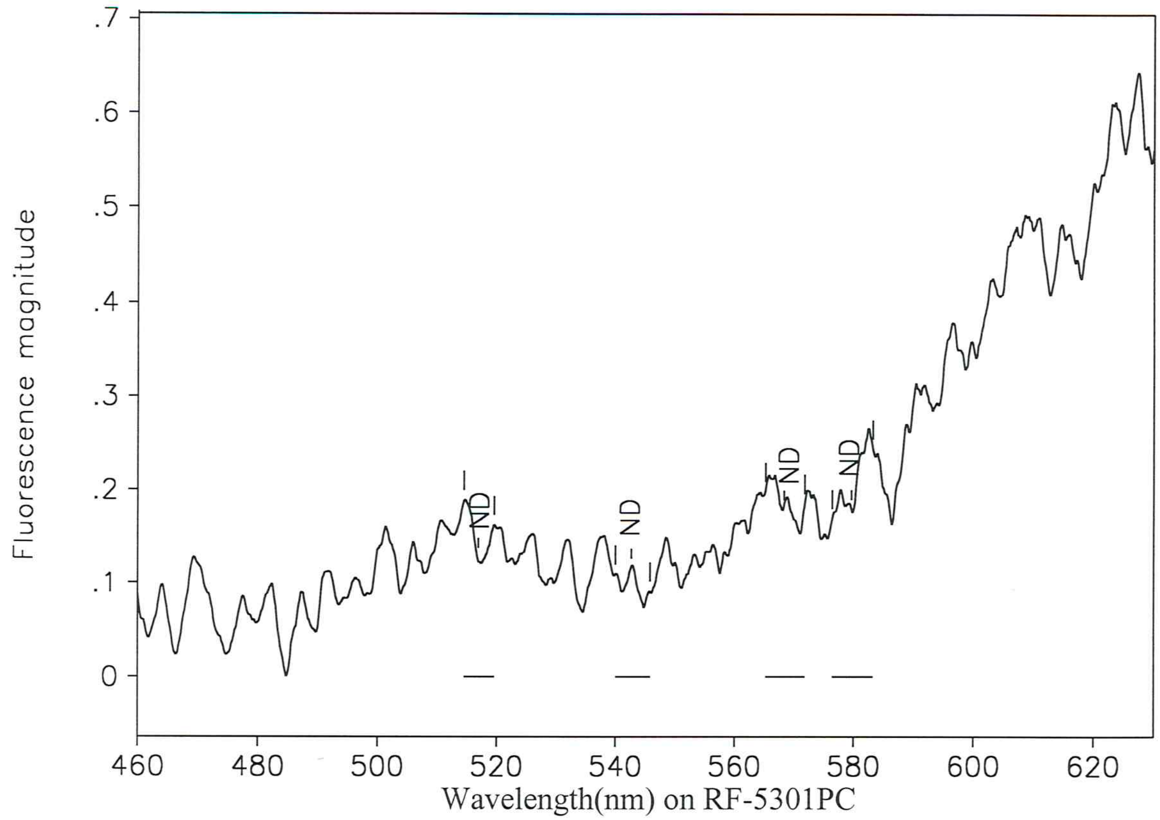
Collected: 09/28/12 0839

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.9	514.5	519.6	0.00	0.00	0.00	ND
542.7	540.0	545.8	0.00	0.00	0.00	ND
568.3	565.2	571.8	0.00	0.00	0.00	ND
579.6	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



Station 106: Ashley Spring
OUL number: W1017
Matrix: Elutant
Placed: 09/28/12 0839

Analyzed: 10/11/12

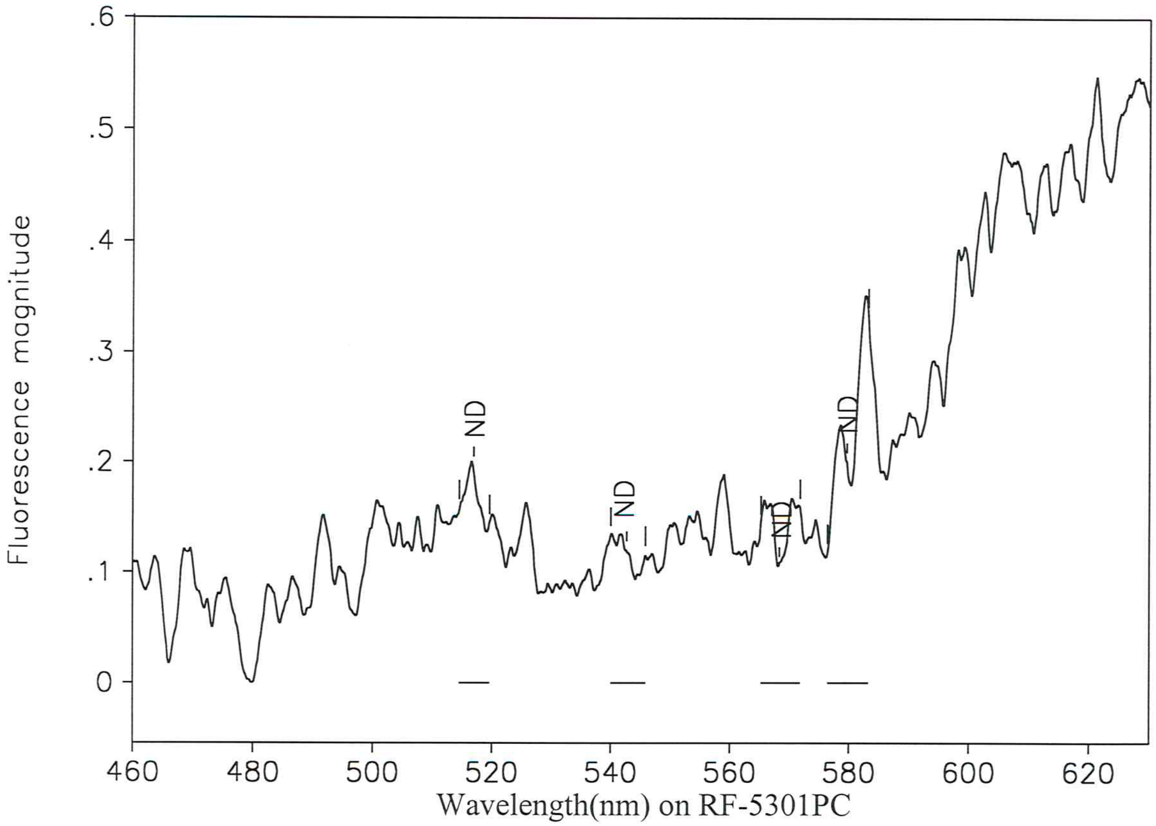
Collected: 09/28/12 1339

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.9	514.5	519.6	0.00	0.00	0.00	ND
542.7	540.0	545.8	0.00	0.00	0.00	ND
568.3	565.2	571.8	0.00	0.00	0.00	ND
579.6	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



Station 107: Ashley Spring
OUL number: W1018
Matrix: Elutant
Placed: 09/28/12 1339

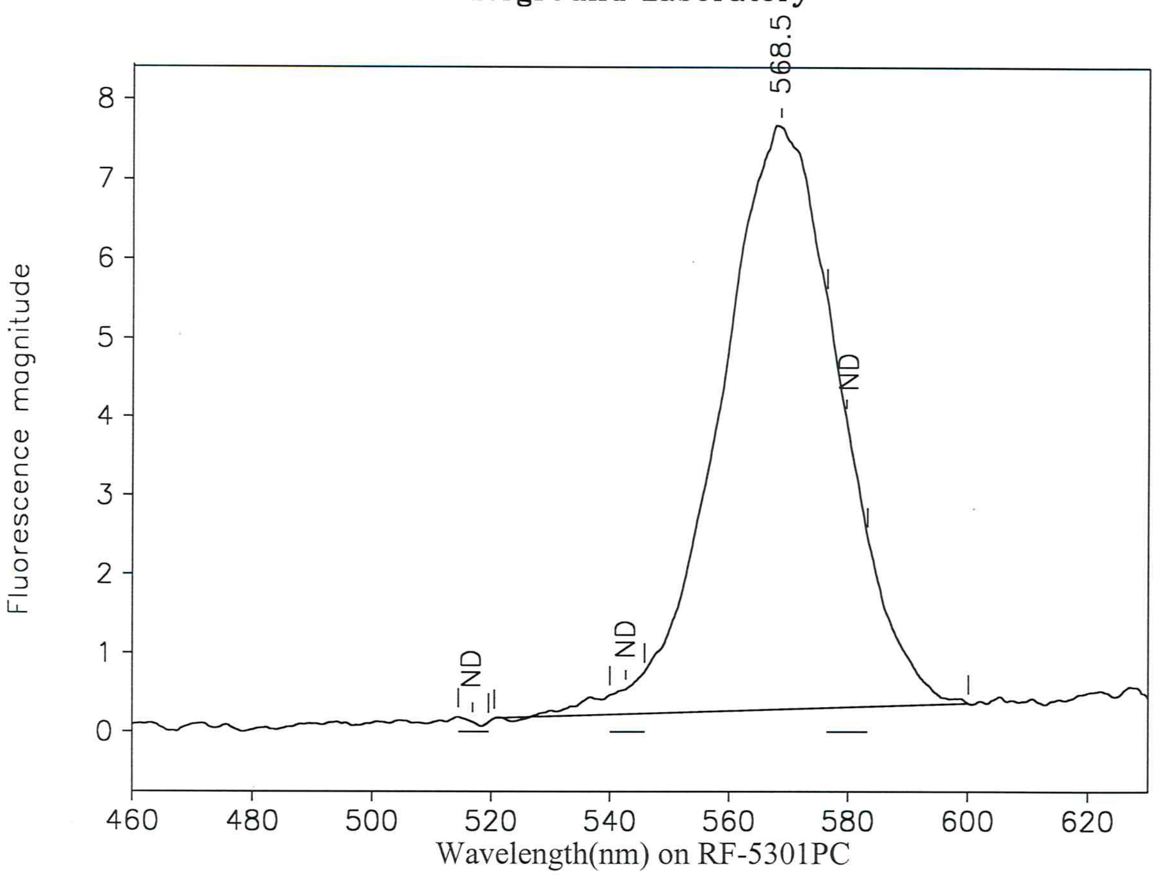
Analyzed: 10/11/12
Collected: 09/28/12 2117

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.9	514.5	519.6	0.00	0.00	0.00	ND
542.7	540.0	545.8	0.00	0.00	0.00	ND
568.3	565.2	571.8	0.00	0.00	0.00	ND
579.6	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



Station 108: Ashley Spring
OUL number: W1019
Matrix: Elutant
Placed: 09/28/12 2117

Analyzed: 10/11/12

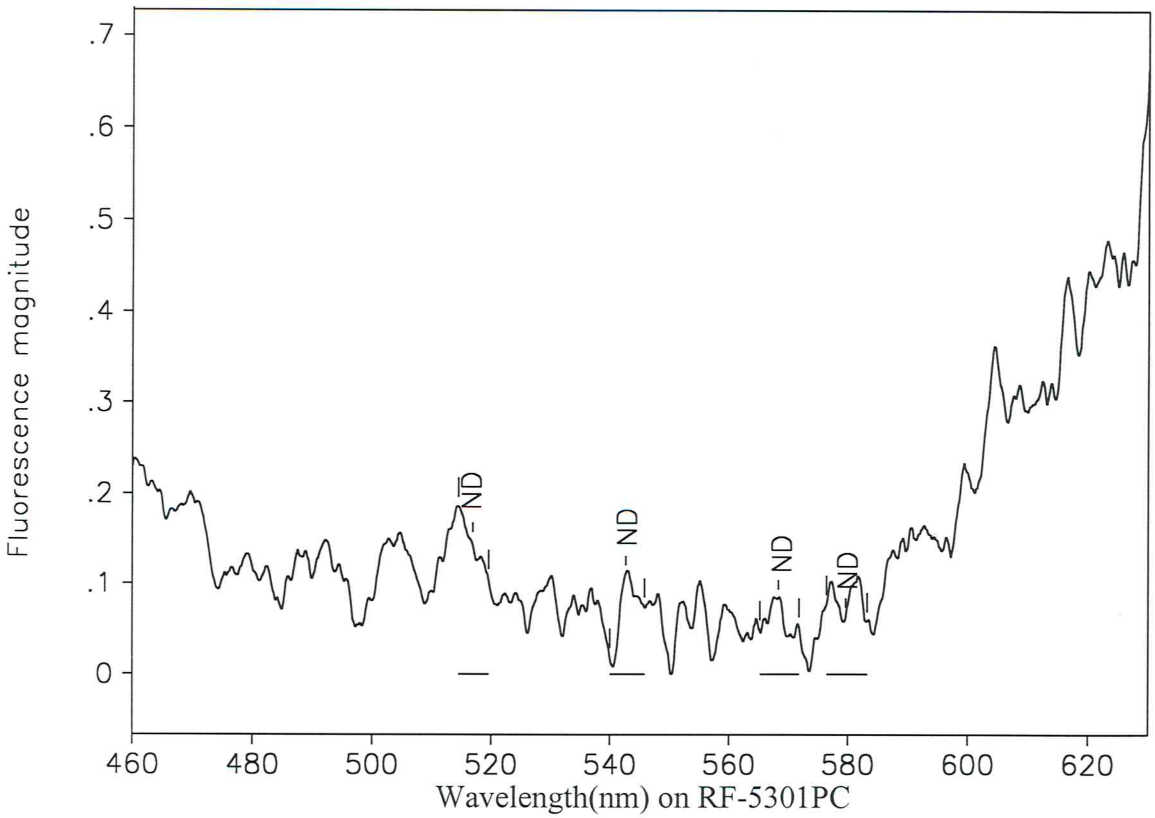
Collected: 09/29/12 0800

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.9	514.5	519.6	0.00	0.00	0.00	ND
542.7	540.0	545.8	0.00	0.00	0.00	ND
568.5	520.5	600.1	7.37	174.33	0.04	25.0
579.6	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



Station 201: Ashley Creek
OUL number: W1021
Matrix: Elutant
Placed: 09/28/12 0824

Analyzed: 10/11/12

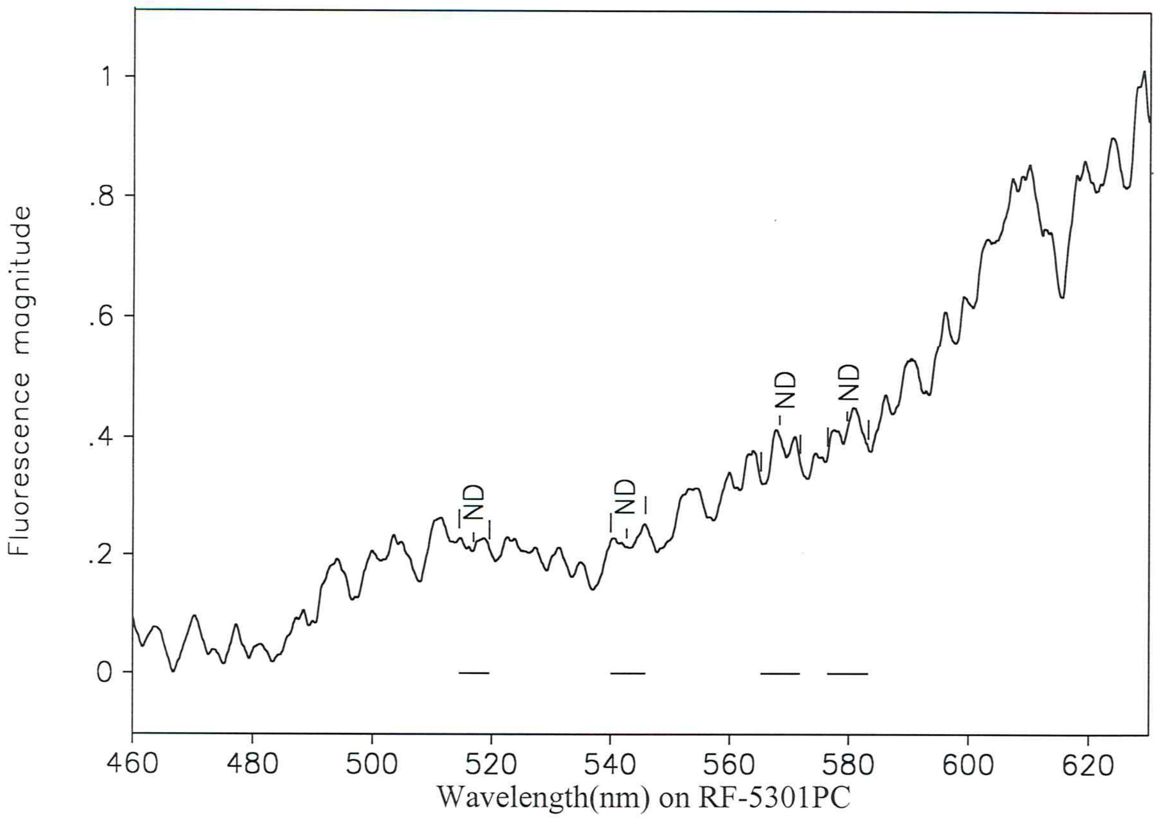
Collected: 09/29/12 0820

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.9	514.5	519.6	0.00	0.00	0.00	ND
542.7	540.0	545.8	0.00	0.00	0.00	ND
568.3	565.2	571.8	0.00	0.00	0.00	ND
579.6	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



Station 000: No Name Spring
OUL number: W1022
Matrix: Elutant
Placed: 09/28/12 0745

Analyzed: 10/11/12

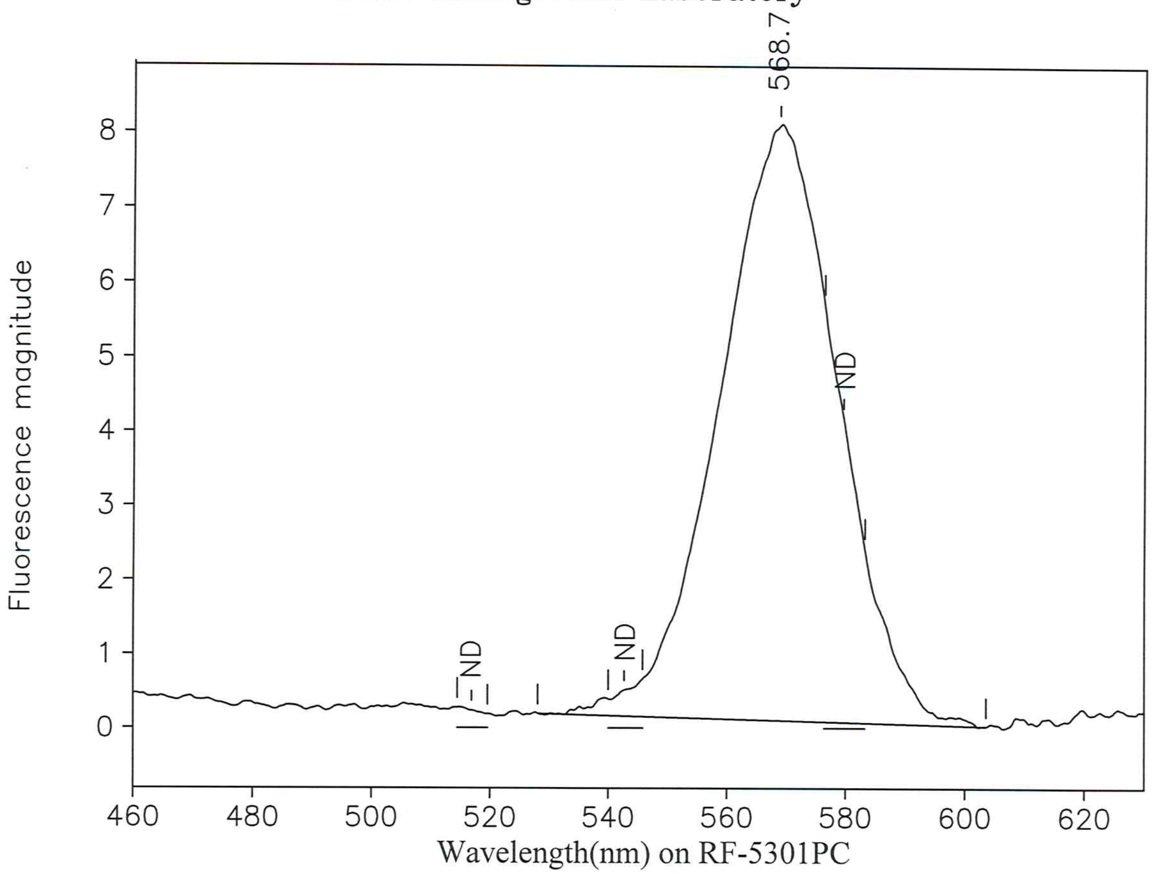
Collected: 09/29/12 0800

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.9	514.5	519.6	0.00	0.00	0.00	ND
542.7	540.0	545.8	0.00	0.00	0.00	ND
568.3	565.2	571.8	0.00	0.00	0.00	ND
579.6	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



Station 401: Spring Streamlet
OUL number: W1023
Matrix: Elutant
Placed: 09/27/12 0756

