National Park Service
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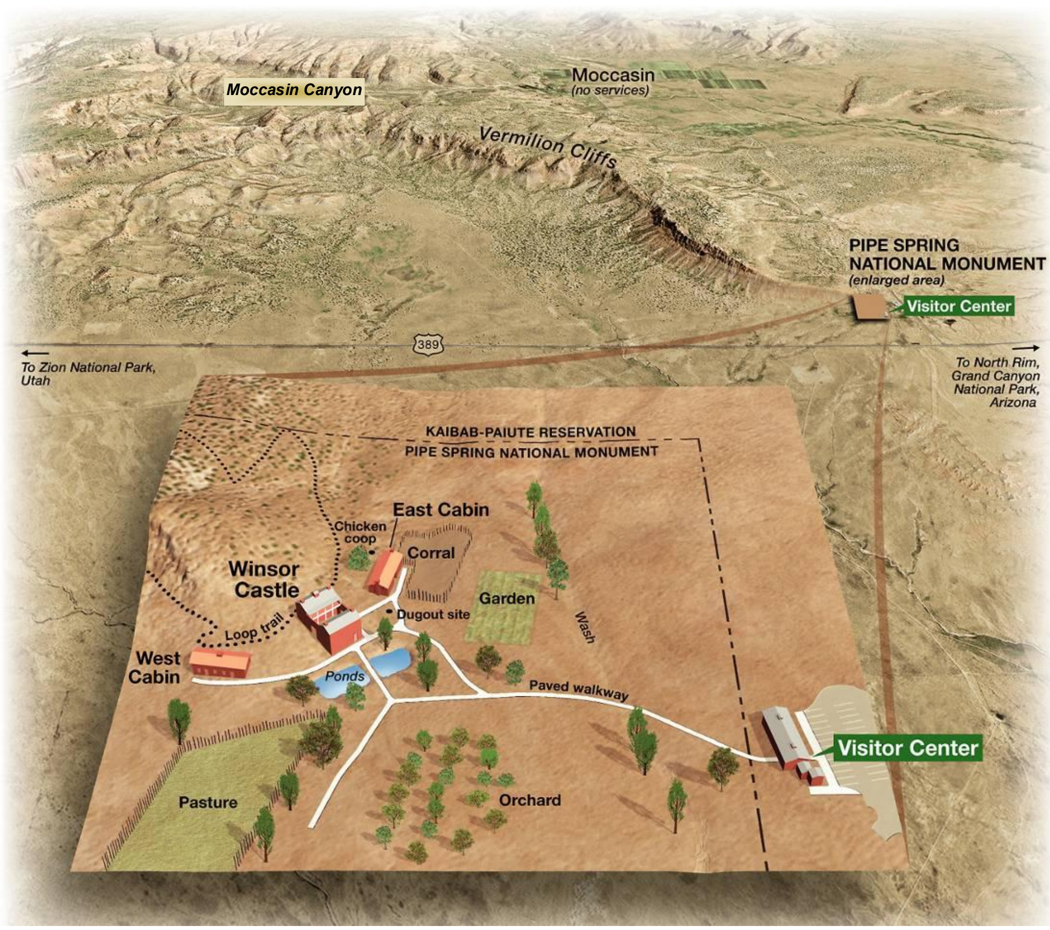
Water Resources Division
Ft. Collins, Colorado

Summary of Spring Flow Decline and Local Hydrogeologic Studies, 1969-2007

Pipe Spring National Monument

Natural Resource Report NPS/NRPC/WRD/NRTR—2007/365



ON THE COVER
Shaded relief map of the area surrounding Pipe Spring National Monument and cultural features at the monument.
Graphic by: National Park Service, Harpers Ferry Center

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U.S. Department of the Interior
National Park Service
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Executive Summary

In the late 1960s, the National Park Service (NPS) began investigating the potential for constructing a potable water supply well to replace or supplement water from Pipe Springs. At the time, it was generally understood that pumping groundwater from a well constructed into the Sevier Fault would ultimately affect flow from the springs, but after drilling five unsuccessful wells at other locations, there was no alternative left but to construct a well in the fault zone. A few years later, the Kaibab-Paiute Tribe constructed a water supply well in the same fault zone near the NPS well. Monument staff noticed a decline in flow from the springs in the mid-1970s, shortly after the NPS and Tribal water supply wells were put into production.

This report summarizes each of the hydrologic and geologic investigations that have been conducted over the past 30 years to determine the source of groundwater discharging at the springs and the cause of the spring flow decline. It also evaluates the future prospects for spring flow at the monument.

Geological investigations have provided a good understanding of the structural geology of the area and its effect on groundwater flow. Movement and offset of geologic formations north of the monument has created a trough of fractured bedrock that acts as a conduit to transport groundwater from north to south along the Sevier Fault zone. Some of the groundwater flowing along the fault zone emerges as springs at Pipe Spring National Monument.

Hydrologic monitoring data show a clear correlation between groundwater pumping and the decline of flow from the springs. Groundwater pumping by NPS and the Kaibab-Paiute Tribe has resulted in lowering the water table and is the primary cause of spring flow decline at Pipe Spring.

Discharge from the springs at Pipe Spring is likely to continue to decline if NPS and the Tribe continue to pump groundwater from their supply wells about a mile north of the monument. It is highly likely that the springs will eventually cease to flow if groundwater pumping continues. It is also likely that spring flow will increase if groundwater pumping from the NPS and Tribal supply wells is stopped.

Introduction

Pipe Spring National Monument staff first noticed a decline in flow from springs at Pipe Spring in the mid-1970s. Interestingly, these observations came shortly after the National Park Service (NPS) and Tribe had constructed water supply wells near the West Branch of the Sevier Fault, about 2 miles north of the monument. A great deal of time, money, and effort have been expended since then to identify the source of water discharging from the springs and the cause for the spring flow decline.

This report documents the development of groundwater in the area, the decline of spring flow, and summarizes each of the previous hydrologic and geologic studies that were conducted to try to better understand the local hydrogeology and the cause(s) of spring flow decline. Hydrologic monitoring data are summarized and discussed.

Pipe Spring National Monument is a 40-acre natural and historic site established in 1923 in northern Arizona. The springs discharge at the base of an escarpment known as the Vermillion Cliffs. The high ground to the north consists of layers of sandstone that capture and transport groundwater on top of lower impermeable layers. Springs occur where lateral movement by groundwater is blocked by faults or where impermeable rock has been removed by erosion. Both conditions occur at the monument where the Sevier Fault cuts directly through the historic site on a north-south trend. Rock layers are folded, fractured, and offset by the fault, forming a barrier to groundwater flow to the east and a conduit for groundwater to flow southward along the west side of the fault.

The monument was established in 1923 to protect the buildings and other structures and to preserve the history of the pioneer settlement founded in the 1860s. Archeological data confirms that the site was occupied by pre-Columbian cultures for thousands of years, including Basketmaker culture, ancestral Puebloans, and the Southern Paiute peoples. This long history of occupation is not surprising because these springs are one of the few reliable water sources in the region and the site provides commanding views across the Kanab and Kaibab Plateaus. The principal pioneer structure, “Winsor Castle,” was actually built over one of the springs to provide a secure source of water. The cooling waters from the spring were used in the production of butter and cheese at the pioneer settlement.

Water-bearing layers are largely absent from the geologic formations to the south of the monument. The vast expanse of plateaus all the way to the Grand Canyon is notable for the lack of surface water. The region is arid, and even where water-bearing strata occur, springs are a rare and valuable resource.

Billingsley et al., (2004) provide current, detailed geologic mapping of the area. Their report includes concise descriptions of the geologic setting, stratigraphy, structural geology, faulting, and the geologic controls on the location and hydrology of springs in the area.

Water supplies for NPS and the Kaibab Paiute Tribe facilities in the vicinity of Pipe Spring are provided by groundwater pumping from wells about two miles north of the monument. New development in the past decade, and concomitant water use, includes irrigated lawns at a new park and pow-wow grounds at Kaibab, new housing, new administrative offices for both NPS and the Tribe, and a gas station and convenience store.