Analyzed: 10/11/12

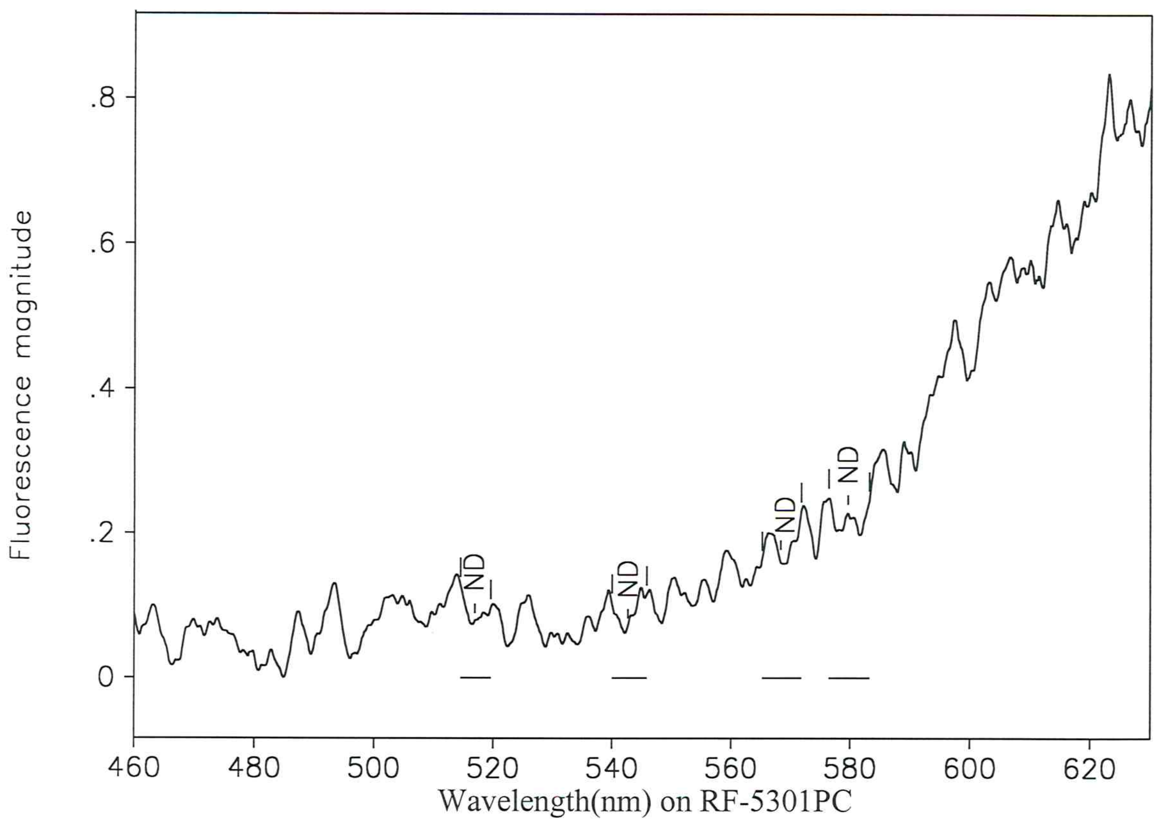
Collected: 09/29/12 0825

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.9	514.5	519.6	0.00	0.00	0.00	ND
542.7	540.0	545.8	0.00	0.00	0.00	ND
568.7	528.1	603.5	8.00	187.55	0.04	26.9
579.6	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



Station 301: Vernal Gorge Well
OUL number: W1024
Matrix: Elutant
Placed: 09/28/12 0854

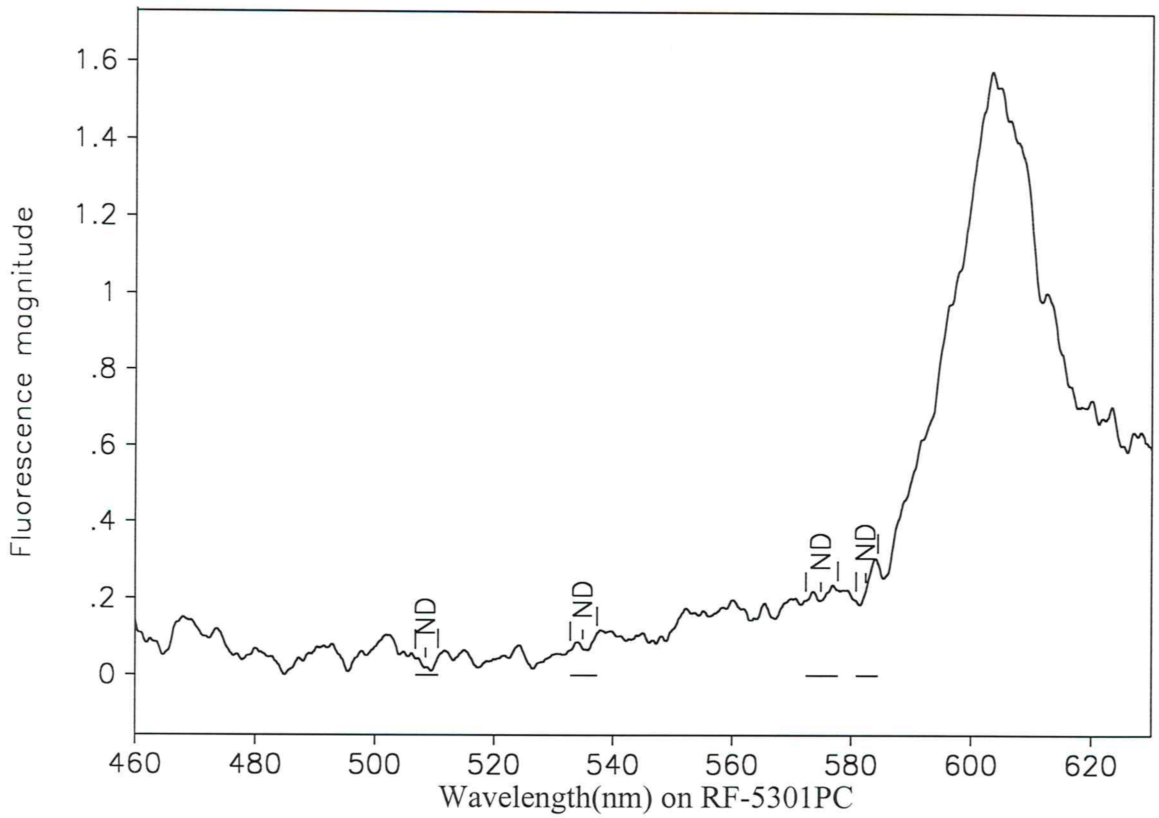
Analyzed: 10/11/12
Collected: 09/29/12 0927

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.9	514.5	519.6	0.00	0.00	0.00	ND
542.7	540.0	545.8	0.00	0.00	0.00	ND
568.3	565.2	571.8	0.00	0.00	0.00	ND
579.6	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



Station 701: Wayne Well
OUL number: W1025
Matrix: Water
Collected: 09/28/12 1018

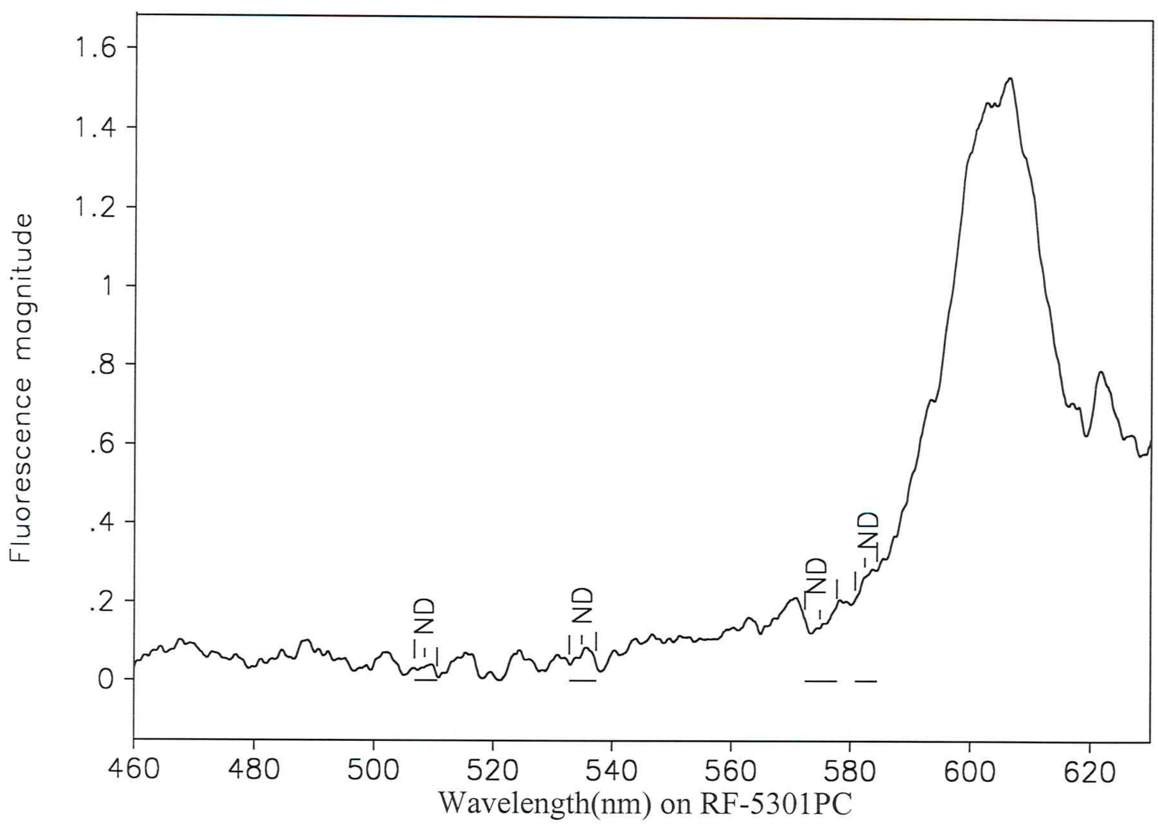
Analyzed: 10/11/12

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
508.5	506.8	510.6	0.00	0.00	0.00	ND
534.9	532.8	537.3	0.00	0.00	0.00	ND
574.9	572.4	577.7	0.00	0.00	0.00	ND
582.4	580.8	584.4	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



Station 601: Thompson Well
OUL number: W1026
Matrix: Water
Collected: 09/29/12 1000

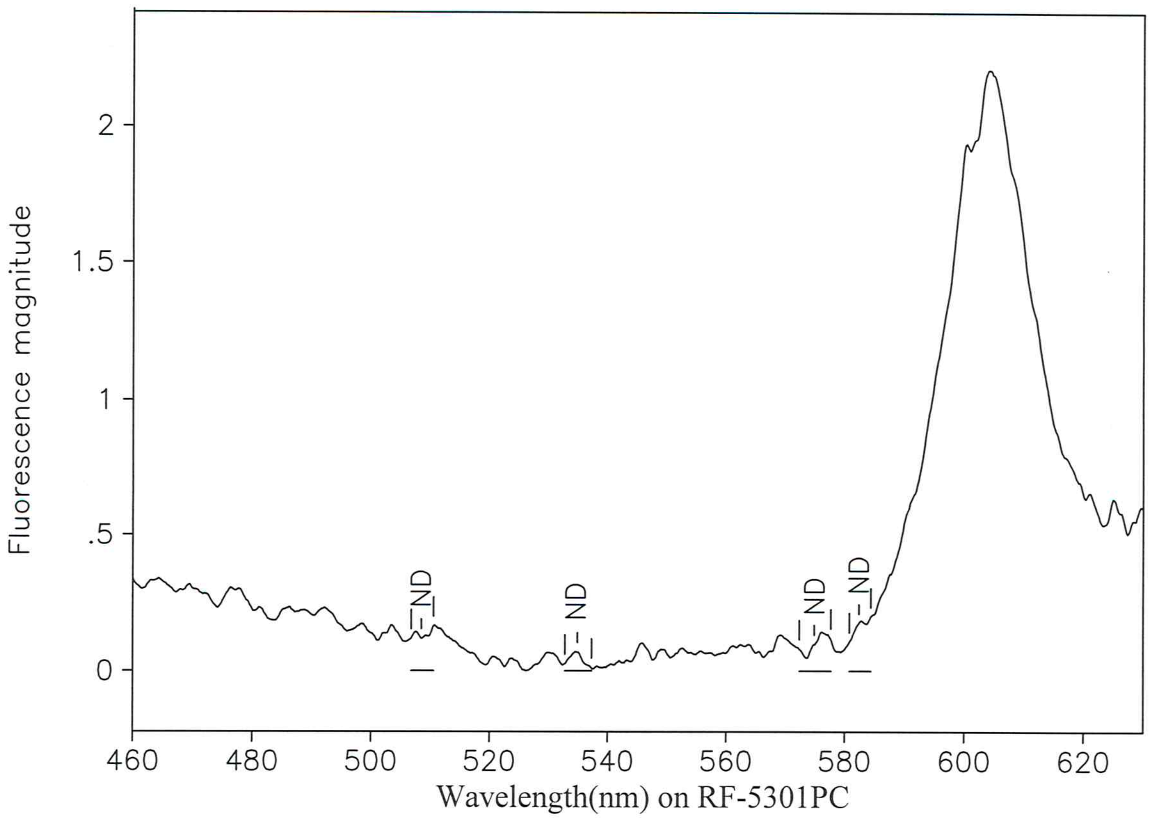
Analyzed: 10/11/12

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
508.5	506.8	510.6	0.00	0.00	0.00	ND
534.9	532.8	537.3	0.00	0.00	0.00	ND
574.9	572.4	577.7	0.00	0.00	0.00	ND
582.4	580.8	584.4	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



Station 801: Russ Well
OUL number: W1027
Matrix: Water
Collected: 09/28/12 1036

Analyzed: 10/11/12

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
508.5	506.8	510.6	0.00	0.00	0.00	ND
534.9	532.8	537.3	0.00	0.00	0.00	ND
574.9	572.4	577.7	0.00	0.00	0.00	ND
582.4	580.8	584.4	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark UNDERGROUND LABORATORY 1572 Aley Lane • Protem, MO 65733 • (417) 785-4289 • fax (417) 785-4290 • contact@ozarkundergroundlab.com

Certificate of Analysis

Date of certificate: March 1, 2013
Client: Utah Geological Survey
Mailing address: 1594 W. North Temple, Suite 3110
Salt Lake City, Utah 84114-6100
Project name: Ashley Springs, Utah
Contact person: PaulInkenbrandt@utah.gov
Project number: PO 314182
Project location: Ashley National Forest, Vernal UT area

Samples collected by: Melissa Hendrickson
Date samples shipped: February 13, 2013
Date samples rec'd at OUL: February 14, 2013
Date analyzed by OUL: February 27, 2013
Included with certificate of analysis:
Table of results, copy of sample collection data sheet and analysis graphs

Results for charcoal samplers analyzed for the presence of eosine and rhodamine WT (RWT) dyes.
Peak wavelengths are reported in nanometers (nm); dye concentrations are reported in parts per billion (ppb).

OUL Number	Station Number	Station Name	Date/Time Placed	Date/Time Recovered	Eosine Peak (nm)	Conc. (ppb)	RWT Peak (nm)	Conc. (ppb)
W4064	109	Ashley Spring	9/29/12 0800	11/29/12 1400	ND		568.7	553
W4065	110	Ashley Spring	11/29/12 1400	2/12/13 1000	ND		566.2	4.90
W4066	302	Vernal Gorge Well	9/29/12 0927	11/29/12 1545	ND		ND	
W4067	303	Vernal Gorge Well	11/29/12 1545	2/12/13 1100	ND		ND	
W4068	901	Deep Creek Spring	9/29/12 0800	11/8/12 1400	ND		ND	

Note: Dye concentrations are based upon standards used at the OUL. The standard concentrations are based upon the as sold weight of the dye that the OUL uses. If the client is not using OUL dyes, the client should provide the OUL with a sample of the dye to compare to the OUL dyes.

Footnotes:

ND = No dye detected

Thomas J. Aley, PHG and RG

Thomas J. Aley

f:\docs\coa\UtahGeoSur_AshleySprings_02.xls

OZARK UNDERGROUND LABORATORY, INC.

1572 Aley Lane Protem, MO 65733 (417) 785 - 4289 fax (417) 785-4290 email: oul@tri-lakes.net

SAMPLE COLLECTION DATA SHEET for FLUORESCENCE ANALYSIS

Project: Ashley Springs, Utah ____ Week No: ____ Samples Collected By: Melissa Hendrickson

Samples Shipped By: Melissa Hendrickson ____ Samples Received By: Rebecca Scott/OUL

Date Samples Shipped: 2 / 13 / 13 Date Samples Received: 2 / 14 / 13 Time Samples Received: 1215 Return Cooler? Yes X No ____

Bill to: Paul Inkenbrandt, Utah Geological Survey Send Results to: Paul Inkenbrandt, Utah Geological Survey

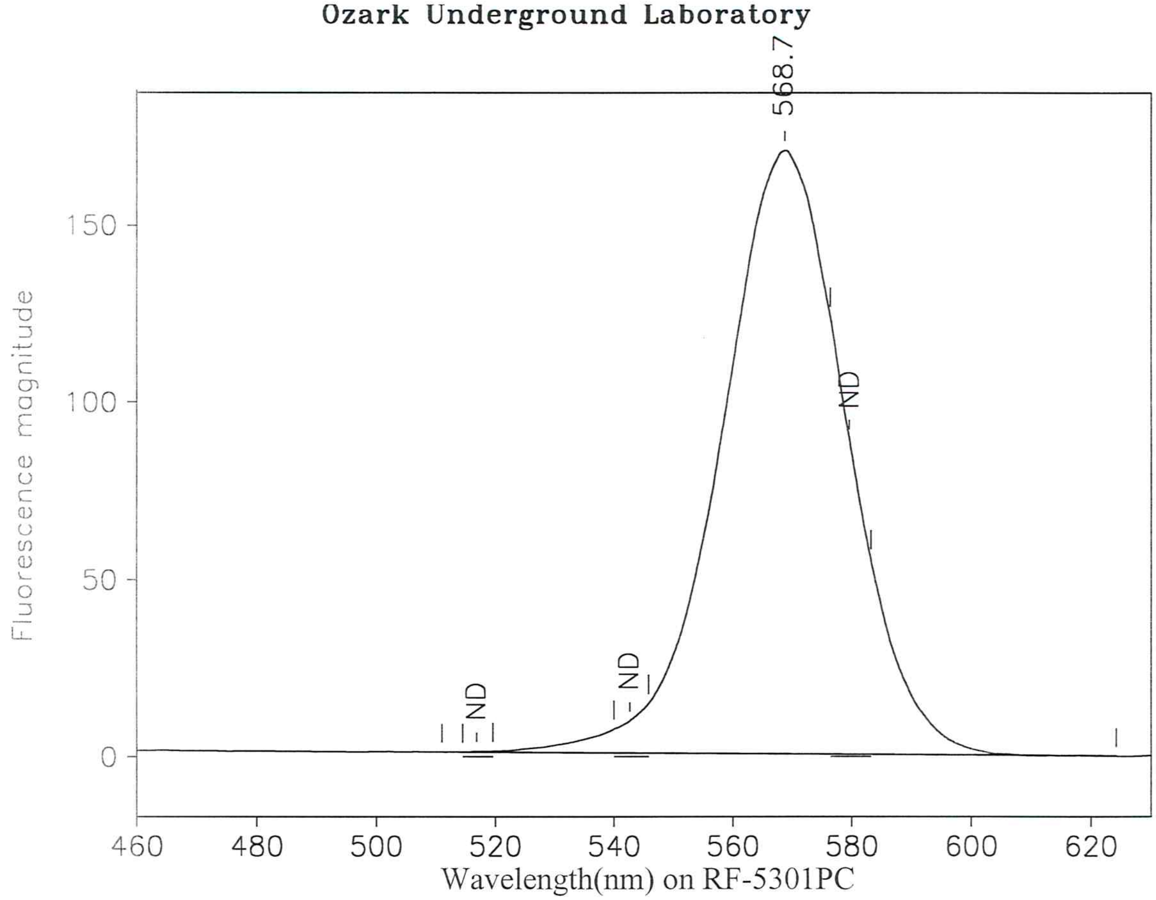
Analyze for: Fluorescein ____ Eosine X Rhodamine WT X Other ____ Ship cooler to: M. Hendrickson, 355 N. Vernal Ave, Vernal UT 84078

OUL use only		Please indicate stations where dye was visible in the field for field technician use - use black ink only						OUL use only
# CHAR REC'D	LAB NUMBER Char	STATION NUMBER 1-4 Numbers	STATION NAME	PLACED		COLLECTED		# WATER REC'D
				DATE	TIME	DATE	TIME	
1	W4064	109	Ashley Spring	9/29/12	8:00	11/29/12	14:00	0
1	W4065	110	Ashley Spring	11/29/12	14:00	2/12/13	10:00	0
1	W4066	302	Vernal Gorge Well	9/29/12	9:27	11/29/12	15:45	0
1	W4067	303	Vernal Gorge Well	11/29/12	15:45	2/12/13	11:00	0
1	W4068	901	Deep Creek Spring	9/29/12	8:00	11/8/12	14:00	0

COMMENTS: Project name: Ashley Springs, Utah. Contact: PaulInkenbrandt@utah.gov
OUL Project 1209 analyzed 2/27/13 by ukl/oul

This sheet filled out by OUL staff? Yes ____ No X Charts for samples on this page proofed by OUL: ar

Ozark Underground Laboratory



Station 109: Ashley Spring
OUL number: W4064
Matrix: Elutant
Placed: 09/29/12 0800

Analyzed: 02/27/13

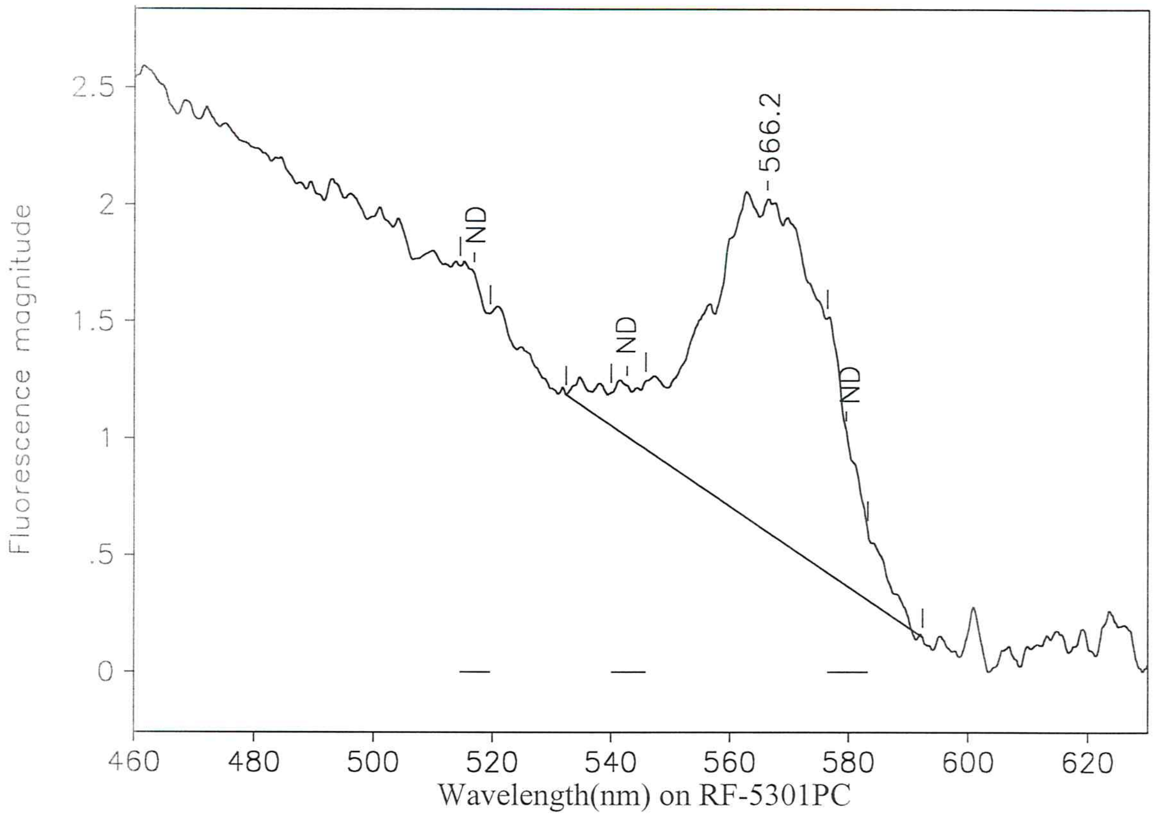
Collected: 11/29/12 1400

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.8	514.5	519.6	0.00	0.00	0.00	ND
542.6	540.0	545.8	0.00	0.00	0.00	ND
568.7	511.0	624.2	170.39	4,198.26	0.04	553
579.5	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



Station 110: Ashley Spring
OUL number: W4065
Matrix: Elutant
Placed: 11/29/12 1400

Analyzed: 02/27/13

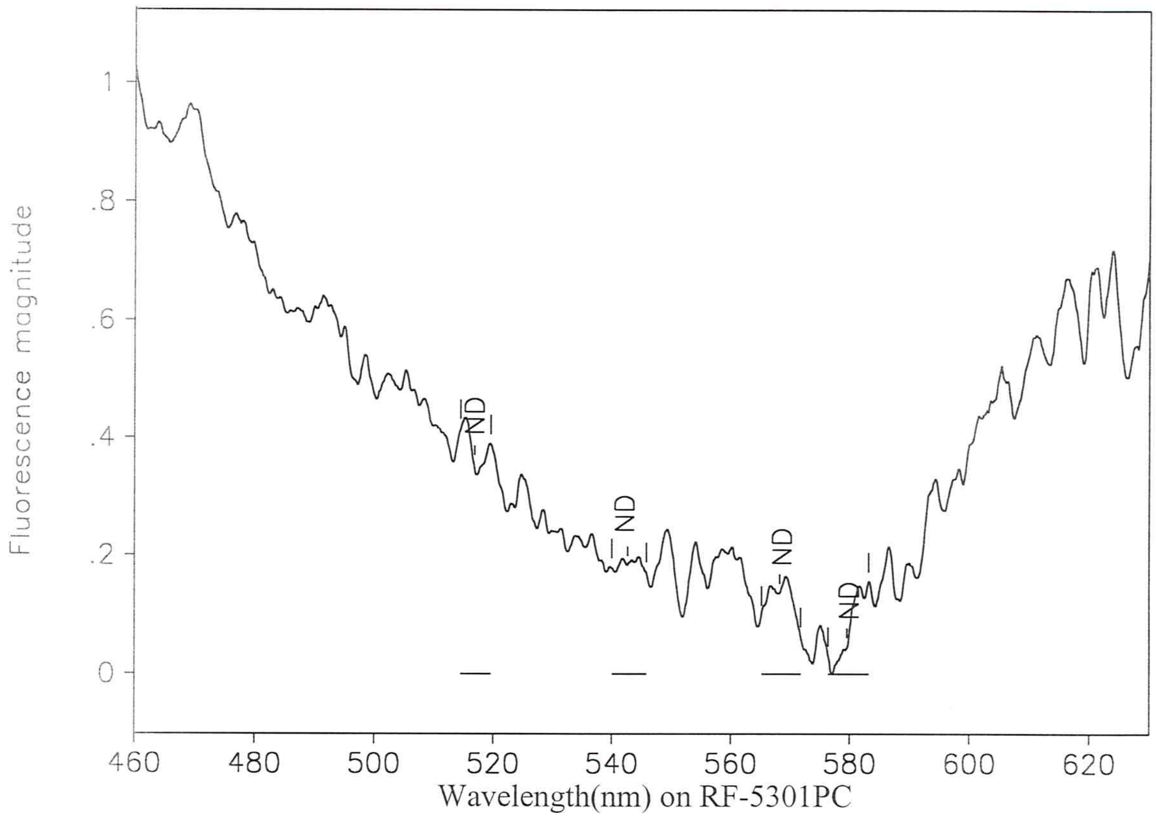
Collected: 02/12/13 1000

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.8	514.5	519.6	0.00	0.00	0.00	ND
542.6	540.0	545.8	0.00	0.00	0.00	ND
566.2	532.4	592.4	1.42	37.25	0.04	4.90
579.5	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



Station 302: Vernal Gorge Well
OUL number: W4066
Matrix: Elutant
Placed: 09/29/12 0927

Analyzed: 02/27/13

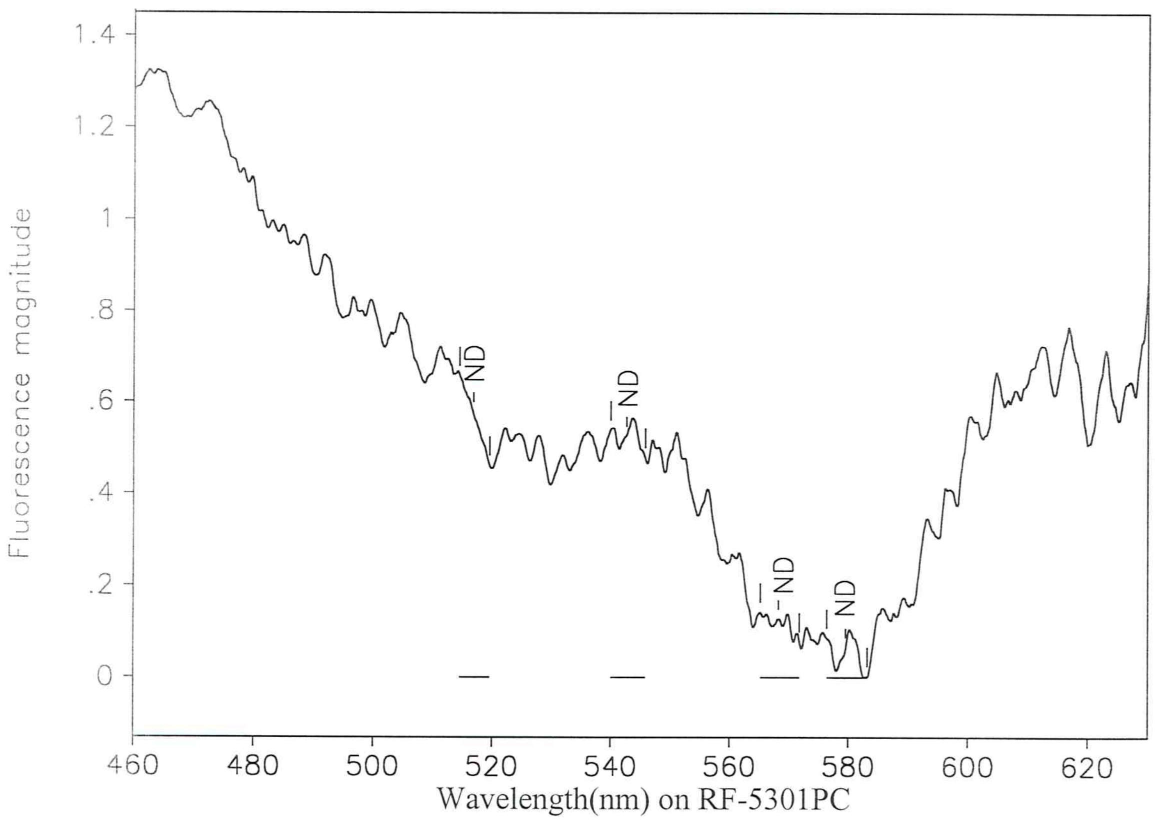
Collected: 11/29/12 1545

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.8	514.5	519.6	0.00	0.00	0.00	ND
542.6	540.0	545.8	0.00	0.00	0.00	ND
568.2	565.2	571.8	0.00	0.00	0.00	ND
579.5	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



Station 303: Vernal Gorge Well
OUL number: W4067
Matrix: Elutant
Placed: 11/29/12 1545

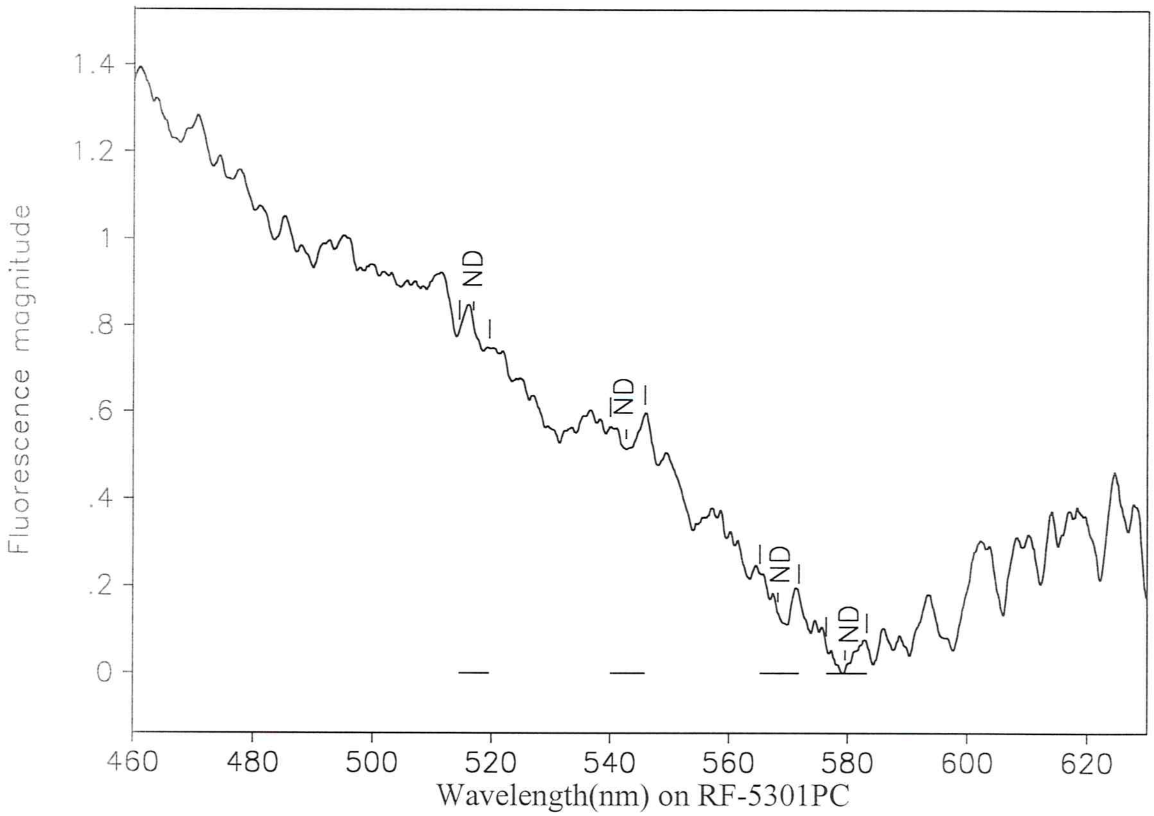
Analyzed: 02/27/13
Collected: 02/12/13 1100

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.8	514.5	519.6	0.00	0.00	0.00	ND
542.6	540.0	545.8	0.00	0.00	0.00	ND
568.2	565.2	571.8	0.00	0.00	0.00	ND
579.5	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Ozark Underground Laboratory



Station 901: Deep Creek Spring
OUL number: W4068
Matrix: Elutant
Placed: 09/29/12 0800

Analyzed: 02/27/13
Collected: 11/08/12 1400

Peaks within the normal range of tracer dyes:

Peak nm	Left X	Right X	Height	Area	H/A	Conc.
516.8	514.5	519.6	0.00	0.00	0.00	ND
542.6	540.0	545.8	0.00	0.00	0.00	ND
568.2	565.2	571.8	0.00	0.00	0.00	ND
579.5	576.4	583.2	0.00	0.00	0.00	ND

Peaks close to the normal range of tracer dyes:

Samples Run:	10/1/2012 11:00:00	Analysis conducted by:	M. Hendrickson

Sample #	Location	Date and time	Reading 1	Reading 2	Reading 3	Reading 4	Average Raw Flrsnc. Unit
Blank 1	Old tap water pre-trace	9/18/12 8:00	55.91	54.94	59.29	59.26	**57.35**
A5004	Vernal Well Water	9/26/12 18:06	54.62	59.14	59.38	56.5	**57.41**
A5003	Vernal Well Water	9/25/12 9:34	61.9	60.03	65.29	65.04	**63.065**
M070	Stevens Well Water	9/25/12 14:36	60.86	59.31	63.57	63.38	**61.78**
M71	Stevens Well	9/28/12 10:18	61.67	60.25	64.79	64.13	**62.71**
M61	Thompson Well Water	9/28/12 9:23	57.5	55.87	60.32	59.75	**58.36**
Blank 2	Tap water	10/1/12 11:00	63.44	56.06	60.1	55.43	**58.7575**
Blank 3	Tap water	10/1/12 14:00	69.02	68.16	68.86	66.03	**68.0175**
MO2	Ashley Spring Carbon 1	9/26/12 14:55	1675.76	1676.36	1675.01	1663	**1672.5325**
		9/29/12 8:00	1675.76	1676.36	1675.01	1663	**1672.5325**
M20	Vernal Well Carbon	9/26/12 14:32	221.32	228.86	220.43	224.97	**223.895**
		9/28/12 8:54	221.32	228.86	220.43	224.97	**223.895**
M00	Ashley Spring Carbon 2	9/25/12 9:40	471.06	461.47	479.66	461.6	**468.4475**
		9/26/12 14:55	471.06	461.47	479.66	461.6	**468.4475**
Elutant		10/1/12 14:00	112.25	108.25	98.95	115.69	**108.785**

DRINKING WATER SOURCE PROTECTION PLAN

DELINEATION REPORT

of

ASHLEY SPRING

prepared for

ASHLEY VALLEY WATER & SEWER IMPROVEMENT DISTRICT
&
UINTAH COUNTY

7700 North 4500 West
Vernal, Utah 84078
(435)789-5844

prepared by

Paul Inkenbrandt
Utah Geological Survey
2013

The Ashley Spring spring house is the white building at the base of the cliff of Weber Sandstone.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Ashley Spring is a large spring approximately 10 miles (16 km) north of Vernal, Utah, along the south flank of the Uinta Mountains and is jointly managed by Ashley Valley Water & Sewer Improvement District and the Central Utah Water Conservancy District (Uintah County). Ashley Spring is a groundwater source under the direct influence of surface water, which requires delineations of both surface and groundwater protection zones. Surface protection zones for Ashley Spring are defined by the location of karst sinkholes and watershed boundaries, whereas groundwater protection zones are defined by the location of the South Flank fault and watershed boundaries. Because of dense, connective fracture networks and karst systems, a large area is required to protect source water for Ashley Spring. The surface protection zones cover an area of 74.6 square miles (193.2 km^2), and the groundwater protection zones cover an area of 226.8 square miles (587.4 km^2).

INTRODUCTION

1.1 System Information:

Ashley Valley Water & Sewer Improvement District and the Central Utah Water Conservancy District (Uintah County) are both existing public community water systems that collect water from Ashley Spring. Ashley Valley Water & Sewer Improvement District has submitted Source Protection Plans in the past for Ashley Spring, and has the source diversion type listed as “withdrawal” (as opposed to “delivery”) on the Utah Division of Water Rights website (Utah Division of Water Rights, 2013a and b), so this entity will be considered the primary system for which this report is created. However, information on the Central Utah Water Conservancy District will also be included for completeness.

The Ashley Valley Water & Sewer Improvement District system identification number is 24013. The Central Utah Water Conservancy District (Uintah County) system identification number is 24038.

Address for Ashley Valley Water & Sewer Improvement District:

Ashley Valley Water & Sewer Improvement District
1344 West Highway 40, P.O. Box 967
Vernal, UT 84078

Address for Central Utah Water Conservancy District (Uintah County):

Central Utah Water Conservancy District (Uintah County)
355 West University Parkway
Orem, UT 84058

1.2 Source Information:

Ashley Spring is an individual spring and an existing source. This spring is the largest spring of a spring cluster, henceforth referred to as Ashley springs, which discharges into Ashley Creek. Based on its discharge of between 10-100 cubic feet per second (cfs), Ashley Spring is a 2nd magnitude spring (Meinzer, 1927). Ashley Spring is a groundwater source under the direct influence of surface water, and the evidence for this designation is provided in this report. The spring house and connections are already constructed. The source is located in Uintah County, Utah, approximately 10 miles (16 km) north of Vernal City, Utah (figure 1). Ashley Spring is 670 feet (200 m) North and 1928 feet (600 m) West from the SE corner of section 1, T. 3 S., R. 20 E., Salt Lake Base Line and Meridian. The coordinates of the spring site are latitude 40.58º N and longitude 109.624º W (North American Datum 1983). The elevation of the spring water intake is 6266 feet (1910 m) above mean sea level. Ashley Spring is listed as source 24013-01 by the Ashley Valley Water & Sewer Improvement District and source 24038-03 by the Central Utah Water Conservancy District (Uintah County).

1.3 Designated Person - R309-600-5:

Designated Person:

David Hatch

Supervisor

Ashley Valley Water & Sewer Improvement District

1344 West Highway 40, P.O. Box 967

Vernal, Utah 84078

Phone: (435) 828-8400

Email: avwater@ubtanet.com

For technical questions regarding the preparation of this report contact:

Paul Inkenbrandt

Project Geologist

Utah Geological Survey Groundwater and Paleontology Program

1594 W. North Temple, Suite 3110

PO Box 146100

Salt Lake City, Utah 84114-6100

Phone: (801)537-3361

Email: paulinkenbrandt@utah.gov

For questions in relation to the Central Utah Water Conservancy District (Uintah County) contact:

Brad Grammer

Plant Manager

Ashley Valley Water Treatment Plant

3550 North 2500 West

Vernal, Utah 84078

Phone: (435)-789-0421

Email: avwtp@easilink.com

2.0 THE DELINEATION REPORT - R309-600-9(5)

This delineation report is associated with a Utah Geological Survey (UGS) contract deliverable (Inkenbrandt and others, in preparation) created for Uintah County officials to help preserve high quality groundwater in Ashley Spring public supply source. Much of the text and many of the figures in this delineation report were taken from the UGS contract deliverable.

2.1 Geologic Data - R309-600-9(6)(a)(i):

Ashley Spring discharges along the southeast flank of the Uinta Mountains. Dry Fork, Ashley Creek, Little Brush Creek, and Big Brush Creek drain the south slopes of the Uinta Mountains north of the Vernal area. Water in these drainage basins starts as mostly snow at elevations of 10,000 to 11,000 feet (3050-3350 m) and eventually drains into the Green River, east of Vernal. The headwaters of these streams are in the Precambrian-age sedimentary rocks of the Uinta Mountain Group, but because the dip of the geologic units is greater than the stream gradient, progressively younger units (figures 2, 3, and 4) are encountered as one moves downstream. When the streams reach areas where Mississippian limestone are at or near the surface, they lose most or all of the water to swallow holes, sinkholes, and fissures in the bedrock underlying and adjacent to the streambeds (Godfrey, 1985; figures 5 and 6).

Ashley Spring issues from alluvium (channel deposits) overlying the Weber Sandstone at the bottom of Ashley Gorge near its entrance (Spangler, 2005). Maxwell and others (1971) used fluorescent dye tracers to determine if water from both Ashley Creek and Dry Fork are the source for Ashley Spring. Water seeps through stream alluvium (boulders) into dissolved and fractured Mississippian limestone below, then travels southeast through karst-enhanced fracture networks in the limestone to Ashley Spring. The water likely mixes with water lost upstream of the spring in Ashley Creek, then rises through about 1400 feet (430 m) of fractured sandstone, limestone, and shale, until it surfaces at the bottom of Ashley Gorge (Godfrey, 1985; figure 6).

Fractures in bedrock contributing to groundwater flow are hypothesized to be related to a series of northwest-southeast trending, near-vertical oblique-slip normal faults (figure 7) called the Deep Creek fault zone (Haddox and others, 2005). The age of faulting is bracketed between the early Paleocene and the Oligocene (Haddox and others, 2005). Folds are also in the region, including the relatively large-scale Uinta Uplift (the south limb of this is displayed in figure 4) and subsidiary folds (figure 7), which, like the faults, are likely related to the Laramide uplift in this region (Hintze and Kowallis, 2009). The combination of deformation from faults and folds contributes to the fractures observed in the study area (Haddox, 2005). Inkenbrandt and others (in preparation) remotely mapped lineaments and stream orientation in the region, independently verifying fracture orientations outlined by Haddox and others (2005) (figure 8).

2.2 Spring Construction Data - R309-600-9(6)(a)(ii) & (iii):

The spring house is a concrete enclosure having a metal roof and a locked metal door. To access the spring house, one must travel through two locked gates and then through Ashley Creek. Spring water flows through the spring house, which is floored with mud and rocks. Most of the spring water rises through the northern chamber of the house (figure 9). There are two spring-water intake pipes in the spring house; that ultimately deliver water to the Ashley Valley Water & Sewer Improvement District treatment plant at the mouth of Ashley Gorge and the Central Utah Water Conservancy District (Uintah County) treatment plant, about three miles southeast of the spring. Water not collected by the pipes overflows from the spring house and then flows a short distance into Ashley Creek.

2.3 Aquifer Data - R309-600-9(6)(a)(iv):

Subsurface connections between Dry Fork and Upper Ashley Creek, and Ashley Spring have been confirmed by multiple dye tests (Maxwell and others, 1971; Godfrey, 1985; Spangler, 2005) and by the presence of red silt found downgradient in Ashley Spring following the 1997 Mosby Canal failure (Wallis, 1997). The main fork of Dry Fork and upper Ashley Creek also reportedly contribute to Brush Creek Spring, east of Ashley Spring (Spangler, 2005).

The Weber Sandstone is likely a conduit for flow to Ashley Spring, and not necessarily a source of water to the springs (Godfrey, 1985). Although the Weber Sandstone may not be the primary source of water to Ashley Spring, it is considered an important aquifer within the study area (Hood, 1976; Chidsey and Sprinkel, 2005).