Groundwater Development North of Pipe Spring

In the mid-1960s, reconstruction and rerouting of Highway 389 past Pipe Spring was completed. Shortly thereafter, the Tribe began to make plans for a commercial development at the intersection of Highway 389 and the access road to the monument. It quickly became apparent that the Tribe's one-third share of the water from spring discharge was insufficient for their existing needs and planned development. Furthermore, up to that time, the Tribe had used water from the spring for irrigation and stock watering; the Tribe's development plans required a source of potable water. Thus, it was not only the increased amount of water, but the kind of water that necessitated a major change in the water supply and distribution system that was shared by the monument and the Tribe (McKoy, 2000).

In the summer of 1969, the Tribe began construction of a new office building. The Tribe also had plans for construction of a motel, campground, and trading post; all of which required potable water. The need for addressing the water supply issue for both the Tribe and the monument had reached a critical point. By mutual accord, it was decided (as a temporary solution only) that the Tribe would tap into the pipeline that transported water from the springs to the Tribe's reservoir (the "Indian pond"). The water would require treatment before it could be used for potable purposes. The agreement bought the NPS additional time to wrestle with the problem and to work with the Tribe to find a permanent solution (McKoy, 2000).

The NPS initiated a program of water exploration and construction of one or more wells to meet the needs of both the monument and the Tribe. In 1969, NPS requested the USGS to conduct a study to identify potential alternative sources and locations for a well to supply groundwater for a joint NPS-Tribal water system. Southwest Regional Office officials gave the project top priority. The goal was to locate an alternate water source that would supply the Tribe's entire planned complex as well as potable water supply for the Park Service. Water flowing from Pipe Spring then could be used for "natural development of the oasis like quality of the area" (Geerdes, 1970). Basic considerations were that the well needed to be as close to the monument as possible, it needed to yield at least 50 gallons per minute, and no reduction in flow of Pipe Spring would be tolerated (i.e., it could not tap the same water source from which Pipe Spring flowed). Consultation by Bill Fields with Geologist William F. Mildner of the Soil Conservation Service confirmed his suspicions that a well drilled along the Sevier fault in the vicinity of the monument would most likely affect the flow from Pipe Spring. Mildner thought that water could be obtained from the alluvial fill adjacent to Twomile Wash (northeast of the monument) without impacting Pipe Spring.

In the spring of 1971 the USGS, under the direction of the Park Service drilled 5 test wells in the alluvium along Twomile and South Moccasin Washes (Figure 1). These test wells were either dry or produced poor-quality water (McGavock, 1974). A sixth test well was then constructed to test the Navajo Sandstone along the Sevier Fault. This well (T-6, aka NPS Well) produced abundant water and was completed as the water supply well for the monument. It has been the

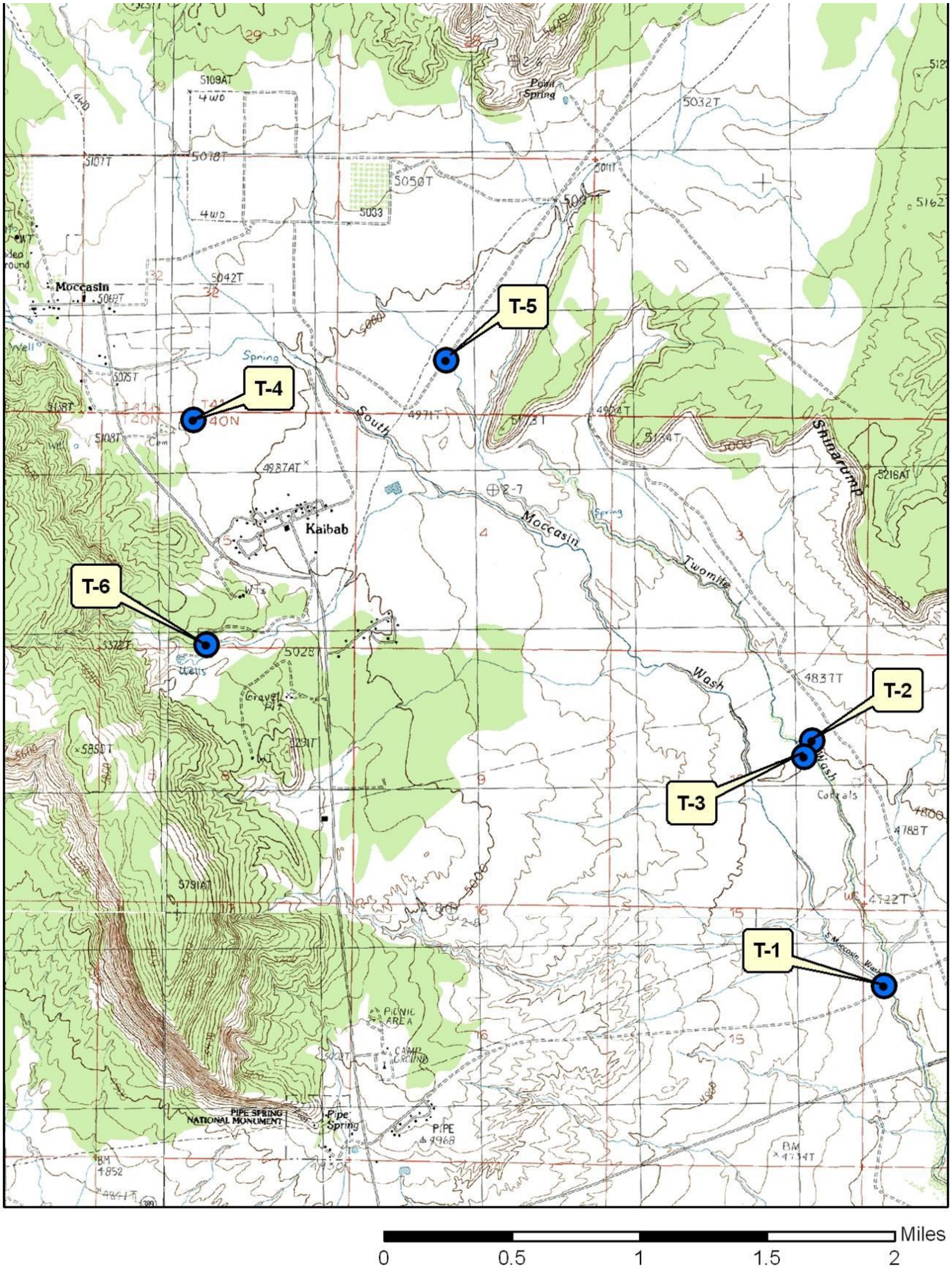

Figure 1. Location of NPS test wells drilled in 1971.

sole source of potable water for the monument since the water system was completed in June 1973.

It appears that despite warnings that pumping groundwater from the fault zone would likely cause spring flow to decline, the supply wells were constructed there anyway. The first five test holes failed to produce acceptable quantity and quality of water. Lack of success and knowledge of local hydrogeologic conditions left them with no alternative but to construct a well in the fault zone.

By 1975, the Tribe had determined that the original well at Kaibab Village (Figure 2) was no longer adequate (McKoy, 2000). A test well was drilled about 1300 feet northeast of the NPS well (on the hill near the current location of the water storage tanks southwest of Kaibab Village), but it reportedly was dry at a depth of 290 feet and was abandoned. A second test well was drilled to 155 feet about 700 feet southwest of the NPS well and was completed by perforating the 6-inch steel casing from 92-142 feet (Tribal Well No. 1). Tribal Well No. 1 has not been pumped for many years, probably since 1980. The well still exists and is occasionally used as a monitoring well, but a bend in the casing prevents installation of a pump. The Tribe constructed a second well at this location (700 feet SW of the NPS well) in 1980 (Tribal Well No. 2). Tribal Well No. 2 is 250 feet deep and has three 10-foot sections of 0.040” well screen from 156-166, 176-186, and 196-206 feet below ground surface (WRD files and McKoy, 2000). Tribal Well No. 2 has been the sole source of water for the tribal water system since it was constructed. The locations of wells discussed in this paragraph are shown on Figure 2.