Because the Weber Sandstone is both an important aquifer and an oil producing unit (Chidsey and Sprinkel, 2005), its hydraulic properties have been researched extensively. The primary hydraulic conductivity of the Weber Sandstone ranges from 2.1×10^{-5} to 0.28 feet per day (6.4×10^{-6} - 0.09 m/d), and porosities range from 11 to 19% (Hood, 1976; Lund, 1981). Fractures zones in the sandstone have a higher hydraulic conductivity than unfractured sandstone (Chidsey and Sprinkel, 2005), and the bulk hydraulic conductivity of the formation is between 0.01 and 20 feet per day (0.003 - 6 m/d) (Chidsey and Sprinkel, 2005). South of the study area, within the Ashley Valley Oil Field, the porosity of the Weber Sandstone ranges between 8 and 20%, and averages of 13% (Chidsey and Sprinkel, 2005). Based on specific-capacity (pumping-drawdown) tests conducted by Vernal City and summarized by Lund (1981), the approximate transmissivity of the Weber Sandstone at the mouth of Ashley Gorge is 17 feet squared per day (1.6 m^2/d). The thickness of the Weber Sandstone in this area is 790 feet (240 m)

(Lund, 1981), yielding a hydraulic conductivity of 0.02 feet per day (0.006 m/d). Refer to section 2.4 (Hydrogeologic Methods and Calculations) for a description of how the aquifer properties were determined.

An investigation by Inkenbrandt and others (in preparation) reports new information about aquifer properties in both the Weber Sandstone and the Mississippian carbonates. Based on a digital elevation model, geologic structure contours, and water well drillers' logs, Inkenbrandt and others (in preparation) determined the source aquifers for several wells and the approximate potentiometric surface of the Weber Sandstone. The potentiometric surface (figure 10) indicates that the mean groundwater-flow direction in the sandstone is 111° from north with a gradient of about 100 feet per mile (0.02).

Inkenbrandt and others (in preparation) also studied the Mississippian carbonates (specifically, the Madison limestone), through which groundwater travels from Dry Fork to Ashley Spring (Godfrey, 1985, Spangler, 2005). Based on dye-tracer tests, water generally flows from the northwest to the southeast (figure 11), following the major fracture orientations. However, localized southerly flow may be possible, assuming an appropriate vertical and horizontal gradient. An example is water flowing from Little Brush Creek cave to Brush Creek Spring (figure 11). Dye tests (Inkenbrandt and others, in preparation) show groundwater travels 10.6 miles (17 km) in between 67 and 115 hours, which translates to groundwater velocities between 0.13 and 0.23 feet per second (0.04-0.07 m/s). Discharge of the spring positively correlates to the velocity of the dye (Inkenbrandt and others, in preparation), where higher spring discharges likely indicate of higher groundwater velocity.

The hydraulic gradient in the karst system of the Mississippian carbonates is not well constrained. Most of the water infiltrates in Dry Fork at an elevation of about 8000 feet (2440 m) and the elevation of Ashley Spring is approximately 6300 feet (1920 m), making the hydraulic gradient about 160 feet per mile (0.03). This gradient is approximate, as the depth to water in the Mississippian carbonates in Dry Fork is not well documented and water infiltrates at different elevations along much of the extent of Dry Fork. Dry Fork Spring is a seasonal karst-influenced spring (Godfrey, 1985) along Dry Fork, 4.6 miles (7.4 km) from Ashley Spring. It marks a discharge point in the Mississippian carbonates at an elevation of 6860 feet (2091 m), with apparent gradient of 120 feet per mile (0.02) to the southeast (from the Dry Fork Sinks).

For the water to travel from the Mississippian carbonates exposed in Dry Fork to the base of the Weber Sandstone along Ashley Creek, it must travel 10.6 miles (17 km) downgradient (figure 11), and vertically through about 1500 to 2900 feet (460-900 m) of rock (figure 3). The most likely path of travel through the vertical section is via fractures, which must have a relatively high vertical hydraulic conductivity to create the observed dye transport times. The maximum vertical hydraulic gradient is calculated to be as high as 0.1 (in this case, the positive value indicates the gradient is up), which assumes that groundwater head from the Madison Limestone rises 200 feet (61 m) above land surface (based on Weber Sandstone groundwater levels presented in figure 10) over the minimum possible thickness separating Ashley Spring from the top of the Madison Limestone (1500 ft [460 m]). Assuming the maximum gradient (0.1) and the velocity indicated by the dye trace (0.15 ft/s [0.05 m/s]), the minimum estimated vertical hydraulic conductivity for the fractures would be about 1.15 feet per second (100,000 ft/day [0.35 m/s]), which is around the range of hydraulic conductivity for cavernous limestone (Heath, 1982). This estimate is based on Darcy's Law (Singhal and Gupta, 2010) and assumes linear flow, which does not occur at such high velocities. However, based on calculated velocities, the groundwater flow through this system seems essentially unrestricted, or at least is through fractures having apertures greater than 0.04 inch (1 mm) (Singhal and Gupta, 2010).

The dense fracture network that enables flow from Dry Fork through the Madison Limestone to Ashley Spring may be related to the Deep Creek fault zone and possibly fractures associated with prevalent folding in the area (Spangler, 2005, Haddox and others, 2005). High permeability fracture systems likely exist in other locations influenced by the Deep Creek fault zone, creating conduits across assumed confining layers to and/or from aquifer units.

The northern section of the watershed is underlain by the Uinta Mountain Group, which includes the Mutual Formation and the Red Pine Shale (figure 3; Hood, 1976). There is little documentation available on the bulk hydrologic properties of the Uinta Mountain Group. Geldon (2003) states that hydraulic conductivity ranges between 0.24 and 0.40 feet per day (0.07-0.12 m/d), which is in agreement with the ranges of hydraulic conductivity listed by Heath (1982) for fractured consolidated rocks. The hydraulic conductivity and effective porosity are likely higher near fault zones (Hood, 1976). Effective porosity for the Uinta Mountain Group is likely near that of metamorphic rocks, because it consists of shale and highly consolidated sandstone (Hood, 1976), which is about 27% (Morris and Johnson, 1967). The hydraulic gradient likely approximates the slope of topography in this area, although it may be different in the fracture zones. The properties of the aquifers in the region have been summarized in table 1.

2.4 Hydrogeologic Methods and Calculations - R309-600-9(6)(a)(vii):

The UGS conducted a dye trace, examined discharge data, and collected water chemistry data to confirm that Ashley Spring is a groundwater source that is influenced by surface water. The dye trace and groundwater chemistry data confirm relatively fast travel times from the infiltration areas in Dry Fork to Ashley Spring.

2.4.1 Dye Trace

I chose two sites to pour two different wavelength fluorescent dyes (figure 12). I chose the first site in the main fork of Dry Fork in an attempt to reproduce results by Maxwell and others (1971). I selected the second site in Rock Canyon in fractured Weber Sandstone, because it is vertically above Ashley Spring, is in the middle of a proposed mining area, and because the natural drainage of Rock Canyon meets Ashley Creek downstream of Ashley Spring, thereby eliminating the probability of overland flow contaminating samples collected at Ashley Spring.

With the assistance of Melissa Hendrikson of the U.S. Forest Service, I conducted two dye-tracer tests, using Rhodamine WT for the first trace and Eosine for the second (table 2). All dye and most of the sample packets were provided by Ozark Underground Laboratory in Missouri. As a precaution and to limit contamination, the dye was injected by Melissa Hendrickson, U.S. Forest Service, who wore protective clothing and used tarps for dye mixing. I collected the carbon sample packets, remained clear of the dye injection areas and avoided contact with contaminated material until after collecting the carbon sample packets. I followed protocol outlined in Taylor and Greene (2002) to determine the approximate amount of dye needed for each test.

To detect dye at the spring and at the wells, I used activated carbon packets and collected water samples. The packets were attached to 10-gauge steel wire loops mounted in about 3 pounds (1.8 kg) of concrete and placed in the Ashley Spring collection box (spring house) (figure 9), another spring about 100 feet (30 m) upstream along the west bank of Ashley Creek and associated with Ashley Spring, the Ashley Gorge Well (Vernal well), Deep Creek Spring, and in Ashley Creek upstream of Ashley Spring (figure 12). At most locations, only one carbon packet per site was used during the entire sampling period. At the Ashley Spring house, carbon packets were exchanged at varying time intervals. Also, at the spring house, I collected water samples to detect any ambient (native) fluorescence in the spring water before the dye trace was conducted. For the carbon packets, I used one duplicate sample and one trip blank sample to ensure sample integrity.

The Dry Fork dye-tracer test conducted for this study substantiated the results of earlier studies conducted in the Dry Fork drainage (Maxwell and others, 1971). Results of these dye-tracer tests also were verified by effects of the Mosby Canal failure on Ashley Spring (Wallis, 1997). Based on mineralogical sediment analysis, Godfrey (1985) concluded that suspended sediment and turbidity observed in Ashley Spring was from the karst network, and not contributed by the sediment in the Dry Fork catchment. However, the appearance of red, highly turbid water for several weeks following the Mosby Canal failure indicates that sediment can be transported from Dry Fork to Ashley Spring. While the source of some sediment in Ashley Spring may be detrital grains released from the dissolution of the limestone bedrock of the karst network (Godfrey, 1985), Dry Fork is likely contributing sediment.

Based on observations at the Ashley Gorge (Vernal) well and results from the second dye-tracer test (no dye detected), flow through the regional aquifer system appears to be highly dependent on the connectivity of fractures and the horizontal/vertical hydraulic gradients. Dye injected for the second tracer test was not detected in either Ashley springs (including Ashley Spring) or the Ashley Gorge Well (figure 12) during the extent of this study (September 2012 to February 2013). Based on limited potentiometric surface data (figure 10) and because water was poured upgradient into the top of the Weber Sandstone is at a higher elevation than Ashley Spring, the hydraulic gradient was vertically down and to the east. That dye did not reach the collection sites was likely due to either lack of connectivity between fracture sets and/or a disparity of hydraulic gradient.

No dye from the tracer tests was detected at the Ashley Gorge well, which is open to the Weber Sandstone (Lund, 1981). Lund (1981) noted that although the driller likely drilled to the bottom of the Weber Sandstone, no significant water-bearing fractures were encountered. Lack of connecting high-permeability fractures between the well and Ashley Spring could explain the differences in groundwater age (table 3) and apparent lack of dye recovery.

2.4.2 Hydrologic Analysis

I compiled hydrologic data from PRISM, the Utah Climate Center, the National Land Data Assimilation System (NLDAS), and several USGS stream gaging sites (figure 13) and examined them for specific trends. I determined an approximate mean annual water budget and a water budget specific to years where sufficient data exist. I examined hydrographs from USGS gaging stations to determine basic characteristics of the nature of groundwater flow in the karst system and statistics for spring flow.

To determine a water budget for Ashley Creek and Dry Fork basins, I used subdivisions of the basins of the named watersheds (figure 13). The watersheds define hydrologic surface-water boundaries within the basins. I calculated the average yearly output for each watershed using measurements from stream gaging stations (USGS, 2013) by calculating the average monthly flow and summing those averages for average yearly flow (table 4). Using digital raster data (continuous surface data) from PRISM (2013), I calculated the cumulative precipitation for each watershed by multiplying the average precipitation (1940-2013) within the boundaries of each watershed by the area of each watershed. I conducted a similar calculation using NLDAS evapotranspiration data (1979-2013). I used National Hydrography Dataset (NHDplus; Horizon Systems Corporation, 2013) data to determine predicted flow accumulation at each watershed boundary. NHDplus offers estimates of watershed flow accumulation based on the Extended Unit Runoff Method (EROM). Watershed flow accumulation is an estimate of the average flow in a creek based on the characteristics of the watershed and the local climate. This method assumes no diversions or unaccounted losses from the creek, as are typically observed in karst environments. I used this estimate to compare the stations' measurements to predicted creek discharge, to estimate water loss (table 4).

I examined Ashley Spring and Ashley Creek discharge data to describe characteristics of the Ashley Spring flow system. I examined the seasonality and statistics of the spring discharge data (figure 14). I performed slope analysis (Taylor and Greene, 2002) to determine the nature of flow through the Mississippian carbonate (Madison Limestone) system, the Taylor and Greene (2002) analysis uses the slope of a hydrograph as a recording of the response of a spring's discharge to precipitation events (figure 15). I used precipitation-influenced discharge data recorded during fall to eliminate the buffering (time delay-release) effect of snowmelt.

2.4.3 Chemistry

Janae Wallace (UGS) and I sampled water at nine sites in the study area during September 2012 (figure 16), to determine a baseline water chemistry and to better understand the water flow paths of the Dry Forks and Ashley Creek hydrologic system. Water was analyzed for general chemistry and nutrients (nitrate, nitrite, ammonia, and phosphorous) content by the Utah Division of Epidemiology and Laboratory Services for most of the sites. Of the nine sites, water samples from seven were analyzed for tritium, oxygen, and deuterium isotopes, and two for carbon-14 isotopes. To determine seasonal changes in water chemistry of Ashley Spring, I used data from the Central Utah Water Conservancy District from 1987 to 2013.

Groundwater chemistry of Ashley Spring varies seasonally, but has not changed significantly over the long term annually. Temperature increases from April to August (figure 17), peaking at about 13°C (55.4°F) in August, and decreases to about 7°C (44.6ºF) in February. The temperature decrease is coincident with snowmelt timing. Also, the temperatures in figure 17 may be higher than water temperature at the spring, as the Utah Central Water Conservancy District recorded them at the water treatment plant, 6 miles (10 km) to the southeast of the spring. Alkalinity, hardness, and conductivity are inversely correlated with discharge and snowmelt rate. Variability of these constituents is highest in the spring and lowest in the winter (figures 17 and 18). Lower concentrations of constituents are likely functions of a faster rate of flow through the system, limiting residence time and subsequent chemical reaction rates. The variability observed in conductivity and temperature is comparable to the variability observed in other alpine karst springs (Despain, 2006). The coefficient of variation (standard deviation divided by mean) of hardness of Ashley Spring is 20%, which is another indication of conduit flow (Shuster and White, 1971).

Comparing surface water chemistry to water from different aquifer systems may indicate the potential path(s) of water in the region. Water in Dry Fork, Brownie Creek, and North Fork above the sinks in each of the drainages has relatively low concentrations of major ions (figure 19A) and a very low conductivity (specific conductance) of 30 μS/cm (figure 19B), whereas Ashley Spring has relatively higher major ions concentrations (figure 19A) than water in the tributaries of Dry Fork and an average conductivity of 140 μS/cm (figure 19B). Water from wells completed in the Weber Sandstone has higher concentrations of most major ions than Ashley Spring (figures 19 and 20), especially sulfate. Water from wells monitored by Simplot Phosphate, and screened to alluvium or the Moenkopi Formation, has higher concentrations of major ions relative to wells screened in the Weber Sandstone and Ashley Spring.

Based on carbon dating and tritium values (table 3), and the dye-tracer tests, most of the water from Ashley Spring is modern water. Results of the dye traces indicate that a significant portion of the groundwater flowing through the karst system between Dry Fork and Ashley Spring is less than a week old, and that increases in solute concentrations between Dry Fork and Ashley Spring can occur within the travel time of the water. Based on empirical research, Martinez and White (1999) have shown that calcium and magnesium can dissolve to concentrations much higher than concentrations in Ashley

Spring in less than 60 hours. Both the hydrographs and chemistry data offer no evidence to support that an older component of groundwater contributes to the water that issues at Ashley Spring. Stable isotope values (table 3) between Dry Fork, Ashley Spring, and the Ashley Gorge well indicate that mixing of older and younger water is possible

Carbon and tritium analyses from samples collected for this study (table 3), as well as results of the dye-tracer tests (see above), indicate that groundwater from the Ashley Gorge (Vernal) well (figure 12) does not have the same travel path as water from Ashley Spring. Groundwater sampled from the Ashley Gorge well is much older (about 2000-4000 years) than water collected from Ashley Spring. Based on the Ashley Gorge well chemistry, water from Ashley Spring has a specific flow path in a specific fracture zone of the Weber Sandstone, of which the Ashley Gorge well does not penetrate. This helps explain the absence of dye tracers in the Vernal Ashley Gorge well.

2.4.4 Delineation

The enclosed spring house, water chemistry, and dye tracers indicate that water collected at Ashley Spring is groundwater, making Ashley Spring a groundwater source. Hydrographs, water chemistry, and dye tracers also indicate that the groundwater from Ashley Spring is under the direct influence of surface water. Because this is a groundwater source under the direct influence of surface water, Utah Code (R309-605-8(1)) requires delineation of both groundwater and surface-water contribution areas.

Dye velocities, seasonal variation in water chemistry (figures 17 and 18), and available hydrographs (figures 14 and 15) indicate that Ashley Spring receives water from a karst conduit system. This karst network allows for relatively rapid groundwater flow from infiltration points to the spring. Infiltration areas into the karst network include Dry Fork drainage upstream of Dry Fork Spring (a discharge point) and Ashley Creek drainage upstream of Ashley springs. Infiltration is likely focused in regions where Mississippian carbonates are at or near the surface, such as in the upper parts of the Dry Fork and Ashley Creek drainages. As a result, Dry Fork and Ashley Creek lose most or all of their flow into the Mississippian carbonates and are generally dry most of the year except during times of peak spring runoff (snowmelt) (Maxwell and others, 1971). Fracture connectivity could contribute water to the Mississippian carbonate aquifer through overlying units.

Based on the description of infiltration areas, I have designated the surface protection areas as the Dry Fork catchment upstream of Dry Fork Spring and the Ashley Creek catchment upstream of Ashley Spring. Zone 1 of the surface protection area is a half-mile wide buffer from the high-water mark of the source, up to 15 miles upstream of the location of where water first infiltrates into the karst network (see caves/sinks figure 11), as per the requirements of Utah Code (R309-605-7(3)(b)(i)(A)). The locations where water in the surface channels first infiltrates are essentially diversions of surface water into the karst groundwater system. Although reaches of these channels can be dry during a significant portion of the year, the channels can serve as recharge areas into the Mississippian carbonate aquifer system, and periods of snowmelt or precipitation can transport contaminants into the aquifer from these channels. I clipped the half-mile wide buffers at watershed boundaries. The source streams and watershed boundaries are defined by NHDplus data (Horizon Systems Corporation, 2013), and by dye-tracer studies (Maxwell and others, 1971). Some canals extend beyond and flow into the natural watersheds of Dry Fork and Ashley Creek. These canals were included, as well as their contributing catchments. Because the 15-mile-long half-mile-wide protection zone extends to the boundary of the watershed, Zones 2 and 3 are grouped into Zone 1, and Zone 4 is the remaining area of the watershed.

I also delineated groundwater protection zones. Groundwater protection Zone 1 is a 100-foot buffer around the perimeter of the spring house (R309-600-9(3)(a)(i)). Groundwater protection Zone 2 is the area within a 250-day travel time of groundwater to the margin of the spring house (R309-600-9(3)(a)(ii)). Dye tests indicated that groundwater traveled over half the total length of the total watershed in less than 5 days, indicating a relatively large Zone 2. However, due to the offset of the South Flank fault (figures 2 and 4), the karst network that allows for rapid groundwater transport is limited to the southern half of the watershed. Because of the geologic setting, groundwater protection Zone 2 is bounded to the north by the South Flank fault system, which juxtaposes Precambrian quartzite north of the fault against karstified Mississippian carbonates south of the fault (figures 2 and 4). To accommodate for potentially enhanced groundwater velocity from fracturing near the South Flank fault, and due to the resolution of the geological map (1:100,000-scale), I included a 200-foot (61 m) buffer north of the fault.

The southern boundary of the groundwater protection zone was created based on the collection elevation of the spring house of 6266 feet (1910 m) above mean sea level, the extent of the upper contact of the Moenkopi Formation (figure 2), NHDplus catchment boundaries (figure 22), and the trace of Dry Fork south of the extent of outcrops of Weber Sandstone. Based on the results of both dye-tracer tests and indications that the hydraulic gradient is generally to the southeast, and because groundwater chemistry indicates most of the spring water is modern, I did not include the Rock Canyon catchment as part of a groundwater protection zone. However, I did include the next drainage north, as this area has the potential to be upgradient of the spring, has a higher elevation than the spring, and has a greater chance of crossing fracture zones shared by the spring. This area is also included in the NHDplus catchment boundary (figure 22) of the spring (Horizon Systems Corporation, 2013).

Although the extent of the Mississippian karst network is limited to focused areas of carbonate dissolution and fractures (likely enhanced by dissolution), I do not know the exact locations of these pathways. Rapid ascent of water from the Mississippian carbonates to Ashley Spring indicates that fractures in the region have high vertical hydraulic conductivity that could allow for contaminant transport to both the Weber Sandstone and Mississippian limestone aquifers.

Groundwater protection Zones 3 and 4 are defined as the 3- and 15-year time of travel for groundwater, respectively. North of the South Flank fault is the Uinta Mountain Group. Based on the equation for groundwater velocity,

$$v = \frac{KI}{\theta} \tag{1}$$

Where,

$v = pore - water\ velocity$ (0.03 ft/d)

$I = hydraulic\ gradient$ (0.02)

$\theta = effective\ porosity$ (0.27)

$K = hydraulic\ conductivity$ (0.4 ft/d)

the 3- and 15-year travel distance of groundwater in the Uinta Mountain Group is 33 feet (10 m) and 164 feet (50 m), respectively. Theses distances are covered by the 200-foot buffer (61 m) added to Zone 2 to accommodate for fractures and potential map error. Due to the limited estimated travel distance, the boundaries of Zones 3 and 4 match those of Zone 2.

The occurrence of springs north of the South Flank fault indicates that groundwater flow occurs in this region. However, the locations of the springs are generally in localized, disconnected regions of unconsolidated material. Due to limited hydraulic connections, potential contaminant transport north of the South Flank fault would likely be by surface-water routes. The surface-water protection zones designated in this delineation should adequately augment the groundwater protection zones to protect the vulnerable aquifer system that supplies Ashley Spring.

2.5 Map Showing Boundaries of the DWSP Zones - R309-600-9(6)(a)(viii):

Boundaries for the surface-water and groundwater protection zones are presented in figures 21 and 22 and plates 1 and 2. These boundaries are also available as shapefiles (ESRI, 2012), and were provided to the Utah Division of Drinking Water.

2.5.1 Surface DWSP

Figure 21 and plate 1 show the location of Ashley Spring and the boundary for each surface-water DWSP zone. Zone 4 is 16 miles (25.7 km) wide (east to west) at the northernmost edge and 16 miles (25.7 km) long (north to south) from Ashley Spring to the surface water divide, and has an area of 226.8 square miles (587.4 km^2). Zones 1, 2, and 3 are as wide as 7 miles in Dry Fork, 6 miles (10 km) upstream from its southernmost end, having an area of 160.7 square miles (416.2 km^2). This width is greater than the stream buffer because the protection zones coalesce at points where the streams are within half a mile of each other. The longest surface protection zones is 20 miles (32 km) along Ashley Creek. This extends beyond the 15-mile (24 km) standard zone because multiple diversion/infiltration points where surface water sinks into the ground exist. There is a half-mile wide buffer along every major stream and tributary acting as a source to the groundwater system.