In 1975, the BIA constructed two test wells (discussed in greater detail in a later section of this report, “Bureau of Indian Affairs (1976)”). One of test wells is located about ½ mile south of Moccasin. Although it produced a good amount of water, it apparently has never been utilized. It is labeled as “USGS Monitoring Well” on Figure 2. The second test well was located about a mile north of Moccasin and produced several hundred gpm. It is one of the wells labeled “Tribal Irrigation Wells” on Figure 2. It has been used as an irrigation supply well by the Tribe. At some later time, a second irrigation well was constructed in the same general area, about a mile north of Moccasin.

Although the NPS water supply well (T-6 on Figure 1) and the Tribal Well No. 2 (Figure 2) are located only about 700 feet apart (Figure 13), they supply two completely independent storage and distribution systems. The systems can be interconnected if either well is inoperative, but under ordinary circumstances the two systems are operated independently. The NPS well pumps water to a buried 500,000-gallon reservoir located about a half mile south of the NPS well. Water from the NPS well is then distributed to the NPS facilities at the monument, the Tribal-NPS partnership visitation center, and Tribal facilities including; the multi-purpose building, the NPS-leased administration building, campground, Red Hills Village, Tribal Court building, Red Cliffs gas station and convenience store, and the Tribal administration building. The Tribal well pumps water to storage tanks with a combined capacity of about 100,000 gallons on the hilltop about 1000 feet northeast of the NPS well. Water from the Tribal well is used primarily to supply the water needs at Kaibab Village and Juniper Village.

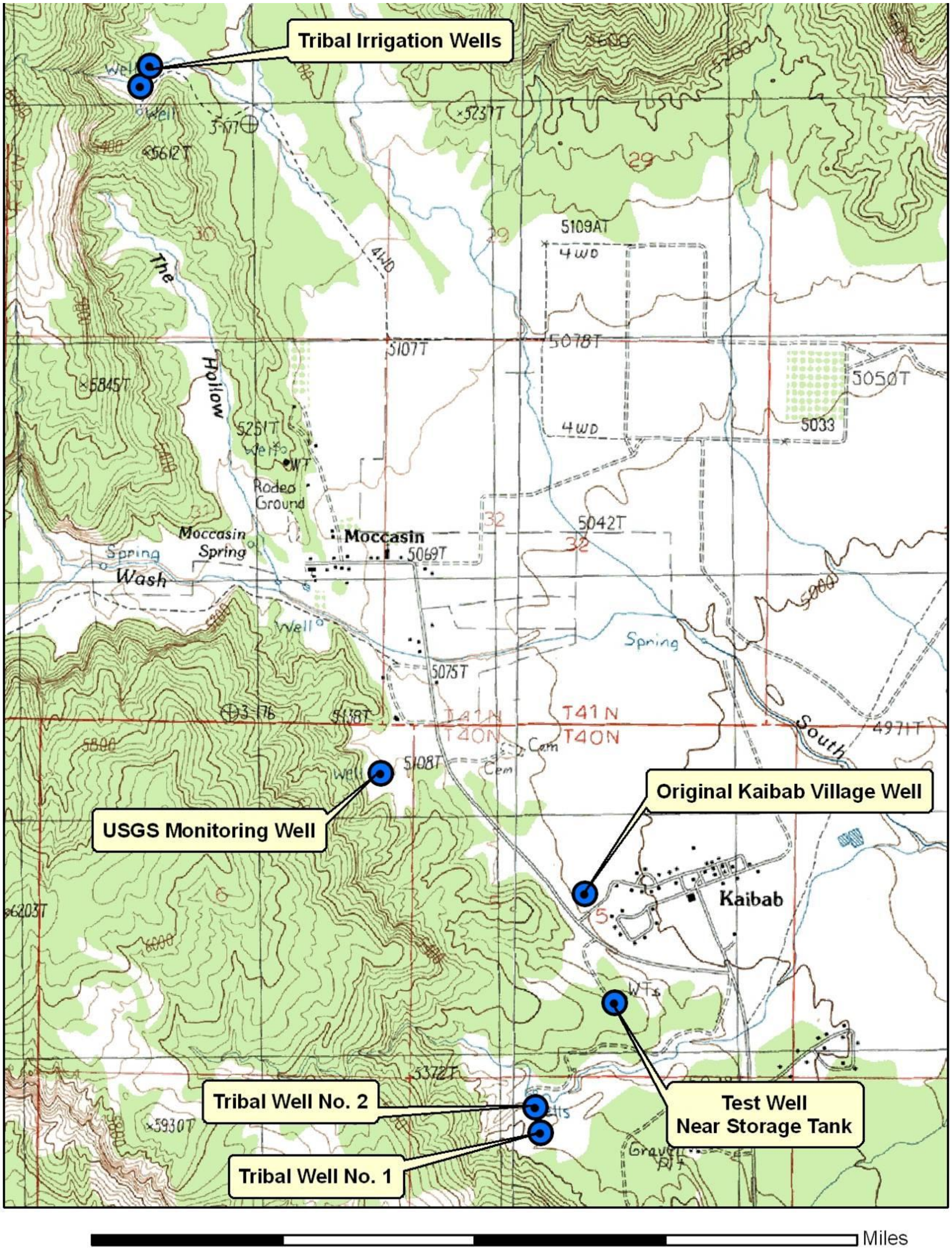

Figure 2. Location of Tribal test wells and supply wells.

Inventory of Wells North of Pipe Spring

In addition to the NPS and Tribal potable supply wells, the Tribe has two irrigation wells along the Sevier Fault about a mile north of Moccasin. The irrigation wells have been used on an intermittent basis; pumped heavily in some years and not pumped at all in other years.

Groundwater records in the USGS National Water Information System (NWIS) database, http://waterdata.usgs.gov/nwis/gw, were searched to identify wells in the vicinity of Pipe Spring. The USGS database contains records for 14 wells (Table 1). The list includes the NPS and Tribal potable supply wells and one of the Tribe's irrigation wells north of Moccasin. Six of the wells (located in Section 31) are probably privately owned wells in Moccasin, but it's impossible to be certain as the USGS database does not include ownership information. The remainder are test wells or are wells that are no longer used.

The Arizona Department of Water Resources (ADWR) well registration database was searched for records of wells in the area (http://imagedrec.water.az.gov). The search area included all of Townships 40 and 41 North and Range 4 West, a total of 72 square miles. The search returned records for 20 wells (Table 2). Five of the well registration permits in the list were for monitoring wells that were planned for construction by NPS as part of an investigation of a leaking underground storage tank at the park. These wells were never constructed. The NPS potable supply well and the monitoring well between the park and the potable supply well are included in the list.

The agreement between the lists of wells obtained from ADWR and USGS is poor. Only 4 wells appear on both lists. The 30 wells on the combined lists probably represent a fairly complete inventory of wells in the area.

Table 2 includes 13 privately-owned wells in the Moccasin area. Pumping capacity of these wells range from 20-420 gpm and represent a potentially large, and unaccounted for, withdrawal of groundwater from the hydrogeologic system in the area. Additional investigation of these wells would be needed to determine which wells are completed in the alluvium of Moccasin Wash and which wells are completed in the Navajo Sandstone or other bedrock aquifers. Tribal wells are not included in the ADWR database.

Domestic water use in Moccasin would probably be a very small component of the overall water budget of the area because of the small population; however, irrigation water use could be significant. The amount of irrigated acreage has not been determined. Some of the irrigation water in the Moccasin area might be provided by flow from Moccasin Spring. Some of it is provided by pumping from wells. Some of the wells are completed in the Navajo Sandstone or other bedrock aquifers and some are completed in the alluvium along Moccasin Wash. We can not assess the potential impact of irrigation use on the local groundwater flow system (with any degree of accuracy) without additional information regarding the source of irrigation water and the amount of irrigated land at Moccasin and Tribal land to the north and east of Moccasin.

Table 1. Basic information for wells in the USGS database in the vicinity of Pipe Spring and Moccasin.