2.5.2 Groundwater DWSP

Figure 22 and plate 2 shows the location of Ashley Spring and the boundary for each groundwater DWSP zone. Groundwater protection Zone 1 is a 100-foot (30.5 m) buffer around the margin of the spring house (figure 9). Groundwater source protection Zones 2-4 have the same area (74.6 square miles [193.2 km^2]). This area is four miles (6.4 km) wide (southwest to northeast) at the south side. The zones are eight miles (13 km) long, from a mile south of Ashley Spring to 200 feet (61 m) north of the South Flank fault. The widest point of the groundwater protection zones is 16 miles (25.7 km) along the northern border of the area (figure 22).

2.6 Protected or Unprotected Aquifer Classification - R309-600-9(4) & (7):

Ashley Spring is a groundwater source under the direct influence of surface water. This is not a protected source. It is possible that some of the unconsolidated alluvium filling the southern portion of the Dry Fork (Lund, 1982) watershed could act as a confining layer, but no evidence supports the existence or continuity of such a layer.

REFERENCES

Chidsey, T.C., and Sprinkel, D.A., 2005, Petroleum geology of Ashley Valley oil field and hydrocarbon potential of the Surrounding Area, Uintah County, Utah: Utah Geological Association Publication in Dehler, C.M., Pederson, J.L., Sprinkel, D.A., and Kowallis, B.J., editors, Uinta Mountain geology: Utah Geological Association Publication 33, p. 205-214.

Despain, J.D., 2006, Hydrochemistry in an alpine karst system, Sequoia and Kings Canyon National Parks, California: Bowling Green, Kentucky, Western Kentucky University, M.S. thesis, 104 p.

ESRI, 2012, ArcGIS - Release 10.1: Redlands, California, Environmental Systems Research Institute computer software (http://www.arcgis.com/home/).

Geldon, A.L., 2003, Hydrologic properties and ground-water flow systems of the Paleozoic rocks in the upper Colorado River Basin in Arizona, Colorado, New Mexico, Utah, and Wyoming, excluding the San Juan Basin; US Geological Survey Professional Paper 1411-B, 153 p.

Godfrey, A.E., 1985, Karst hydrology of the south slope of the Uinta Mountains, Utah, *in* Picard, M.D., editor, Geology and energy resources, Uinta Basin of Utah: Utah Geological Association Publication 12, p. 277-293.

Haddox, D.A., 2005, Mapping and kinematic structural analysis of the Deep Creek Fault Zone, south flank of the Uinta Mountains, near Vernal, Utah: Provo, Utah, Brigham Young University, M.S. thesis, 144 p.

Haddox, D.A., Kowallis, B.J., and Shakespeare, J.D., 2005, Mapping and Kinematic Analysis of the Deep Creek Fault Zone, South Flank of the Uinta Mountains, Utah, *in* Dehler, C.M., Pederson, J.L., Sprinkel, D.A., and Kowallis, B.J., editors, Uinta Mountain geology: Utah Geological Association Publication 33, p. 205-214.

Haddox, D.A., Kowallis, B.J., and Sprinkel, D.A., 2010, Geologic map of the Dry Fork quadrangle, Uintah county, Utah: Utah Geological Survey Miscellaneous Publication 10-3, 2 plates, scale 1:24,000.

Heath, R.C., 1982, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 84 p.

Hintze, L.F., and Kowallis, B.J., 2009, Geologic history of Utah: Brigham Young University Geologic Studies Special Publication 9, 225 p.

Hood, J.W., 1976, Characteristics of aquifers in the northern Uinta Basin area, Utah and Colorado: Utah Department of Natural Resources Technical Publication 53, 71 p., 3 plates.

Horizon Systems Corporation, 2013, National Hydrography Dataset Version 2 (NHDPlusV2): Online, http://www.horizon-systems.com/NHDPlus/NHDPlusV2_home.php, accessed March, 2013.

Inkenbrandt, P., Wallace, J., and Hendrickson, M., in preparation, Baseline hydrology of Ashley

Spring: Utah Geological Survey Special Study.

Lund, W.R., 1981, Summary report on the drilling and pump testing of a proposed water well in the bedrock Weber Sandstone aquifer, Uintah County, Utah: Utah Geological Survey Report of Investigation No. 161, 11 p.

Lund, W.R., 1982, Geologic evaluation of septic tank and soil absorption system suitability, Dry Fork Canyon, Uintah County, Utah: Utah Geological Survey Report of Investigation No. 176, 36 p.

Martinez, M.I., and White, W.B., 1999, A laboratory investigation of the relative dissolution rates of the Lirio Limestone and the Isla de Mona Dolomite and implications for cave and karst development on Isla de Mona: Journal of Cave and Karst Studies v. 61(1), p. 7-12.

Maxwell, J.D., Bridges, B.L., Barker, D.A., and Moore, L.G., 1971, Hydrogeology of the eastern portion of the south slopes of the Uinta Mountains, Utah: Utah Department of Natural Resources Information Bulletin Number 21, 58 p.

McWorter, D.B., and Sunada, D.K., 1977, Groundwater hydrology and hydraulics: Ft. Collins, Colorado, Water Resources Publications, 304 p.

Meinzer, O.E., 1927, Large springs in the United States: U.S. Geological Survey Water Supply Paper 557, 94p.

Morris, D.A., and Johnson, A.I., 1967, Summary of hydrologic and physical properties of rock and soil materials, as analyzed by the hydrologic laboratory of the U.S. Geological Survey: US Geological Survey Water Supply Paper 1839-D, 42 p.

NASA, 2013, National Land Data Assimilation Systems (NLDAS): Online http://ldas.gsfc.nasa.gov/nldas/NLDASspecs.php, accessed May 2013.

PRISM, 2013, U.S. Precipitation Data: Oregon State University, online http://www.prismclimate.org, accessed May 2013.

Shuster, E.T., and White, W.B., 1971, Seasonal fluctuations in the chemistry of limestone springs – a possible means for characterizing carbonate aquifers: Journal of Hydrology, v. 14, p. 93-128.

Singhal, B.B.S., and Gupta, R.P., 2010, Applied hydrogeology of fractured rocks, 2nd edition: Springer, London, 429 p.

Spangler, L.E., 2005, Geology and karst hydrology of the eastern Uinta Mountains – an overview, *in* Dehler, C.M., Pederson, J.L., Sprinkel, D.A., and Kowallis, B.J., editors, Uinta Mountain geology: Utah Geological Association Publication 33, p. 205-214.

Sprinkel, D.A., 2006, Interim geologic map of the Dutch John 30′ x 60′ quadrangle, Daggett and Uintah Counties, Utah, Moffat County, Colorado, and Sweetwater County, Wyoming: Utah Geological Survey Open File Report 491DM, 3 plates, scale 1:100,000.

Taylor, C.J., and Greene, E.A., 2002, Hydrogeologic characterization and methods used in the investigation of karst hydrology, *in* Rosenberry, D.O., and LaBaugh, J.W., editors, Field techniques for estimating water fluxes between surface water and ground water: U.S. Geological Survey Techniques and Methods 4-D2, p. 75-114.

U.S. Geological Survey, 2013, National Water Information System (NWIS): Online, http://waterdata.usgs.gov/nwis, accessed March 2013.

Utah Division of Water Rights, 2013a, Public water supplier information - Ashley Valley Water & Sewer Improvement District: Online, http://www.waterrights.utah.gov/cgi-bin/wuseview.exe?Modinfo=Pwsview&SYSTEM_ID=1349, accessed October 2013.

Utah Division of Water Rights, 2013b, Public water supplier information - Central Utah Water Conservancy District (Uintah County): online, http://www.waterrights.utah.gov/cgi-bin/wuseview.exe?Modinfo=Pwsview&SYSTEM_ID=1417, accessed October, 2013.

Wallis, S., 1997, Red water causes emergency: Vernal, Utah, Vernal Express newspaper, printed 5/21/1997.

TABLES

Table 1. *Summary of aquifer properties for aquifers associated with Ashley Spring.*

Unit	Parameter	Value (metric)	Source
Weber Sandstone	aquifer thickness	790 ft (240 m)	Lund, 1981
	bulk hydraulic conductivity	0.02 ft/day (0.006 m/day)	Lund, 1981
	vertical fracture hydraulic conductivity	1.15 ft/s (0.35 m/s)	dye trace
	horizontal hydraulic gradient	0.02	well water levels
	direction of groundwater flow	111°	well water levels
	effective porosity	14%	McWorter and Sunada, 1977
Mississippian carbonates (Madison Limestone)	aquifer thickness	490-980 ft (150-300m)	Sprinkel, 2006
	groundwater velocity	0.13-0.23 ft/s (0.04-0.07 m/s)	dye trace
	hydraulic gradient	0.03	dye trace
	direction of groundwater flow	Generally southeast	Godfrey, 1985
Uinta Mountain Group	aquifer thickness	up to 14,760 ft (4500 m)	Sprinkel, 2006
	hydraulic conductivity	0.24-0.40 ft/d (0.07-0.12 m/d)	Geldon, 2003
	hydraulic gradient	0.02	based on Weber Sandstone
	direction of ground-water flow	160°	mean topographic slope of region
	effective porosity	27%	Morris and Johnson, 1967

Table 2*. Timeline of events for the UGS dye tracer study.*

9/19/2012 11:43	Two carbon packets placed in Ashley Spring house to measure ambient fluorescence.
9/24/2012 13:26	Three pounds of Rhodamine WT dye poured into Dry Fork at 600347 m E and 4497942 m N (UTM, Zone 12, NAD 1983).
9/24/2012 14:45	Leading edge of dye visible in Dry Fork 750 feet downstream of injection site.
9/24/2012 18:57	Retrieved ambient fluorescence carbon packets.
9/27/2012 16:27	Four pounds of Eosine dye and 4000 gallons of water from a water truck poured at 618255 m E and 4493345 m N (UTM, Zone 12, NAD 1983), the Rock Canyon pour site.
9/27/2012 7:56	Carbon packet OUL #W1023 placed in a small spring 250 feet northwest of Ashley Spring house, on the west side of Ashley Creek, at 616421 m E and 4493093 m N (UTM, Zone 12, NAD 1983).
9/28/2012 21:17	Carbon packet OUL #W1018 collected from Ashley Spring, later showing no measurable Rhodamine WT. Carbon packet OUL # W1019 placed into Ashley Spring house.
9/29/2012 8:00	Carbon packet OUL #W1019 collected, showing positive match for Rhodamine WT dye.
9/29/2012 8:25	Carbon packet OUL #W1023 collected, showing positive match for Rhodamine WT dye.
2/12/2013 10:00	Final carbon packet collected from Ashley Spring. As of this time, no Eosine was detected in Ashley Spring.

Table 3. *Results of carbon, tritium, and stable isotope analyses for Ashley Spring and Ashley Gorge Well.*

Site Name	Sample Date	Temperature (°C)	pH	Dissolved Oxygen (mg/L)	$\delta^{18}O$(‰)	δD (‰)	Tritium (TU)	Carbon 14 (pmc)
Ashley Gorge Well	9/25/2012	9.7	7.5	3.6	-16.86	-124.4	<0.2	17.416
Ashley Spring	9/25/2012	8.46	7.5	7.4	-16.01	-117.2	3.9	60.972

Table 4. *Estimates of water flowing into and out of Dry Fork and Ashley Creek.*

	Estimates Using USGS Stations			Estimates Using Climate Data				Comparison	Estimate Using NHDplus[5]	Comparison
	USGS Station Number	Name	Gage	Watershed (s)[1]	PRISM Precip[2]	NLDAS Evap.[3]	Precip Minus Evap[4]	Gage / (Precip Minus Evap)	Flow	Gage / Flow
			ac-ft/yr		ac-ft/yr	ac-ft/yr	ac-ft/yr		ac-ft/yr	
Water Lost in Dry Fork Drainage	9269500	Lower Brownie	6800							
	9269000	Middle Brownie	5700							
	9268900	Upper Brownie	9500	9	14500	6000	8500	112%	8900	107%
		Lost Between Upper and Lower Brownie	2700							
		Lost Between Upper and Middle Brownie	3800							
	9268500	North Fork	4800	2	11000	4800	6200	77%	8000	60%
	9268000	Upper Dry Fork	26100							
		Three Forks Above Sinks	**40300**	1+2+9	89700	34200	55500	73%	50100	80%
	9267500	Mosby	4000							
		Total flow from Upper Dry Fork (9267500+9268000)	30000	1	64200	23500	40700	74%	42100	71%
	9270000	Dry Fork Below Dry Fork Spring	26600	1+2+9+3	122000	52700	69300	38%	75000	35%
		Amount Lost in Sinks of All Forks of Dry Fork (Three Forks Above Sinks - Dry Fork Below Spring)	**13800**							
Water Gained by Ashley Spring	9265300	Middle Ashley Creek	48500	4	77900	31700	46200	105%	49100	99%
	9265500	Ashley Creek Upstream of Spring	52700	4+6	122300	56400	65900	80%	70300	75%
	9266500	Ashley Creek Downstream of Spring	67200							
		Gain between Middle Ashley Creek and Station below spring (9266500 - 9265300)	18700							
	9266000	Ashley Spring	19500							
		Estimated Ashley Spring (9265500 - 9266500); Excludes water used	14500							
		Ashley Spring: Average Reported Use	4700							
		Estimated input from springlets	300							
		Ashley Spring After Use	14800							

[1] See figure 13

[2] PRISM, 2013

[3] NASA, 2013

[4] PRISM Precip data minus NLDAS Evap. Data

FIGURES

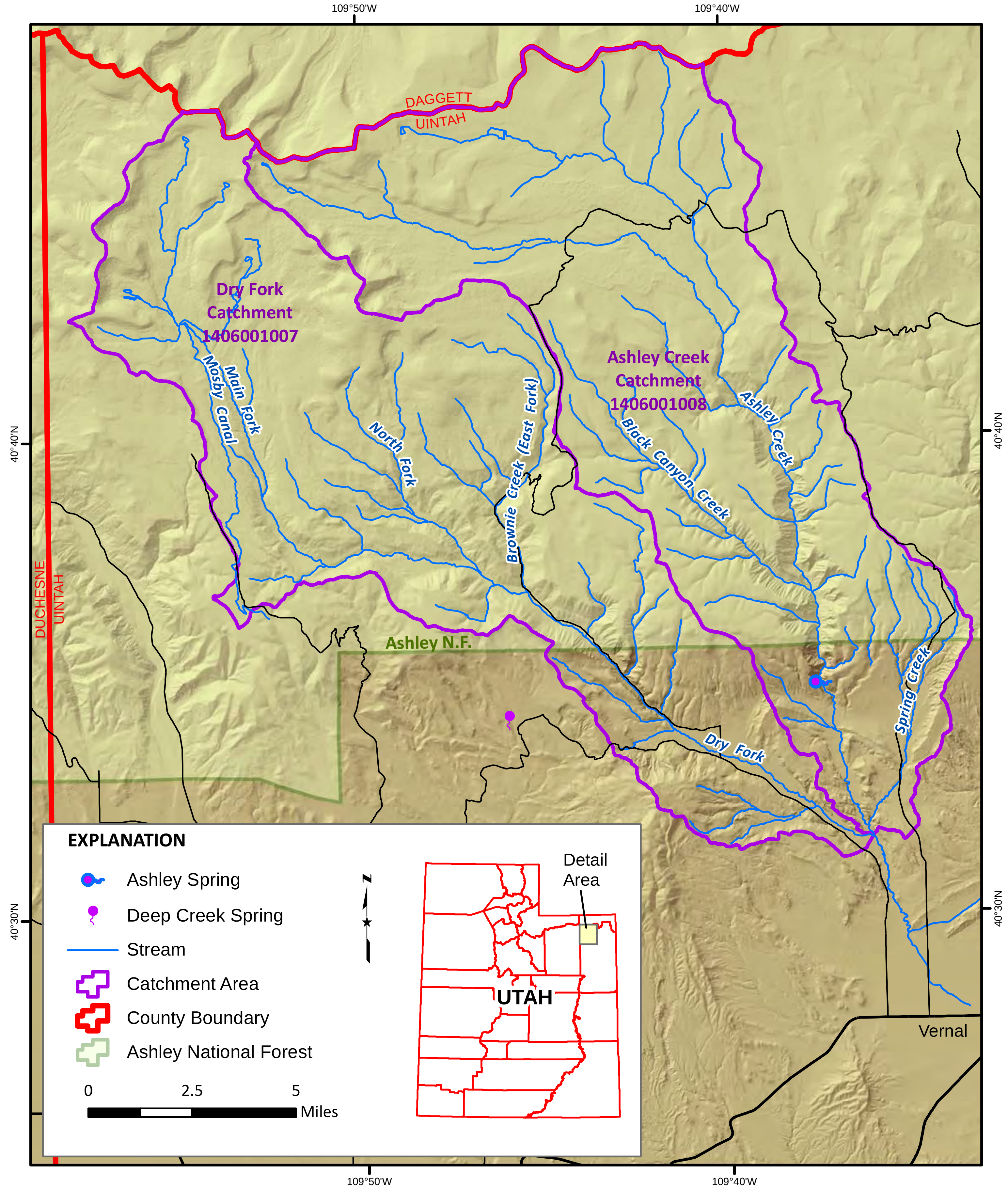


Figure 1. *Ashley Spring is in northeastern Utah. It receives water from Ashley Creek and Dry Fork catchments.*

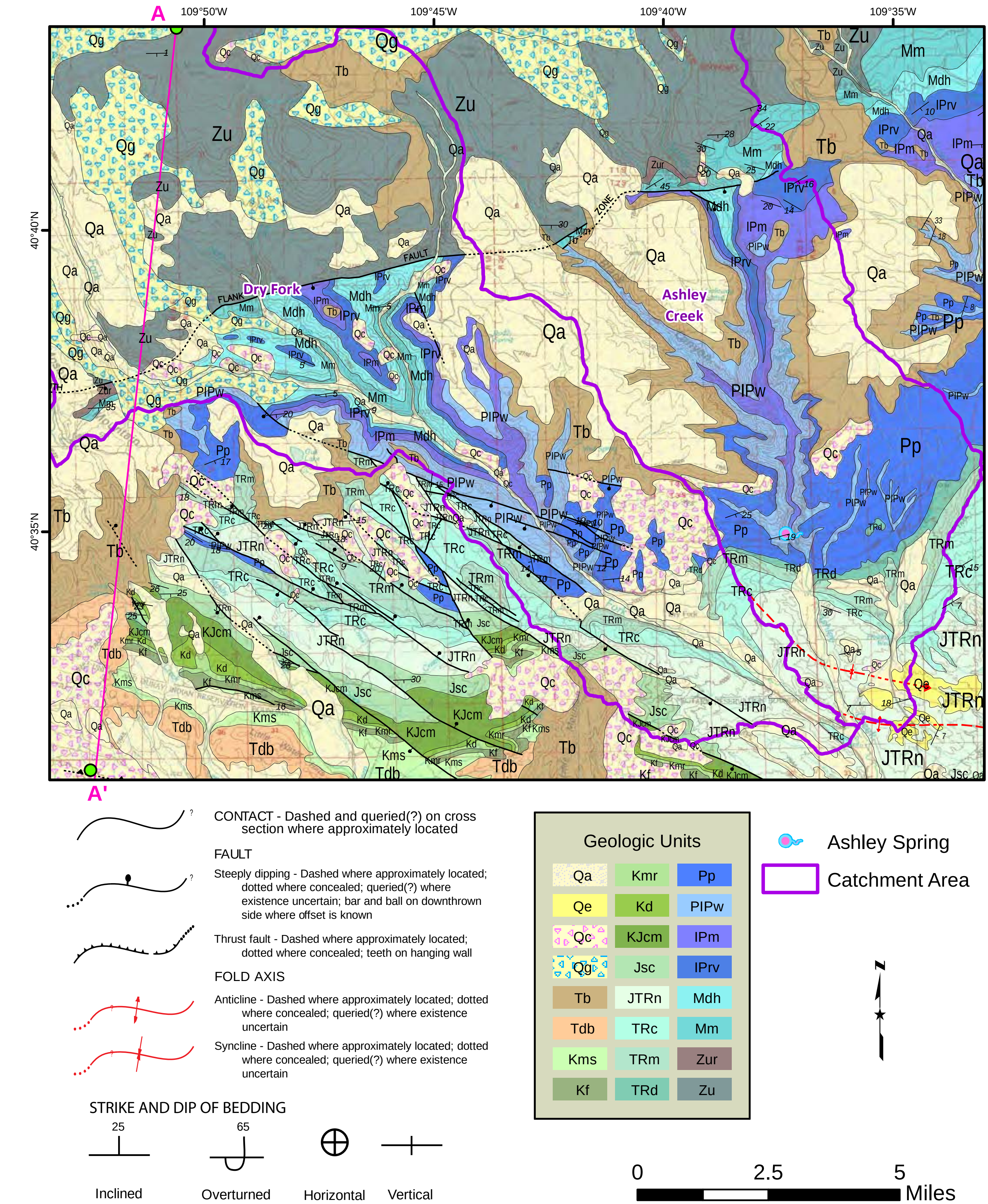


Figure 2. *Geology of the study area (modified from Sprinkel, 2006). Refer to the stratigraphic column in the next figure for geologic unit names.*

AGE	SYMBOL	FORMATIONS	Thickness (feet) (not to scale)	NOTES
Quaternary	Q	Unconsolidated deposits: Qa ALLUVIUM; Qe EOLIAN DEPOSITS; Qc COLLUVIUM; Qg GLACIAL TILL	less than 160	Alpine glaciers in Uinta Mountains
Tertiary – Oligocene	Tb	Bishop Conglomerate	0-500	Capture of Green River by Colorado River
Tertiary – Oligocene	Td – Tds	Starr Flat Member of Duchesne River Formation	130-750	Regional extension tilted and faulted the Bishop Conglomerate
Tertiary – Eocene	Td – Tdl	Lapoint Member of Duchesne River Formation	200-1050	Crustal stability; Gilbert Peak erosion surface forms and Bishop Conglomerate is deposited
Tertiary – Eocene	Td – Tdd	Dry Gulch Creek Member of Duchesne River Formation	500-660	
Tertiary – Eocene	Td – Tdb	Brennan Basin Member of Duchesne River Formation	720-2000	
Tertiary – Eocene	Tu	Uinta Formation	0-2050	Duchesne River Formation unconformably deposited on a variety of Mesozoic formations after uplift of Uinta Mountains in Late Cretaceous through early Tertiary
Tertiary – Eocene	Tg	Green River Formation	1310-2620+	
Tertiary – Eocene / ? Paleocene	Tw	Wasatch Formation	2000	
Cretaceous	Kmv	Mesaverde Group	920-2620	
Cretaceous	Kms	Mancos Shale	4590-5580	Mancos Shale represents last formation of great Western Interior Seaway
Cretaceous	Kf	Frontier Sandstone	140-280	Unconformity, 5 m.y.
Cretaceous	Kmd – Kmr	Mowry Shale	30-210	Fossil fish scales and bones in Mowry
Cretaceous	Kmd – Kd	Dakota Sandstone	50-170	
Cretaceous	KJcm	Cedar Mountain Formation	0-200	K-1 unconformity, 2 m.y.
Jurassic	KJcm	Morrison Formation	660-890	K-0 unconformity, 25 m.y.; Abundant dinosaur remains
Jurassic	Jsc – Js	Stump Formation	130-260	*Belemnites* fossils
Jurassic	Jsc – Je	Entrada Sandstone	100-250	J-3 unconformity, 1 m.y.
Jurassic	Jsc – Jc	Carmel Formation	100-400	J-2 unconformity, 14 m.y.
Jurassic ? Triassic	JTRn	Nugget Sandstone	660-1030	
Triassic	TRc	Chinle Formation	230-460	Gartra Member; TR-3 unconformity, 15 m.y.
Triassic	TRmd – TRm	Moenkopi Formation	520-1120	Pinches out westward
Triassic	TRmd – TRd	Dinwoody Formation	0-200	TR-1 unconformity, 6 m.y.
Permian	Pp	Park City and Phosphoria Formations	60-250	Phosphate deposits; Unconformity, 3 m.y.
Permian	PIPw	Weber Sandstone	650-1310	Forms cliffs and important oil reservoir in the Rocky Mountains
Pennsylvanian	IPm	Morgan Formation	620-950	
Pennsylvanian	IPrv	Round Valley Limestone	210-400	
Mississippian	Mdh	Doughnut Shale	80-300	
Mississippian	Mdh	Humbug Formation	100-300	
Mississippian	Mm	Madison Limestone	490-980	Karst; Forms cliffs, contains marine fossils; Unconformity, about 350 m.y.
Proterozoic	Uinta Mountain Group – Zur	Red Pine Shale	0-1970	
Proterozoic	Uinta Mountain Group – Zu	Undivided Uinta Mountain Group (includes Mutual Formation in Hood, 1976)	as much as 14,760	Forms the core of the Uinta Mountains; Flaming Gorge Dam constructed on this unit

Figure 3. *Stratigraphic column of geologic units in the area of study. Units without a color in the column are not shown on the map in figure 2 or the cross section in figure 4 (modified from Sprinkel, 2006).*

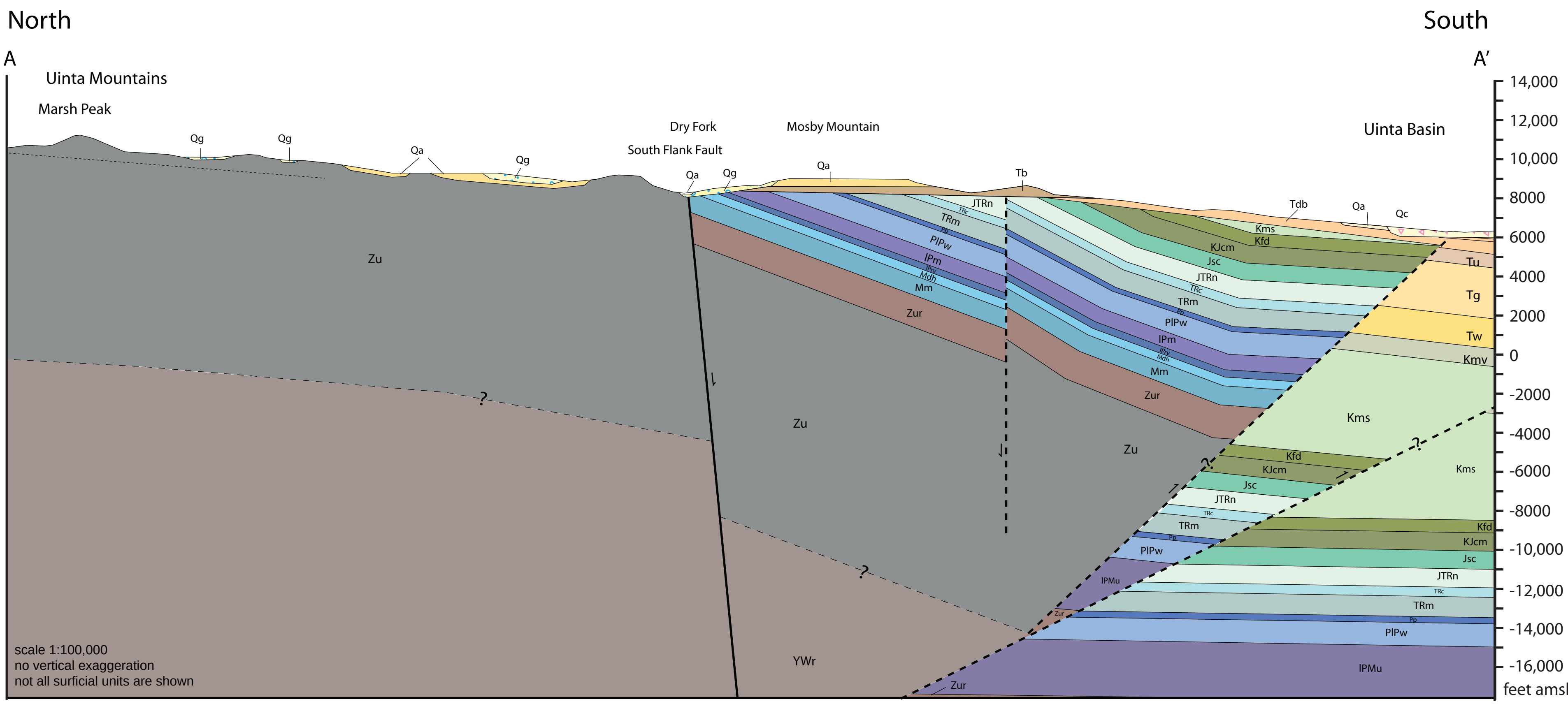


Figure 4. *Geologic cross section across the field area (modified from Sprinkel, 2006). See figure 2 for the location of the cross section and figure 3 for the names of the geologic units.*

Figure 5. *Sinkhole near USGS gaging station adjacent to the channel of the Main Fork of Dry Fork.*

Figure 6. *Solutionally enlarged fractures exposed in the stream bed of the losing reach of the Main Fork of Dry Fork about a half-mile downstream of the dye pour site.*

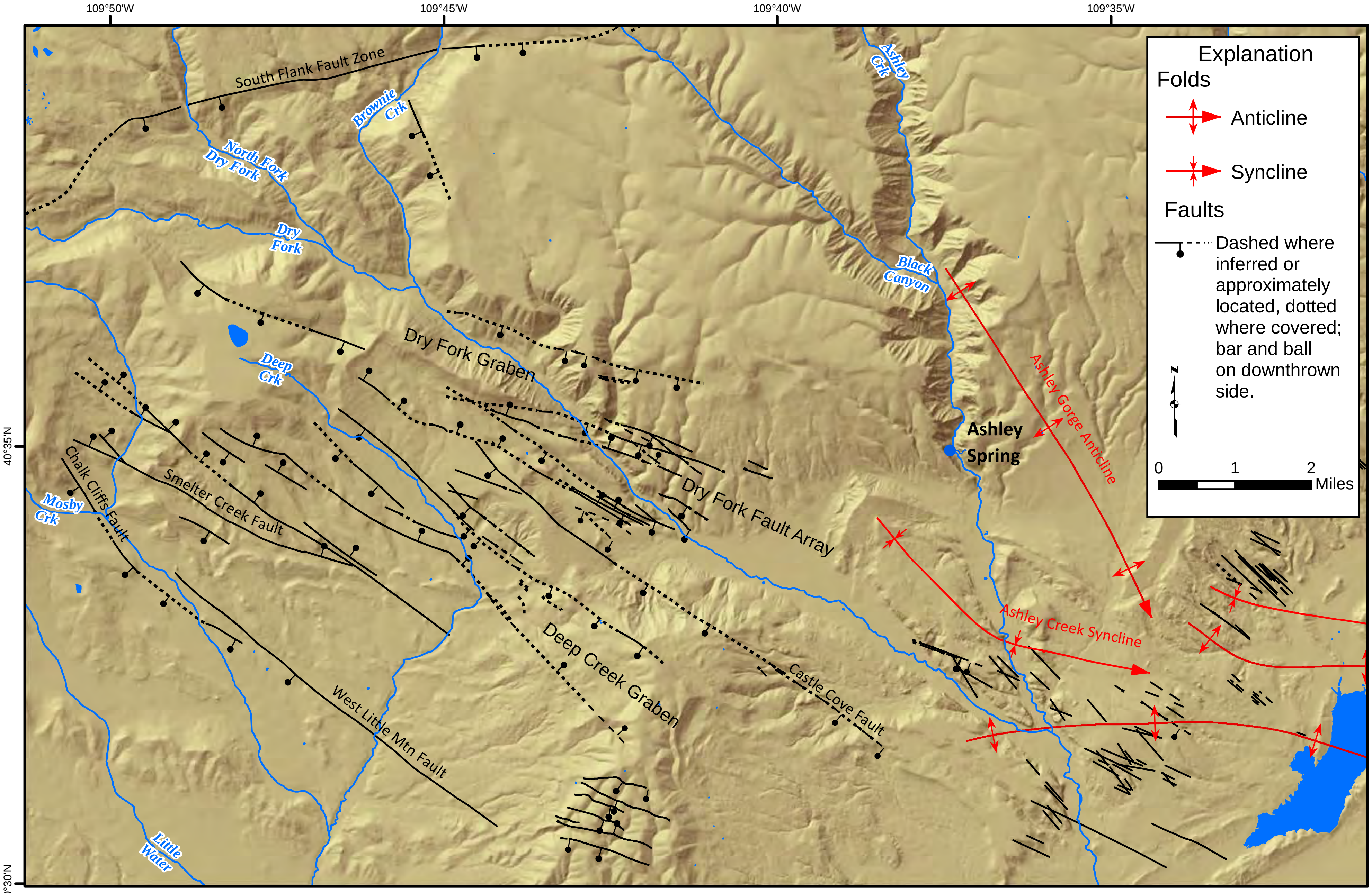


Figure 7. *Faults and folds in the study area. Modified from Haddox and others (2005), Sprinkel (2006), and Haddox and others (2010).*

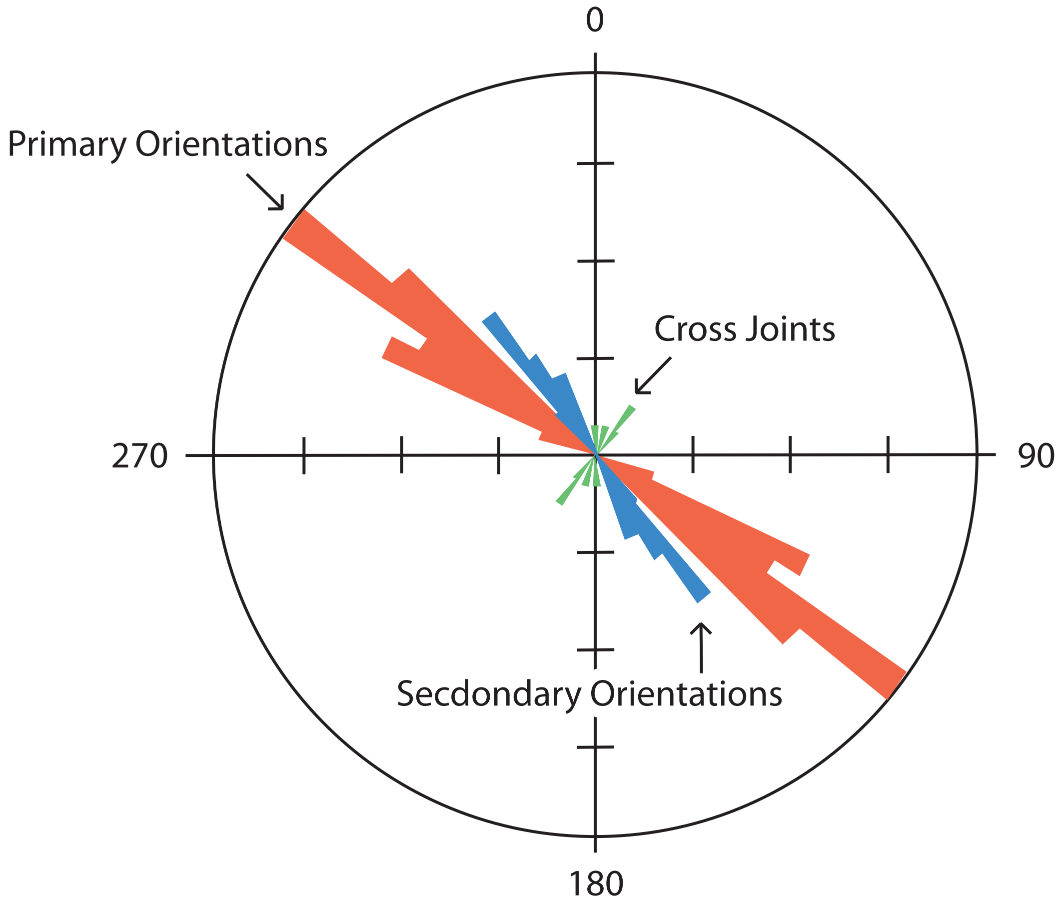


Figure 8. *Rose Diagram showing the joint orientations from Haddox and others (2005). The mean of the primary orientations is 314° +/- 8°.*

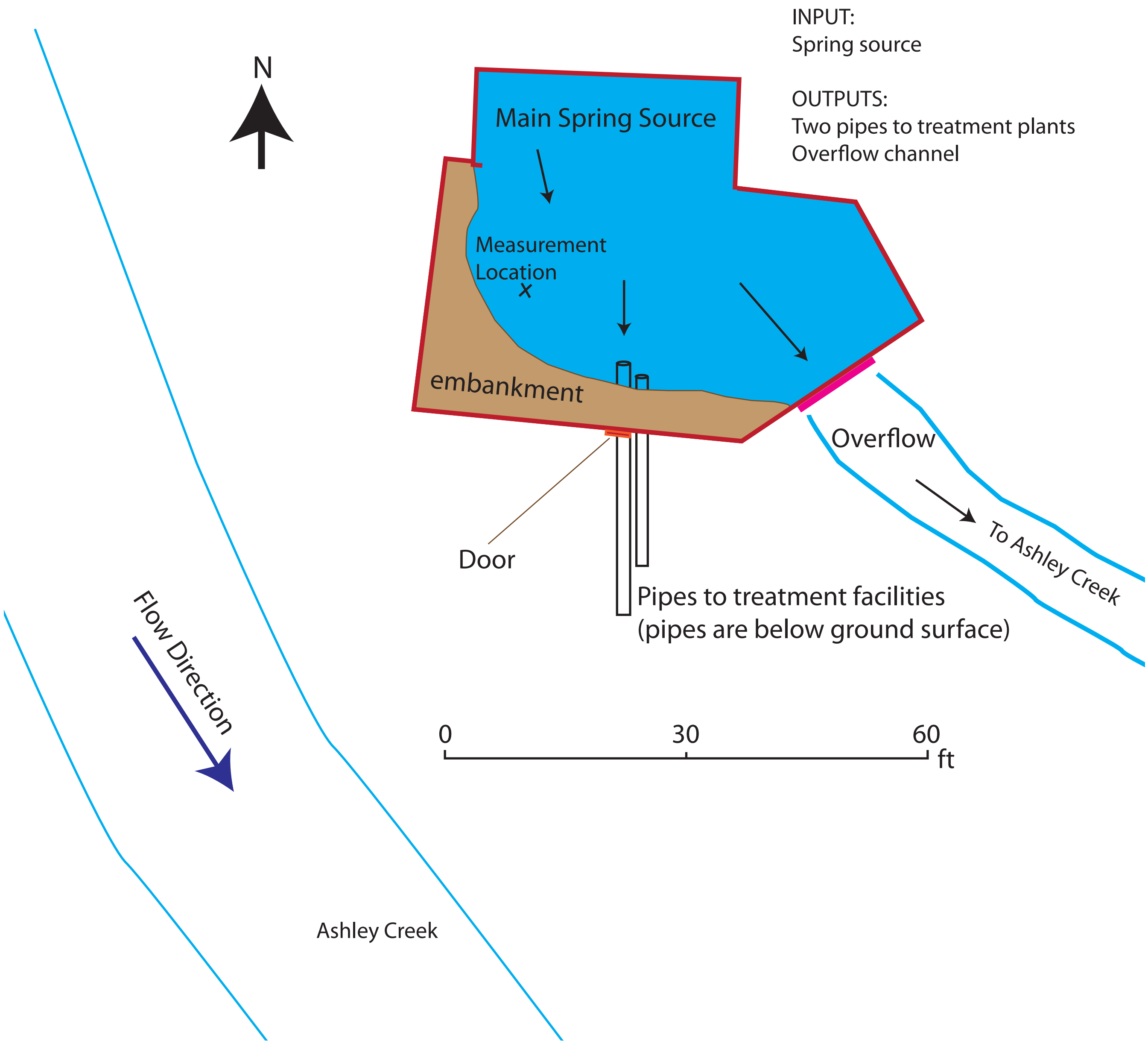


Figure 9. *Layout of inputs and outputs of water at the Ashley Spring house.*

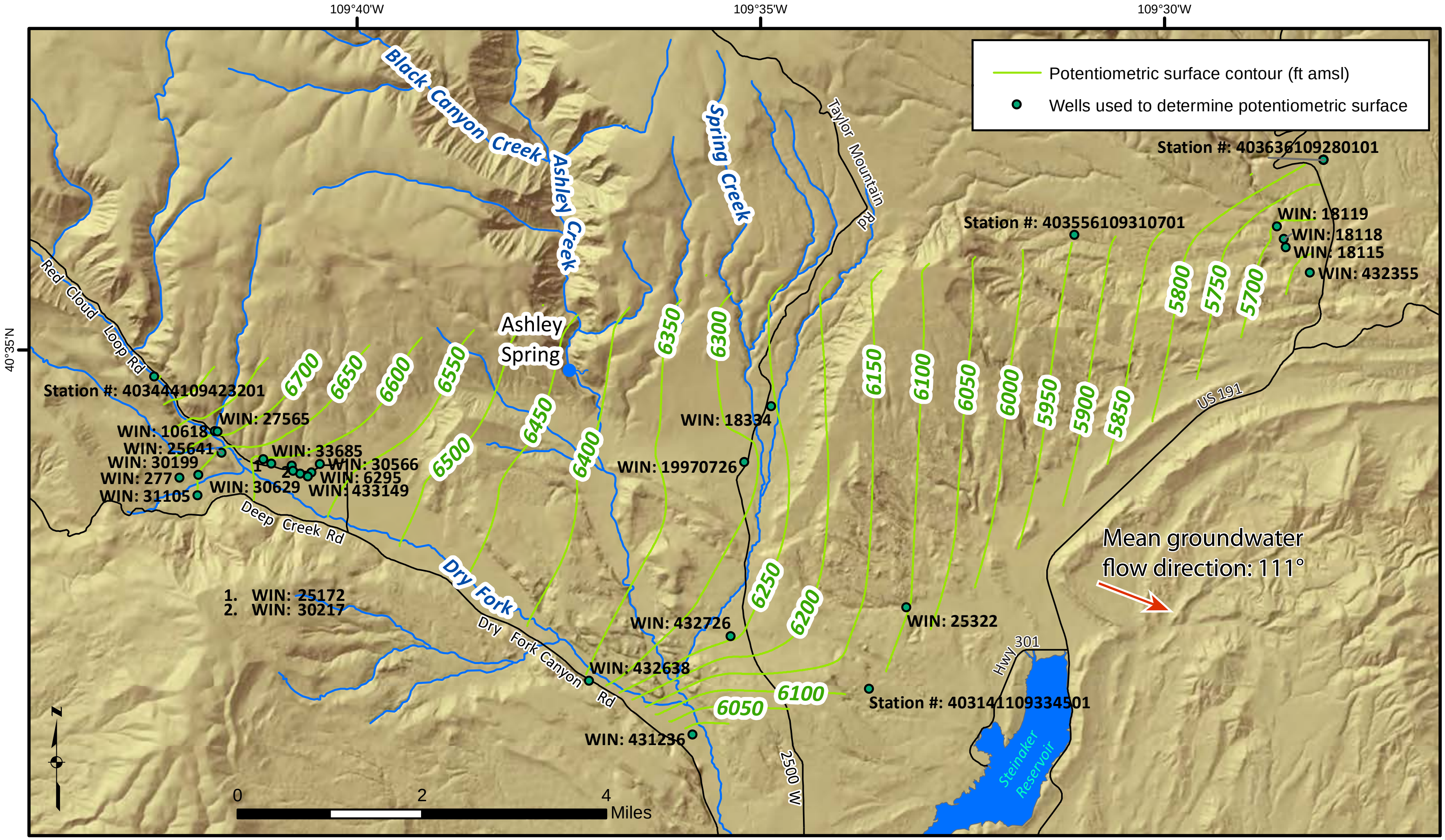


Figure 10. *Potentiometric surface map of the Weber Sandstone aquifer, contoured using elevation of water levels in wells in feet above mean sea level (amsl). The mean flow direction of 111 degrees from north (standard deviation = 25 degrees) is represented by the red arrow.*