Aquifer*	Total Depth Feet	Land Surface Elevation Feet	Lat Long DMS	Cadastral Location Twn-Rng-Sec	Comments
NVJO	200	5080	36-52-36 112-44-25	B-40-04 17ACC	NPS Monitor Well
ALVM	100	4820	36-53-10 112-42-25	B-40-04 10ACA	T-2, 1971 test well
MNKP	100	4810	36-53-10 112-42-28	B-40-04 10ACB	T-3, 1971 test
NVJO	155	5080	36-53-24 112-44-55	B-40-04 08BAB	Tribal potable supply well
NVJO	205	5080	36-53-25 112-44-52	B-40-04 05CDD	NPS potable supply well
SRMP	99	5020	36-53-47 112-44-43	B-40-04 05ACC	Kaibab Village Well
KYNT	202	5140	36-54-03 112-45-28	B-40-04 06AAC	1975 BIA Test Well No. 1 (USGS monitor well)
ALVM	95	5120	36-54-24 112-45-34	B-41-04 31DDB	Private well at Moccasin
ALVM	120	5110	36-54-33 112-45-45	B-41-04 31DBA	Private well at Moccasin
ALVM	80	5120	36-54-35 112-45-37	B-41-04 31DAB	Private well at Moccasin
NVJO	80	5140	36-54-40 112-45-41	B-41-04 31ACD	Private well at Moccasin
ALVM	70	5170	36-54-46 112-46-40 Incorrect Lat-Long	B-41-04 31ACA	Private well at Moccasin
ALVM	110	5200	36-54-52 112-45-42	B-41-04 31ABD	Private well at Moccasin
NVJO	309	5240	36-55-40 112-46-05	B-41-04 30CDC	1975 BIA Test Well No. 2 (Tribal irrigation well)

*Aquifer Abbreviations

ALVM - HOLOCENE ALLUVIUM
NVJO – NAVAJO SANDSTONE OF GLEN CANYON GROUP
KYNT - KAYENTA FORMATION OF GLEN CANYON GROUP
SRMP – SHINARUMP MEMBER OF CHINLE FORMATION
MNKP - MOENKOPI FORMATION

Table 2. Wells recorded with Arizona Department of Water Resources

ADWR Well Reg. #	Cadastral Location Twn-Rng-Sec	Completion Date	Owner	Depth, Feet	Comments
55-526126	B-40-4-17AAC	11/2/1989	NPS	200	Monitor well, 1 mile north
55-547325	B-40-4-17DDB	1995?	NPS	LT 40	Not Constructed
55-547326	B-40-4-17DDB	1995?	NPS	LT 40	Not Constructed
55-547327	B-40-4-17DDB	1995?	NPS	LT 40	Not Constructed
55-547328	B-40-4-17DDB	1995?	NPS	LT 40	Not Constructed
55-547329	B-40-4-17DDB	1995?	NPS	LT 40	Not Constructed
55-611159	B-40-4-5CDD	2/24/1973	NPS	205	NPS potable supply well
55-518690	B-41-4-31DDA	11/15/1987	Owen Johnson	295	150 gpm
55-526741	B-41-4-31CAA	6/6/1990	Moccasin Water District	150	145 gpm
55-527559	B-41-4-31BCA	4/6/1990	I. McKay Heaton	140	----
55-528195	B-41-4-31BCB	6/16/1990	I. McKay Heaton	160	420 gpm
55-556288	B-41-4-31DAD	12/20/1996	Keith Iverson	108	----
55-621237	B-41-4-31ADB	6/20/1973	Ivan McKay Heaton	200	60 gpm
55-621238	B-41-4-31AAC	2/30/1972	Ivan McKay Heaton	150	50 gpm
55-621499	B-41-4-32CCC	1/26/1972	Melvin C. Heaton	70	175 gpm
55-624434	B-41-4-31DAC	3/--/1972	J. Grant Heaton	95	100 gpm
55-648424	B-41-4-31ADB	4/--/1972	Derryll Heaton	100	20 gpm
55-649200	B-41-4-32CB0	7/14/1978	Bernard Tracy	130	25 gpm
55-650645	B-41-4-31ADC	1967?	Moccasin Water Assoc.	80	20 gpm
55-651144	B-41-4-31DBA	1966	J. Grant Heaton	123	----

Spring Flow Measurements

Spring flow data have been reported for three distinct locations at Pipe Spring (Figure 3). West Cabin Spring is a small, undeveloped spring discharging on the hillside above West Cabin. It is about 400 feet west of Winsor Castle. Tunnel Spring is a horizontal adit that was constructed into the hillside between 1902 and 1907 to capture diffuse spring flow. Main Spring and Spring Room Spring are really part of the same spring outlet, the cistern in the courtyard of Winsor Castle. Water is piped from the cistern to the Spring Room and to Main Spring. Main Spring is outside the castle walls.

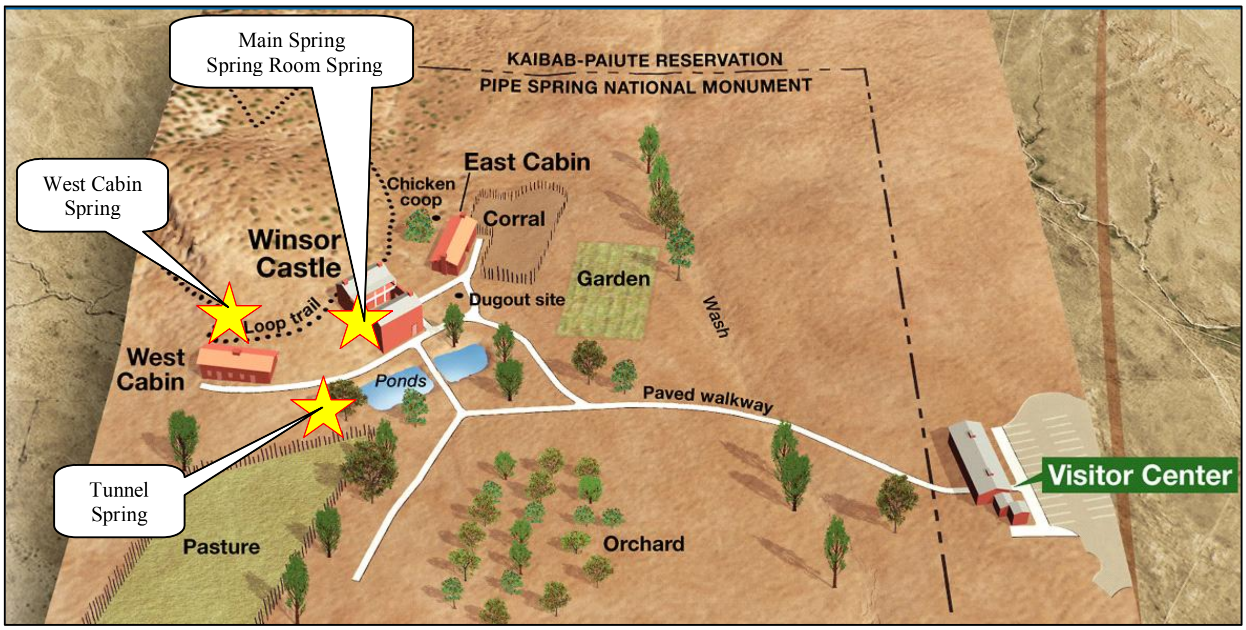

Figure 3. Spring flow monitoring locations at Pipe Spring.

Discharge from springs at Pipe Spring has occurred for some time as indicated by marsh deposits that have been radiocarbon dated to 210±40 years ago (Beta Analytic Inc., 2001 and Cummins et al., 2001). Records indicate that the Tunnel Spring adit extended more than 200 feet into the hillside when it was originally constructed in 1902-1907, and when it was inspected and repaired in 1933 and 1934 (Heaton, 1933). The thin rock and soil cover near the adit entrance collapsed over the years, so when the entrance was stabilized in 1987 only about 140 feet of the adit remained (Herr, 1987). Continued instability of the adit forced a major reconstruction of the outer part of the adit in 2000 and 2001. The first 94 feet of the adit was excavated and concrete walls and ceiling were poured. Caving and collapse of the tunnel prevented entry or stabilization in the remainder (56 feet) of the adit, where most of the water enters the tunnel. A steel culvert was driven through the rubble pile at the end of the stabilized section of the adit to provide a conduit for water to flow from the back end of the tunnel to the reconstructed part of the tunnel.