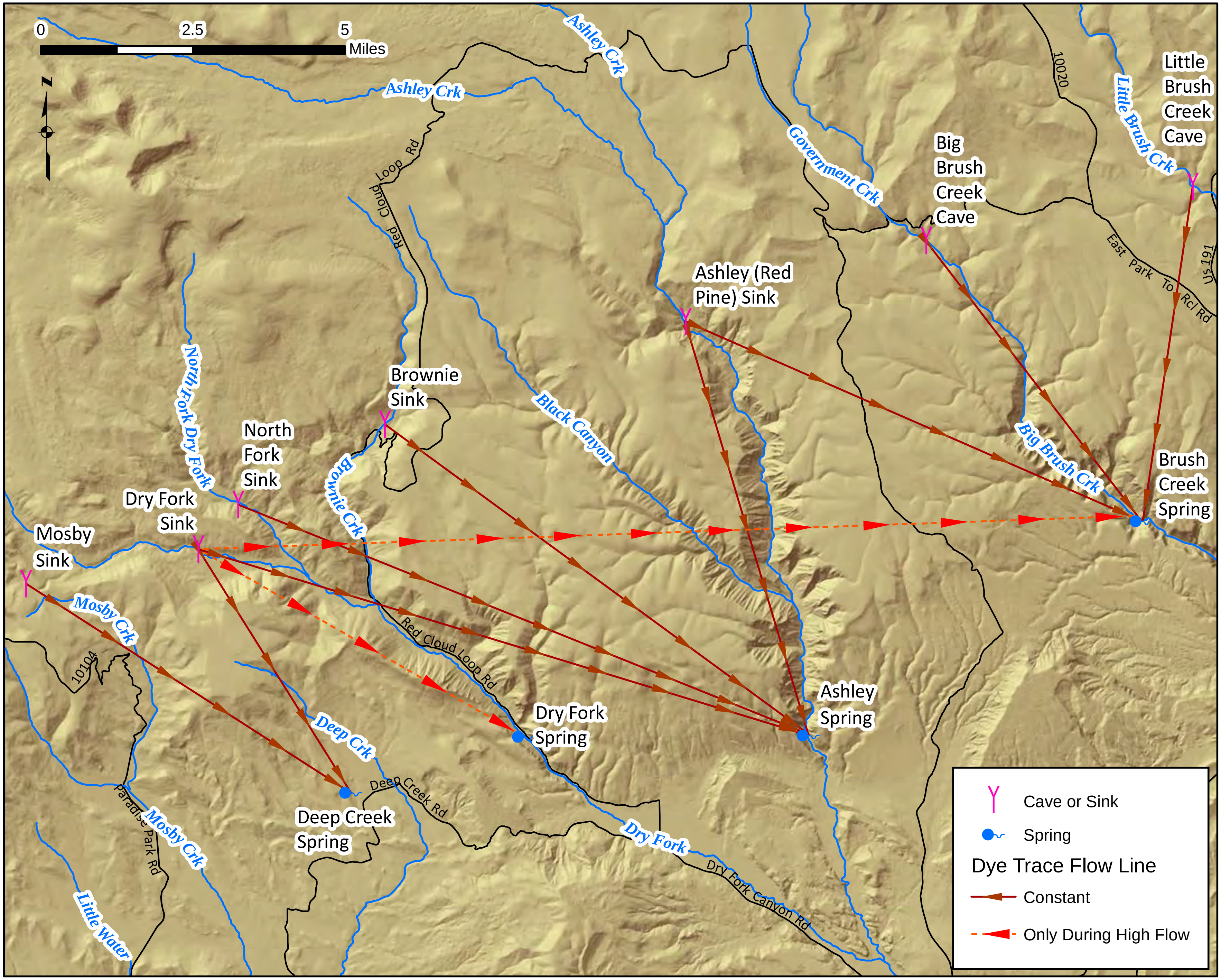


Figure 11. *Compilation of dye trace lines for the Deep Creek, Dry Fork, Ashley, and Brush Creek Spring basins (modified from Godfrey, 1985).*

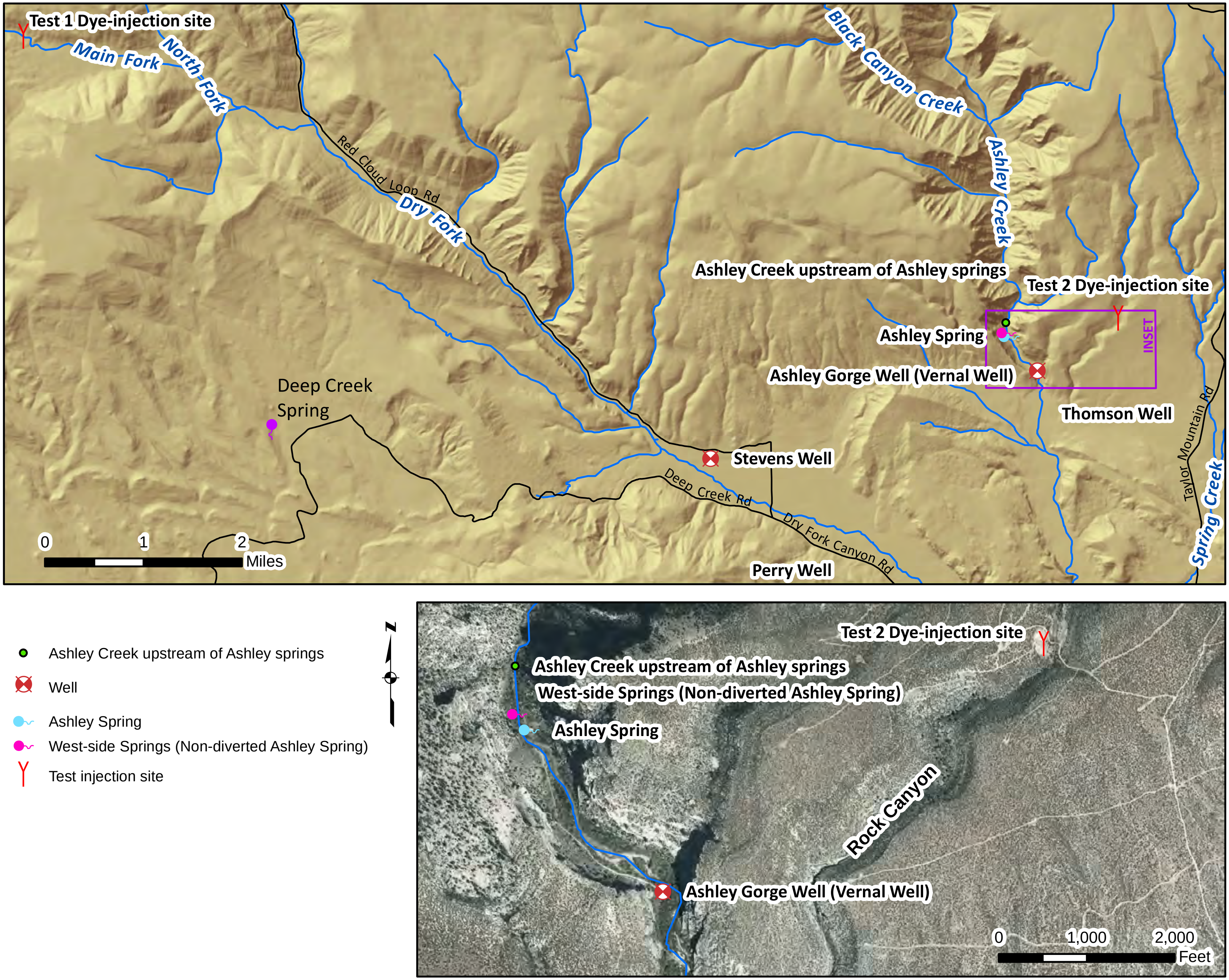


Figure 12. *Locations of dye pour sites and dye monitoring sample collection for dye tracer tests conducted in this study.*

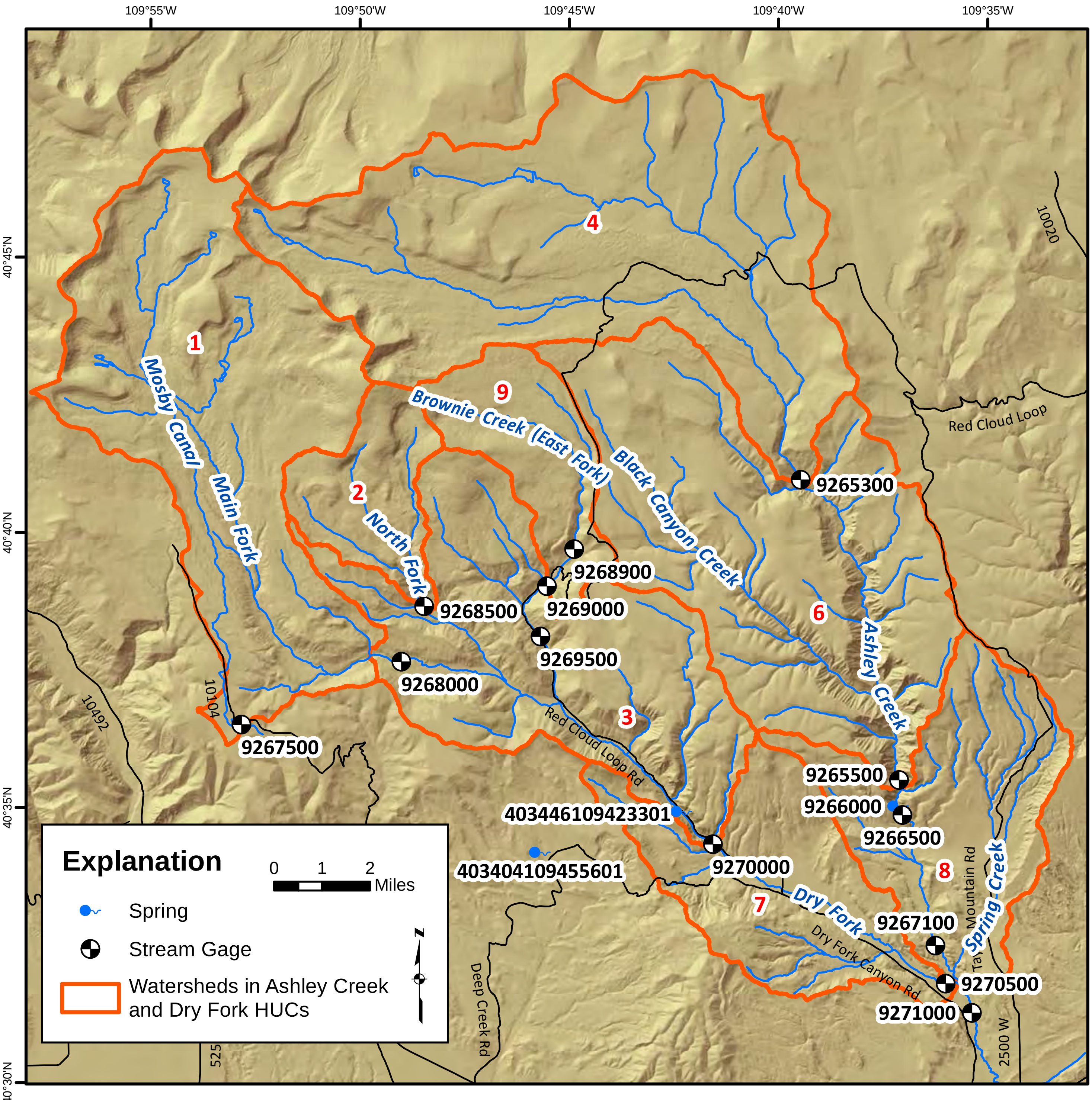


Figure 13. *Watersheds and gaging stations used to estimate water budget of Dry Fork and Ashley Creek basins.*

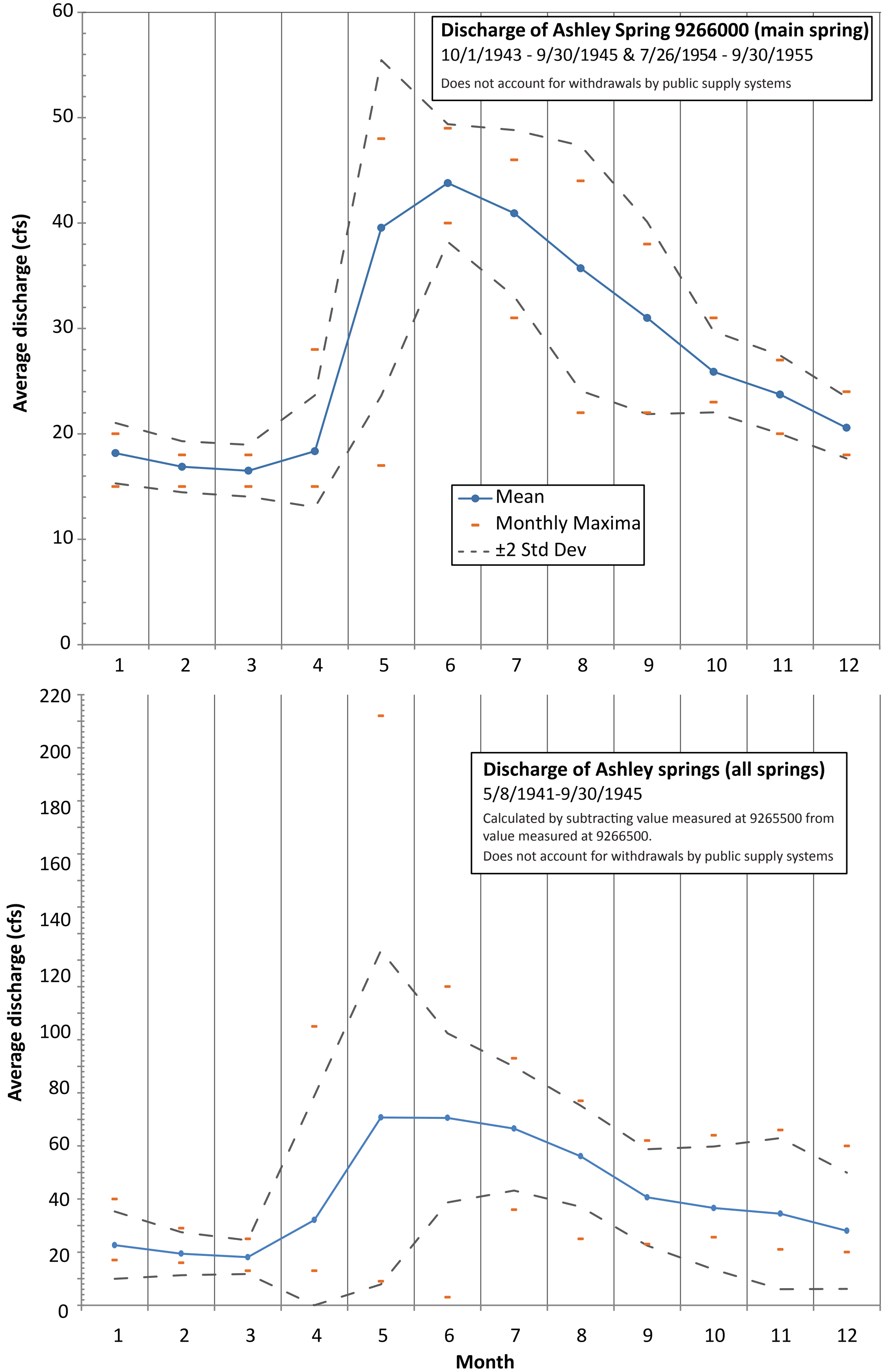


Figure 14. *Average monthly flow of Ashley Spring based on daily measurements of discharge (USGS, 2013).*

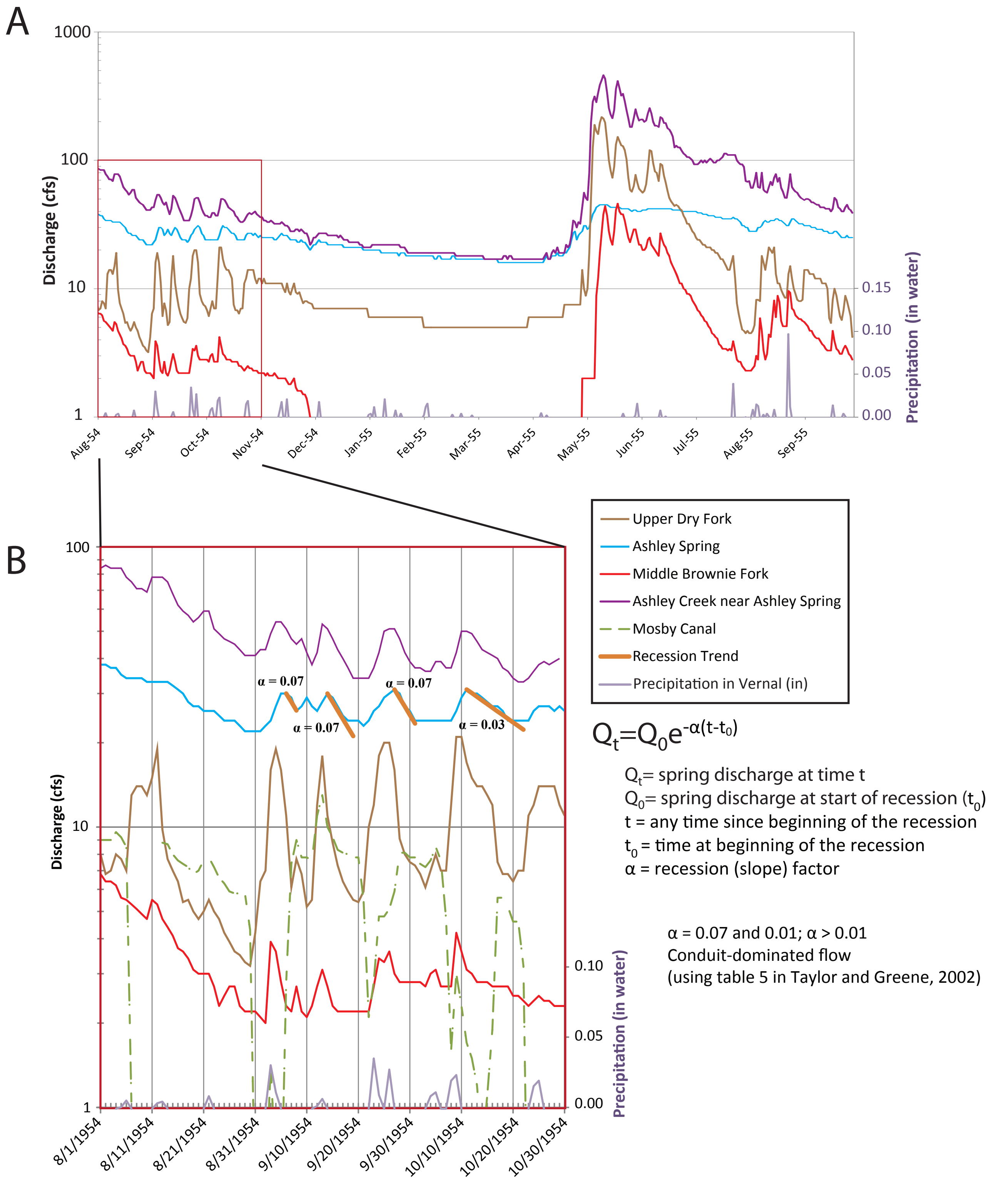


Figure 15. *A. Discharge data from various gages (USGS, 2013) in the study area. B. Slope analysis (Taylor and Greene, 2002) of Ashley Spring discharge recession.*

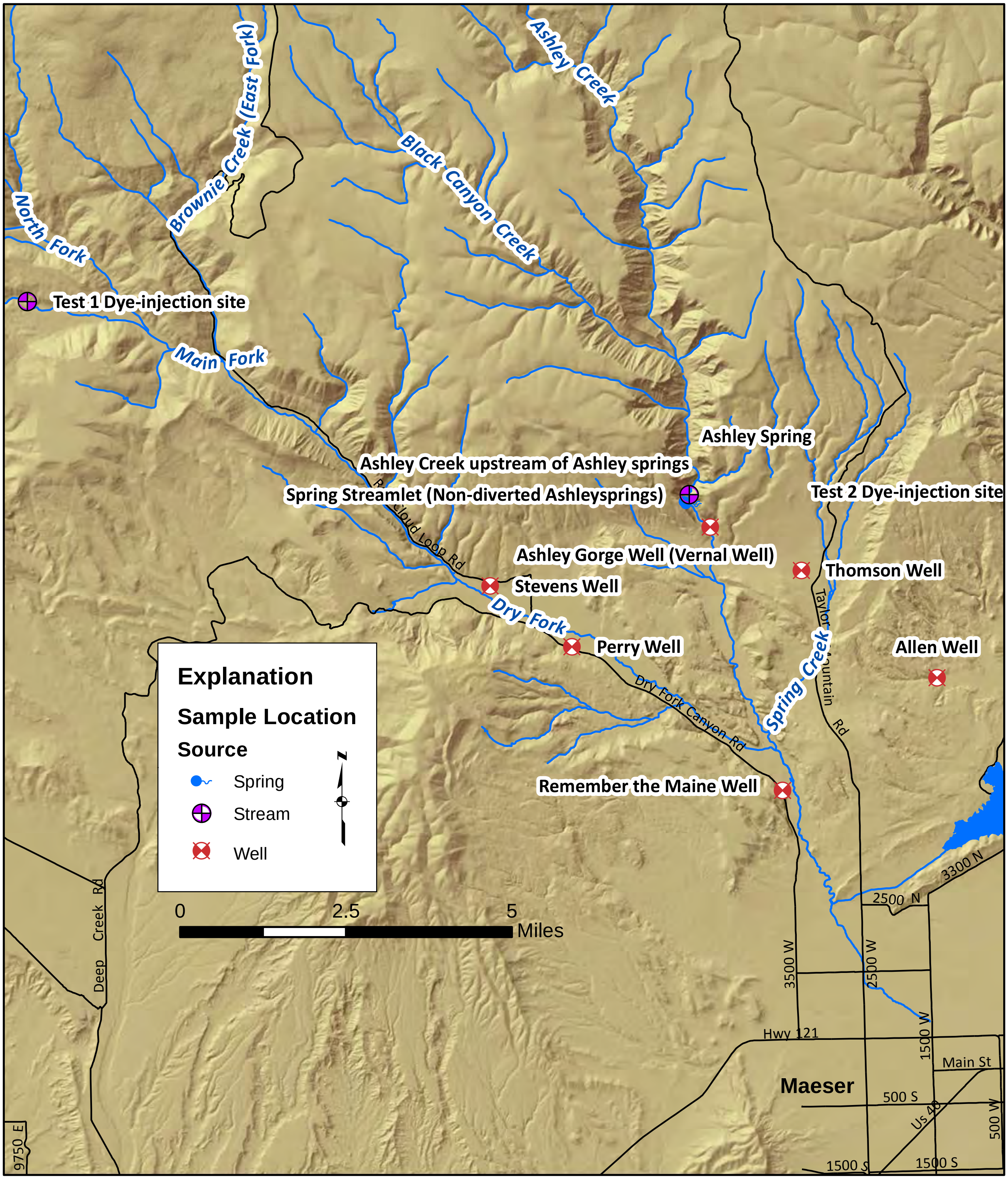


Figure 16. *Water chemistry sample sites for this study.*

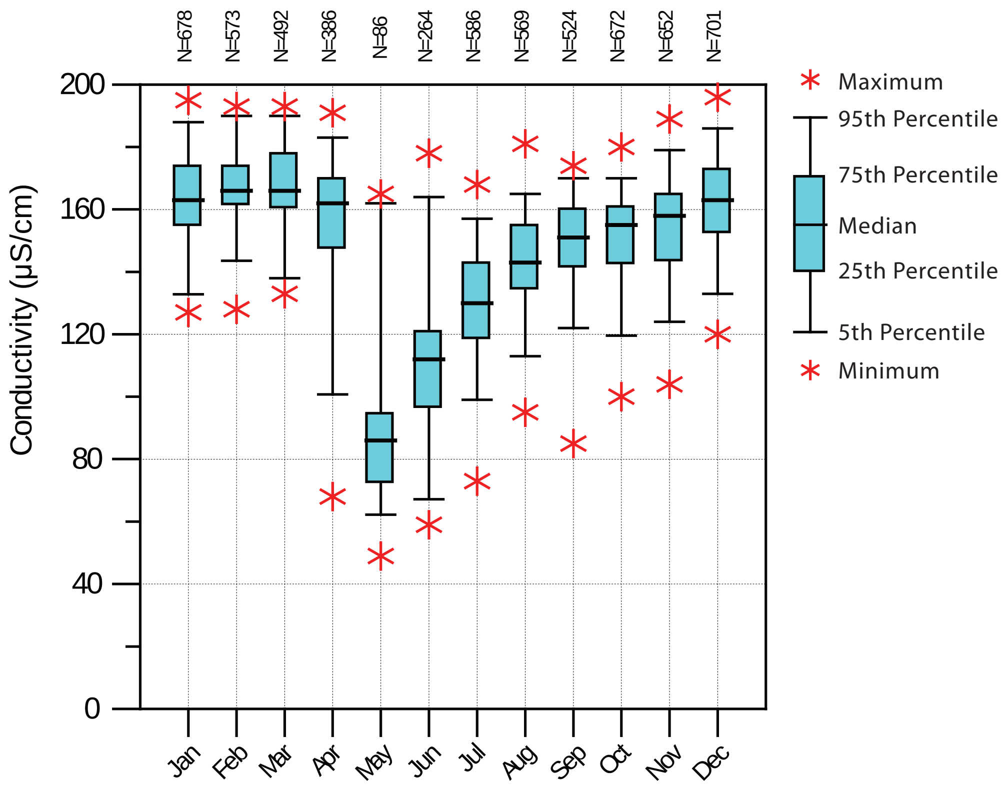


Figure 17. *Monthly statistics of daily water chemistry data of water from Ashley Spring collected by the Central Utah Water Conservancy District from 1987 to 2013. Relatively few samples exist for May because the water treatment plant used Red Fleet Reservoir as an alternative water source during this time.*