Winsor Castle was built over the original location of the primary spring at Pipe Spring. The original spring orifice appears to have been under the floor boards of the parlor room. At some time in the past (perhaps as early as the 1880s), a cistern was constructed outside the front door of the parlor room to provide more efficient collection of water. Flow from the cistern was conveyed to Spring Room Spring (discharging to a trough in the cheesemaking room) and Main Spring (aka Big Spring) located about 20 feet west of Winsor Castle. Flow from both Main Spring and Spring Room Spring has flowed through ditches to discharge into the historic masonry ponds since the 1880s.

Prior to 1977, there were very few measurements of the flow from the springs. The earliest reported NPS measurements reported a flow of 42 gpm in September 1933 and 43 gpm in May 1934. Later measurements reported 35 gpm on March 12, 1959, 38 gpm on July 2, 1969, and 32 gpm on August 6, 1976 (Barrett and Williams, 1986). Levings and Farrar (1979) reported a measured the flow of 35 gpm on July 27, 1976. It is not known if these reported flows represent the cumulative discharge from all of the spring outlets or if it is only the flow from the springs at Winsor Castle.

In July 1976, a routine spring flow monitoring program was initiated. Discharge measurements were made at each of the springs (Main and Spring Room Spring, Tunnel Spring, and West Cabin Spring) at approximately the same time each month. The data showed a steady decrease of total spring flow of about 2 gpm per year for the period from July 1976 through June 1986 (Figure 4). Spring flow stabilized at approximately 20 gpm from 1985-99. Measurements were not available from September 1999 to September 2003 while Tunnel Spring and its associated collection and measurement devices were being rebuilt. Since September 2003, total spring flow at the monument has averaged around 13 gpm.

The NPS spring flow monitoring program measures flow at West Cabin Spring, Tunnel Spring, Main Spring, and Spring Room Spring. Flow from Main Spring and Spring Room Spring are added together and reported as the combined flow of water obtained from the cistern in the courtyard of the Castle.

Figure 4 shows the monthly spring flow data for each of the springs. Most of the decreased outflow from the springs from 1976-85 was a result of declining flow from the courtyard cistern to Main Spring and Spring Room Spring. Total flow was fairly steady from 1986-90. After 1990, flow from Tunnel Spring increased and flow from the courtyard cistern decreased. In mid-1999, flow from the courtyard cistern ceased and there has been no natural flow at Main Spring or Spring Room Spring since then. A system of pumps and pipes has been constructed to pump water from Tunnel Spring to Main Spring and Spring Room Spring to recreate the historical scene. About 90% of the total spring flow at Pipe Spring now occurs from Tunnel Spring. Flow from West Cabin Spring has remained fairly steady between about ½-1½ gpm throughout the monitoring period.

It is a little easier to illustrate the spring flow patterns at Pipe Spring by looking at the total combined flow from all of the springs (Figure 5). Some of the “spikiness” has been removed from the data by plotting it as a 3-month running average. The flow data for each month is the average of the previous month, the current month, and the following month. These data show an annual pattern with highest flow in late-winter to early-spring and the lowest flow in summer to early-autumn. Several years of above average precipitation (and therefore greater recharge to the aquifer system) may partially explain the slowing of the rate of decline during the 1990s.

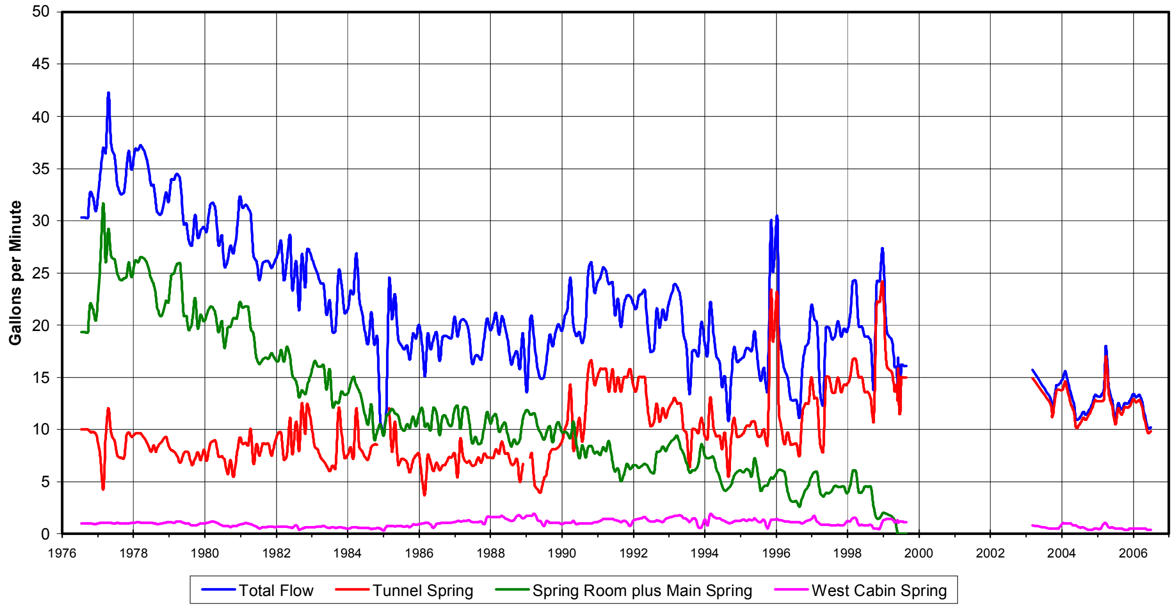

Figure 4. Spring flow at Pipe Spring National Monument.

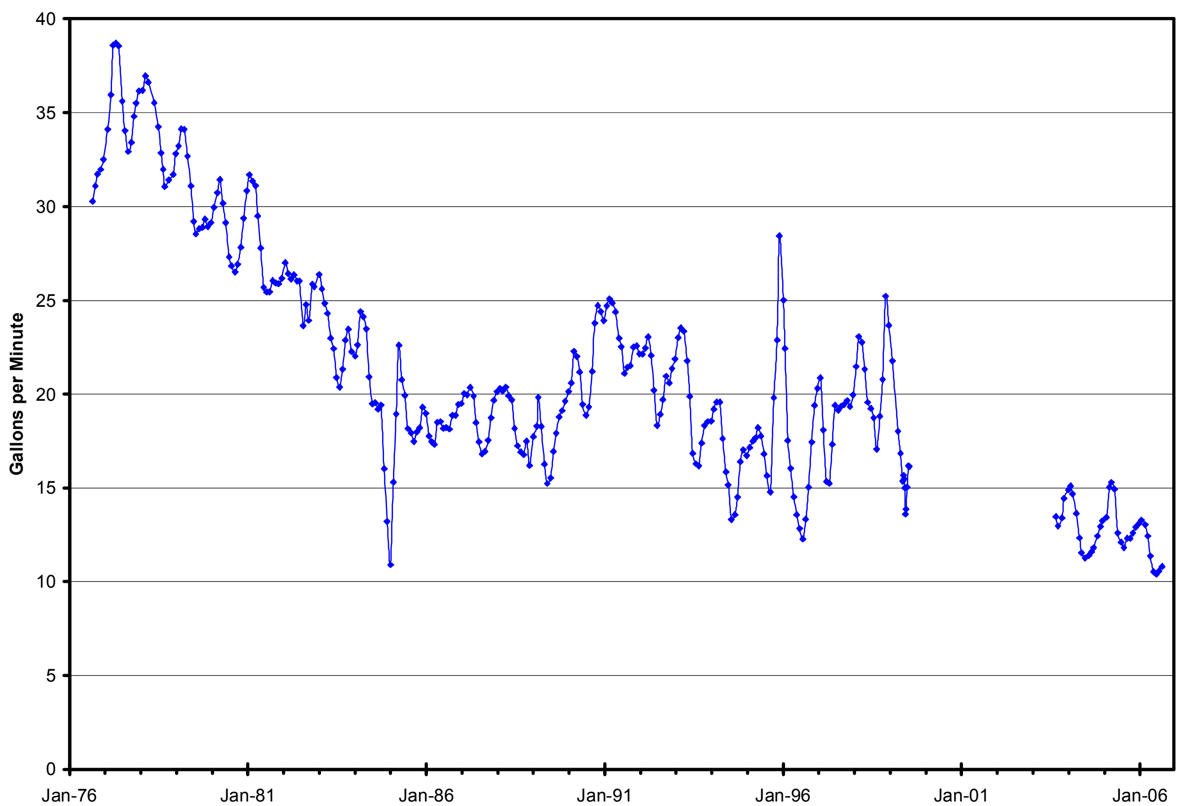

Figure 5. Total spring flow at Pipe Spring National Monument, three month running average.

It was not possible to monitor spring flow during (and for some period after) the reconstruction of Tunnel Spring until the new weir box was installed at the mouth of the tunnel. Regular monthly monitoring resumed in September 2003. Since then, total flow has varied from 10-15 gpm. There is a continuing trend of decreasing spring flow.

Summaries of Previous Reports and Investigations

The following sections contain summaries of the results and inferences of the many memos, letters, and reports describing the hydrology and geology of the Pipe Spring area. The date following each author's name in the section heading is the date of publication of the report, which may be several years after completion of the field studies.

Mildner (1969)

William Mildner, with the Soil Conservation Service, prepared a two-page memo with recommendations for a proposed test well for Pipe Spring National Monument. He recommended constructing a well in the alluvium along Twomile Wash near Kaibab Village. Mildner offered the opinion that a well constructed near the Sevier Fault in the Navajo Sandstone would be likely to affect the flow of Pipe Springs.

Levings (1974)

During 1972-74, Gary Levings (hydrologist, USGS) conducted an investigation to evaluate the quantity and quality of groundwater available from the Shinarump Member of the Chinle Formation and the potential for development of groundwater from the Navajo Sandstone in the vicinity of Kaibab. Apparently he did not produce an official report, but did perhaps issue his findings in the form of a memo report, as his work is invariably cited by subsequent investigators as "written communication."

Levings concluded that water from the Shinarump Member contained excessive concentrations of sulfate, but that groundwater from the Navajo Sandstone would be suitable for domestic use. Levings also stated that large-scale pumping of groundwater from the Navajo Sandstone near Moccasin or the monument might cause the spring flow in these areas to decrease.

McGavock (1974)

In the spring of 1971 the USGS supervised drilling and testing of six test wells in the area. The first three holes (Figure 1) were drilled to test the water-yielding characteristics of the alluvium along a perennial reach of Twomile Wash. The test holes each produced about 5 gpm of fair to poor quality water. It was hypothesized that the poor quality water was caused by gypsum beds in the underlying Moenkopi Formation.

Test wells 4 and 5 (Figure 1) penetrated 44 and 120 feet of alluvium along Moccasin Wash and were dry.

Test Well 6 (Figure 1) was located to test the water-yielding potential of the Navajo Sandstone where it has been fractured by the Sevier Fault. The well was drilled to 205 feet and produced about 150 gpm with 12 feet of drawdown after 24 hours of pumping. The water is of very good quality. A storage tank and water distribution system were constructed, and the well became the water supply for the monument and Tribal facilities south of Kaibab Village to Hwy. 389. These facilities include all potable and irrigation water for NPS purposes at the monument (residential and utility areas), the Tribal-NPS partnership Visitor Center, Tribal use at the multi-purpose building, leased NPS administration building, Tribal campground, Red Hills Village, Tribal Court building, Red Cliffs gas station and convenience store, and the Tribal administration building.

McGavock offered the opinion that, "The possibility of diminishing the flow of Pipe Spring at the monument by pumping 150 gpm from Test Well 6 is believed to be negligible owing to the 2-mile distance between the well site and Pipe Spring and the fact that the water is under unconfined conditions." [While this statement is true for short-term propagation of impacts to spring flow, it has no bearing on the long-term effect of groundwater pumping on the water budget and decline of spring flow.]

Currently, in Spring 2007, Test Well 6 is still the water supply for the combined NPS/Tribal water system for facilities south of Kaibab Village to Hwy. 389. In December 2006, a replacement well was constructed about 200 feet to the north because the original well is threatened by streambank erosion of the adjacent creek. Testing has shown that the new well has nearly the same production capacity and hydrologic characteristics as the original well. The new well will become the main supply well after testing and permitting have been completed. The old well will be retained as a monitoring well.

Bureau of Indian Affairs (1976)

The USGS and BIA conducted a study to inventory existing water resources on the Reservation and constructed two test wells in August 1975. Test well locations are shown on Figure 2. The first well was completed in the Kayenta Formation about a half mile south of Moccasin and has commonly been referred to as the "USGS Monitoring Well." The second well was completed in the Navajo Sandstone about a mile north of Moccasin and is one of the "Tribal Irrigation Wells." Both wells are located very close to the Sevier Fault where fracturing of the rocks causes larger permeability.

The USGS Monitoring Well was test pumped at 230 gpm for 31 hours with no indication the water level was drawn down to the pump intake at 167 feet below ground surface. We do not know how much drawdown occurred during pumping, only that it was less than 167 feet below ground surface. The static water level in the well was 80 feet below ground surface. The well was never used as a water supply source. Since 1975, the USGS has regularly monitored the water level in this well, and thus it has acquired the moniker of "USGS monitoring well."

The Tribal Irrigation Well was test pumped at 470 gpm for 17 hours, resulting in 29 feet of drawdown (from 58 to 87 feet below ground surface). Analyses of the pumping test data indicated the well could produce much more, perhaps 750 gpm. Furthermore, the authors opined that a more efficiently constructed well at this site would have less drawdown during pumping and could possibly produce more water.

The BIA report also evaluated the groundwater potential for the Shinarump Member of the Chinle Formation. There were five wells believed to obtain water from the Shinarump Member in or near the reservation. The wells produced between 10-150 gpm, but the water is poor quality. The water contains excessive amounts of sulfate, calcium, and sodium and is unsuitable for drinking without treatment. The five wells are not included in the inventory of wells on Tables 1 and 2. These wells are located several miles from Pipe Spring, mostly toward the northeast; they are not shown on maps for this report as they are of no consequence to the hydrology of Pipe Spring.

The BIA report offered the opinion that, “Large-scale pumping of groundwater from the Navajo Sandstone near the Pipe Spring National Monument and along the west branch of the Sevier Fault near Moccasin will decrease the flow of springs in these areas.”

Barrett and Williams (1986)

In September 1986, Barrett and Williams (NPS hydrologists) prepared a summary report of the hydrogeology, water rights, and evaluation of spring flow decline at Pipe Spring National Monument. They concluded that the spring flow decline was real and likely caused by the cumulative effects of groundwater pumping from wells along the Sevier Fault north of the monument, rather than related to natural variations in precipitation.

Analyses of monthly spring flow data collected by park staff showed that spring flow for the period 1977-86 declined an average of 2 gpm per year. Additionally, they showed that the decline was generally uniform between years; i.e., January flows had declined each year, February flows declined each year, etc.

Barrett and Williams also summarized the water rights situation and past water use agreements between NPS, the Tribe, and the Cattlemen’s Association. They identified data gaps that needed to be filled before sound management strategies could be developed. Their recommended approach to determine the cause(s) of spring flow decline included: 1) monitoring water levels in the NPS potable supply well, 2) constructing a monitoring well in the Navajo Sandstone near the Sevier Fault, 3) monitoring spring flow at Moccasin Spring, and 4) monitoring spring flow at Pipe Spring. These recommendations were mostly followed with the implementation of regular monitoring and construction of a monitoring well. Monitoring at Moccasin Spring was conducted for only a short period.

Inglis (1990)

Inglis (NPS Hydrologist) assembled much of the information that had been presented by previous investigators including; the background information about groundwater development, spring flow decline, and description of the local hydrogeology. Inglis also provided detailed descriptions of the various monitoring sites: the four discharge points at Pipe Spring, Moccasin Spring, and the three monitoring wells. He also documented monitoring procedures and protocols.