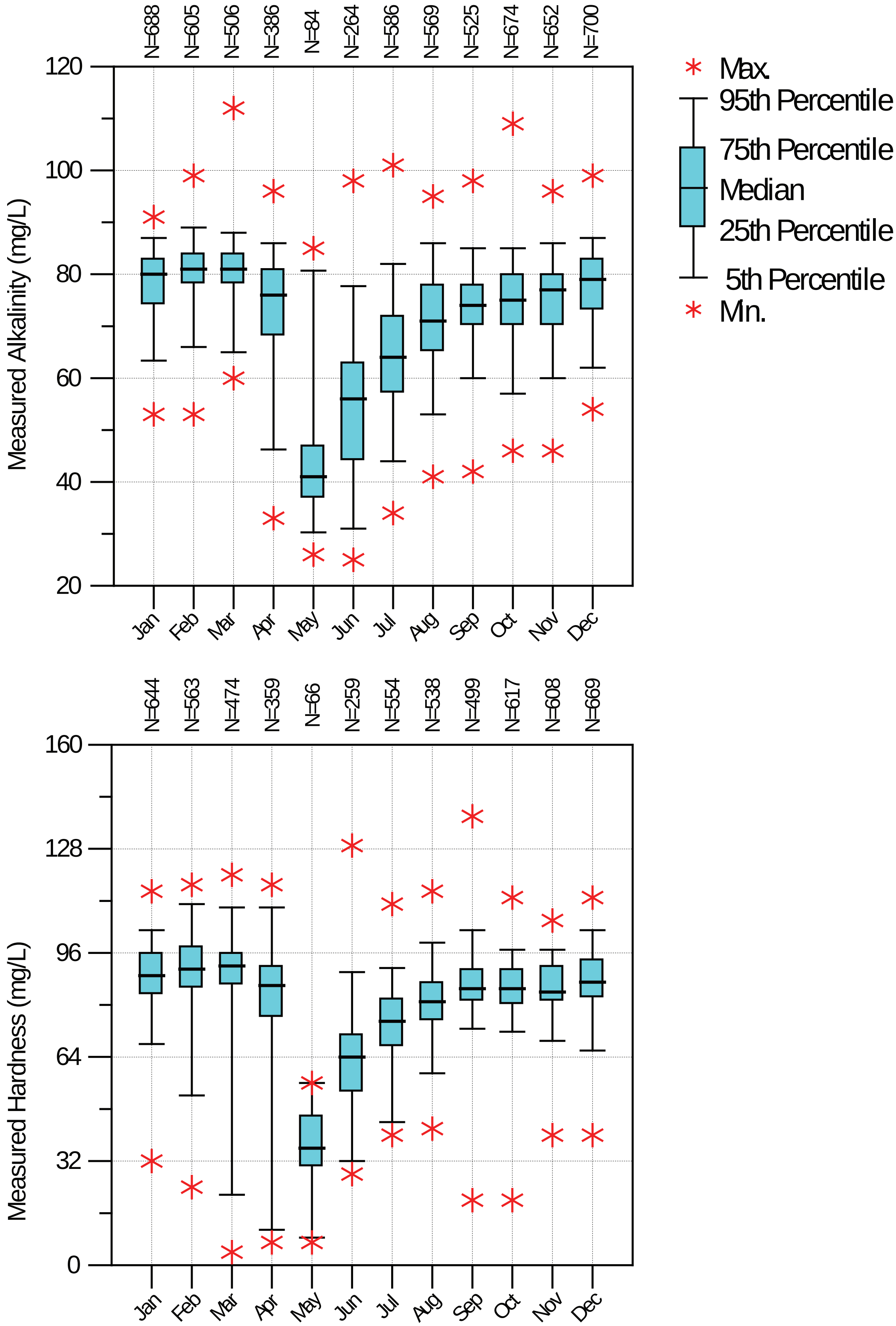


Figure 18. *Monthly statistics of daily water chemistry data of water from Ashley Spring collected by the Central Utah Water Conservancy District from 1987 to 2013. Relatively few samples exist for May because the water treatment plant used Red Fleet Reservoir as an alternative water source during this time.*

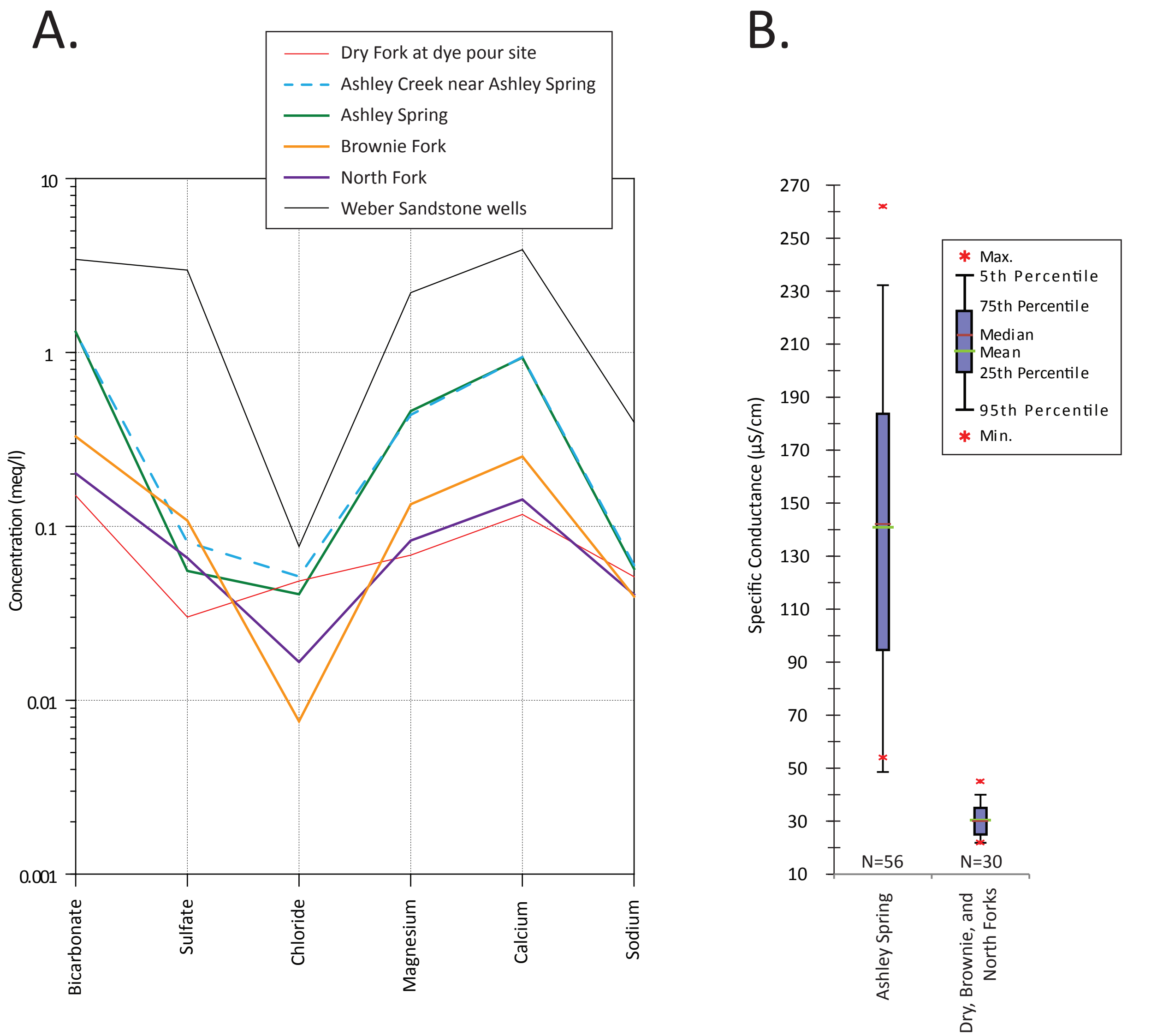


Figure 19. *A. Relative average concentrations of major ions of average water chemistry from various locations in the study area. Note that the concentration is in milliequivalents per liter and that the concentration scale is a log scale. B. Summary statistics of specific conductance of water for Ashley Spring and Dry, Brownie, and North Forks .*

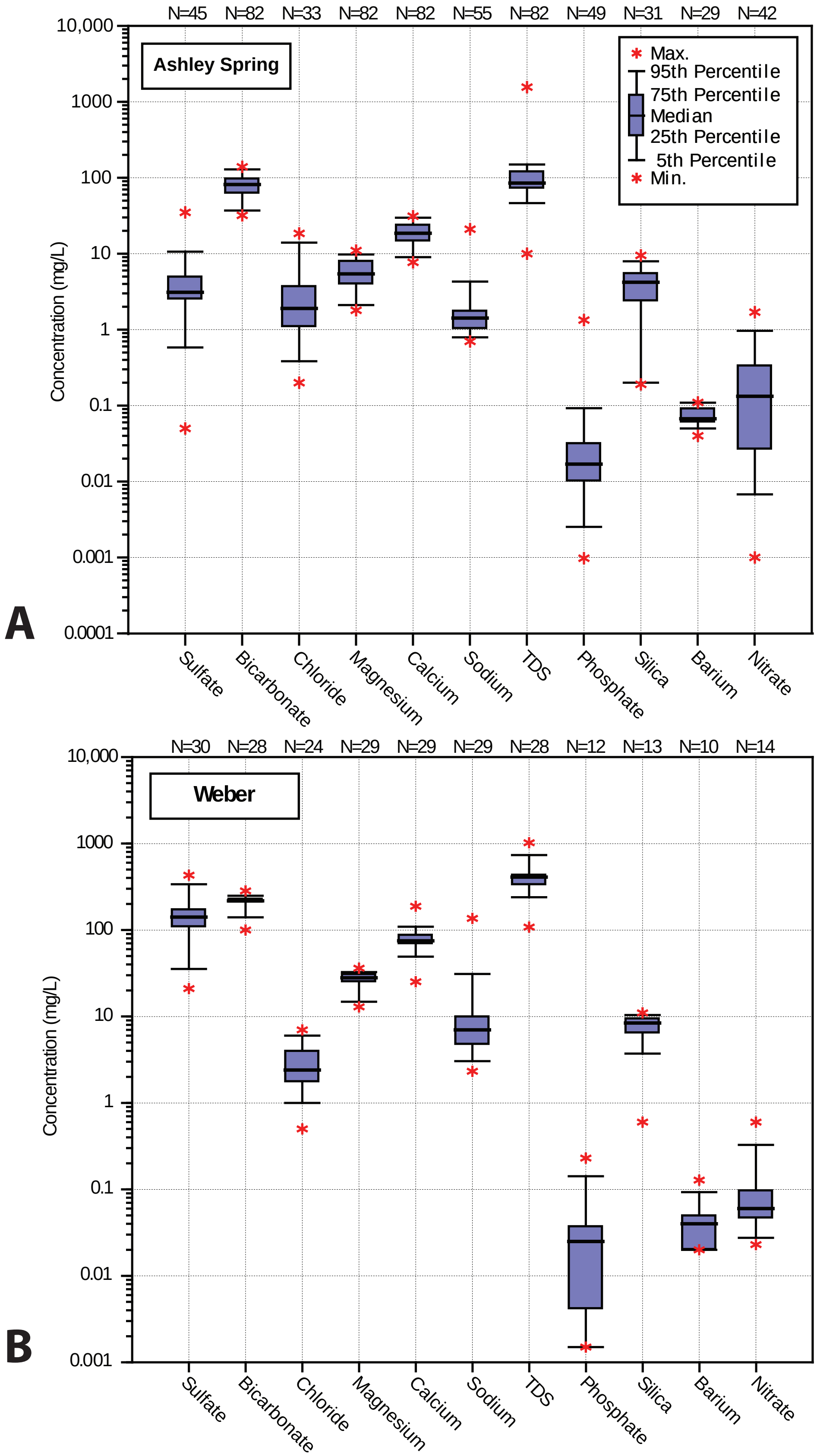


Figure 20. *Distribution of concentrations of major chemical parameters in A. Ashley Spring and B. Weber Sandstone groundwater.*

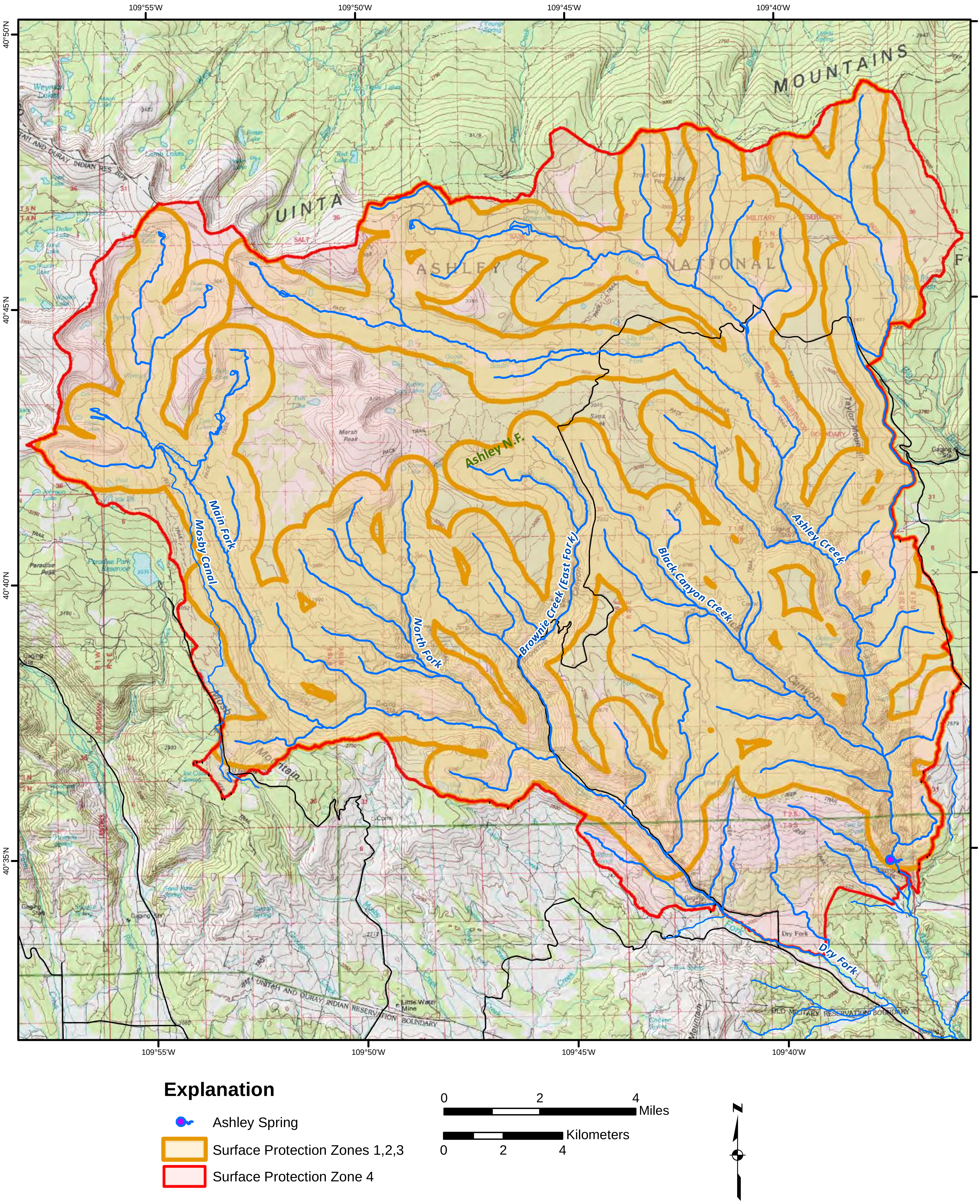


Figure 21. *Delineation of the surface water protection zones for Ashley Springs.*

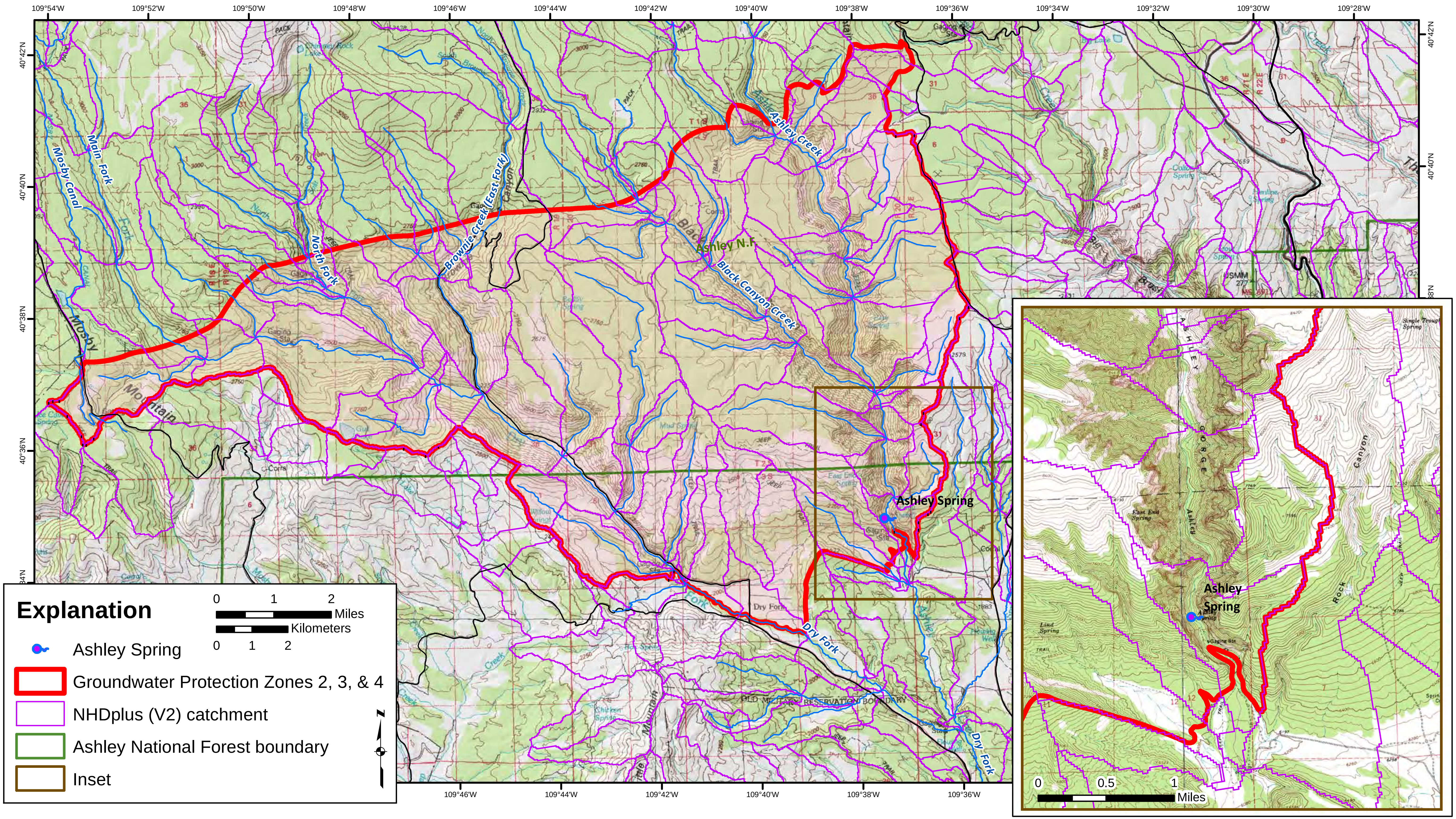


Figure 22. *Catchment boundaries (Horizon Systems Corporation, 2013) and groundwater source protection Zones 2, 3, and 4 for Ashley Spring.*