Water level monitoring at the Tribal Well No. 1 (Figure 2) and NPS Monitor Well No. 1 (Figure 18) showed that water levels in the immediate vicinity of the Tribal and NPS Supply Wells (Figure 18) had declined about 5 feet in the period since the initial construction of the wells and development of the potable water supply systems (1971-1989). Pumping for the NPS Well showed no trend toward increasing amounts of water consumption. Power consumption records were obtained for 18 irrigation wells in the Moccasin area to estimate the amount of groundwater being pumped in the area. There was no apparent trend of the amount of water pumped for local irrigation supplies during the period of investigation (1976-85).

As of 1989, the data were inconclusive with respect to determining the potential relationship of groundwater pumping north of the monument to the observed decline of spring flow at Pipe Spring.

The appendix of the report contains details of the construction and testing of the NPS Monitor Well No. 1. This well was constructed in response to the recommendations of Barrett and Williams (1986).

Inglis (1997)

Inglis provided a summary of the history of water development at and near the monument. Much of the report focused on analyses of the spring flow and water level data that had been collected during the preceding twenty years. Figure 1 in Inglis's report showed a "dried up seep" about 100 feet north of the fort and a "new wet area" about 50 feet south of West Cabin. These features lend some credence to the theory that part of the observed spring flow decline may be caused by natural migration of groundwater discharge to new spring openings.

Inglis attempted to correlate spring flow decline with groundwater pumping north of the monument and variations in rainfall (recharge to the groundwater system). There was no clear trend between groundwater pumping and spring flow decline. In fact, during the monitoring period from 1990-96, water levels in the NPS monitoring well rose about a foot in spite of the large amount of water pumped from the NPS and Tribal wells. During this same time period, total spring flow decreased from about 22 to 18 gpm.

Continuous monitoring of water levels showed that the water level in the NPS monitoring well responded to pumping from the NPS and Tribal wells, but water levels in the monitoring well quickly recovered when pumping stopped (Figure 6). There was no obvious long-term trend of declining water levels in the monitoring well, even though more than 12 million gallons per year were being pumped from the NPS and Tribal wells. When we compare the water level data from the 1991-95 period with the longer record (Figure 21) we see that the groundwater levels were rising and stable in the 1991-95 period, whereas the long-term trend has been that of declining groundwater levels. Inglis had the misfortune of trying to correlate groundwater pumping with water table decline during a wetter than normal period (Figure 17) when groundwater levels were rising.

Inglis hypothesized that the recharge area for the springs might be primarily the outcrop area of Navajo Sandstone to the north and west of the monument and south of Moccasin Wash. The geochemistry of water in wells and springs north and south of Moccasin Wash is different (as reported in Levings and Farrar, 1979, suggesting some difference in the source areas or groundwater flow patterns for the two areas. Geologic mapping provides some evidence that the

Navajo Sandstone outcrop south of Moccasin Wash is mostly separated from other areas where the Navajo Sandstone outcrops.

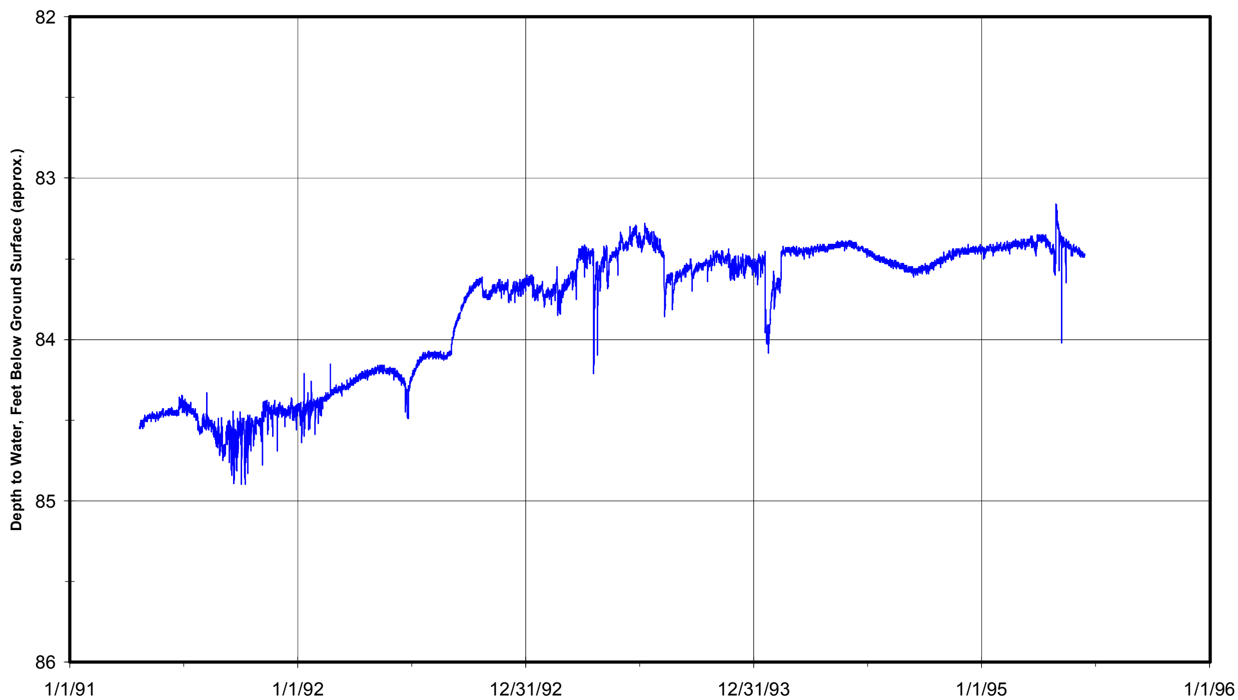

Figure 6. Water level in the NPS monitoring well 1991-95.

Inglis made recommendations for additional hydrogeologic studies to better understand the cause of spring flow decline, including:

1. Geochemical sampling of groundwater from springs and wells in the area to better understand source areas and groundwater flow paths.
2. Geophysical investigations to better define the location of faults in the immediate vicinity of the monument and the relationship of spring locations to faults.

These investigations were subsequently conducted by USGS investigators (Truini, 1999; Truini, Fleming, and Pierce, 2004; and Rymer et al., 2005). Geophysical investigations are continuing in Spring 2007 with additional field work in an area north of the town of Moccasin. Additional geophysical investigations are planned at the monument to delineate fracture-flow pathways to the springs.

The monitoring program that had been in place during the time preceding Inglis's report included continuous recording of water levels in Tribal Well No. 1 near the NPS and Tribal supply wells, continuous recording of water levels at the NPS monitoring well approximately midway between the supply wells and Pipe Spring, and discharge from the springs. Inglis concluded that the monitoring program was unlikely to provide evidence regarding the relationship between groundwater pumping and spring flow decline. The monitoring program was subsequently scaled back to include only monthly monitoring of spring flow at Pipe Spring and the water level in the NPS monitoring well. In December 2004, a continuous water level recorder was again installed in the NPS monitoring well.

Truini (1999)
Truini conducted an investigation of the geohydrology of the Pipe Spring Area, including an inventory of springs and wells, determination of water levels and mapping groundwater flow direction, groundwater sampling and analyses of chemical and isotopic data, and estimating a water budget. Results of the study indicate that local groundwater flow is from north to south along a narrow corridor of fractured rock on the west side of the West Branch of the Sevier Fault. Truini concluded that the springs at the monument appear to be at the south end of a local groundwater flow path west of the West Branch of the Sevier Fault.

Results of chemical analyses showed two general groundwater compositions in the study area. Groundwater south of Moccasin Wash has a higher concentration of dissolved solids than groundwater north of Moccasin Wash. It was hypothesized that the increase could be due to the longer contact time between the groundwater and rocks and therefore greater mineralization of the groundwater south of Moccasin Wash. Groundwater south of Moccasin Wash in the fracture zone west of the West Branch of the Sevier Fault is more in contact with rocks of the Kayenta Formation, which might be another cause for the increased dissolved solids concentration.

Truini's estimates of the water budget for the study area indicated that total discharge from springs and wells greatly exceeds the estimated recharge for the local area. Truini concluded that the deficit indicated that the recharge area for the local groundwater flow system must be a much larger area. [However, with the benefit of several additional years of monitoring data and hindsight, it appears that the water budget was showing the effects of a budget deficit. Groundwater pumping is an additional outflow from the groundwater system that is being balanced by a slow decline of the water table over a very large area. So it's not a case of underestimating the size of the recharge area rather, it's a case of an additional outflow source that causes the water budget to be unbalanced.]

Isotopic analysis showed that groundwater south of Moccasin Wash was younger than groundwater north of the wash, indicating that recharge of some amount of younger water is occurring in the area between Moccasin Wash and Pipe Spring.

Truini concluded (based on hydrogeologic and chemical data) that the spring flow at the monument is part of the groundwater flow system that supplies water to the Tribal irrigation wells north of Moccasin Wash, Moccasin Spring, and the NPS and Tribal water supply wells south of Moccasin Wash. Groundwater flow in the area primarily moves through fractured rocks of the Navajo and Kayenta Formations along the west side of the West Branch of the Sevier Fault. The fine-grained sediments below the upper sandstone facies of the Kayenta Formation function as a confining unit, restricting vertical downward movement of groundwater and forcing groundwater to flow along the bedding planes and fractures in the Navajo Sandstone and upper sandstone facies of the Kayenta Formation.

Truini, et al., (2004)
Truini, Fleming, and Pierce conducted a geophysical investigation in an attempt to identify discrete fracture zones and local groundwater flow paths to individual spring openings. The method/equipment used for the seismic-refraction survey was unable to resolve geologic

structural features at the level of detail that would have been necessary to identify small fracture zones. Electromagnetic surveys were used to delineate differences in apparent conductivity of the shallow subsurface deposits. Those differences were attributed to variation in saturation, lithology, and structure of those deposits. The steep gradients observed between areas of high and low conductivity are probably indicative of north-south trending fractures that would provide secondary permeability in the bedrock and control the location of spring discharge. Spikes in the apparent conductivity along east-west transects north of the monument probably coincide with saturated fractures in the bedrock. These fractures may be conduits for groundwater flow from north to south in the area. Data from the geophysical investigation helped to verify the geologic mapping of Billingsley et al. (2004) and show that groundwater flow to the springs at Pipe Spring is controlled by geologic structure.

Billingsley et al., (2004)

Billingsley, Priest, and Felger produced a geologic map covering the four quadrangles surrounding Pipe Spring National Monument (Moccasin, Kaibab, Pipe Valley, and Pipe Spring). They provided a detailed description of the geologic structure associated with groundwater flow to the springs. The West Branch of the Sevier Fault branches from the main segment of the fault about 1 mile north of the monument. The Moccasin Monocline occurs along the west side of the West Branch of the Sevier Fault, dipping toward the east at about 10 degrees. At the base of the monocline, immediately to the west of the fault, is a small syncline that parallels the strike of the syncline. These geologic structures effectively form a trough bounded on the east by relatively impermeable rocks; creating a preferred pathway for groundwater flow. These features and geologic structure are shown on Figure 7.

They found several commonalities of structural geology and bedrock characteristics controlling groundwater discharge at Moccasin Spring and Pipe Spring. Both springs:

1. Are on the down-thrown (west) side of either the West Branch or Main Branch of the Sevier Fault.
2. Discharge at the bottom of the syncline at the base of the east-dipping Moccasin Monocline.
3. Occur at or near the contact between the Navajo Sandstone and the underlying Kayenta Formation.
4. Are associated with north-south or northwest-southeast oriented bedrock joints.

Groundwater flow occurs primarily in the lower part of the Navajo Sandstone and upper part of the Kayenta Formation, mostly in the syncline at the base of the Moccasin Monocline. The relatively impermeable rocks of the Chinle and Moenkopi Formations on the east side of the West Segment of the Sevier Fault form an effective barrier to the easterly flow of groundwater, forcing the groundwater to flow south in the syncline. Moccasin Wash has eroded deep enough to intercept much of the groundwater flowing south in the syncline, creating Moccasin Spring and providing a source of recharge for the alluvial sediments in South Moccasin Wash. Discharge at Pipe Spring is similar in that a small drainage (Heart Canyon) has eroded headward into the syncline about ¼ mile northwest of Pipe Spring, allowing groundwater to flow east and southeast from the eroded syncline adjacent to the fault.

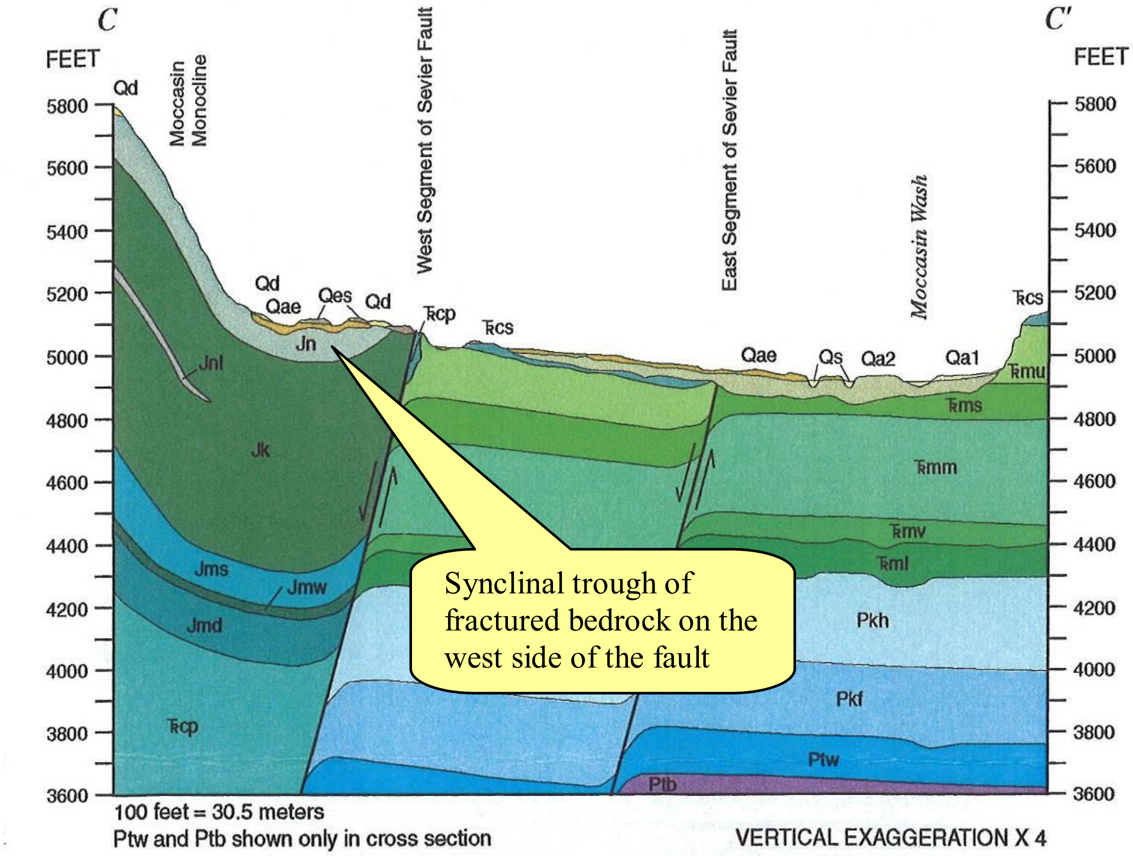

Figure 7. Southwest-Northeast geologic cross section through the Pipe Spring area. From Billingsley, et al., 2004.

Sabol (2005)

Sabol conducted computer modeling of the groundwater flow system to delineate source areas for wells and springs on the Kaibab Paiute Reservation. Sabol created a digital geologic framework model for conceptual visualization and then used that model in the creation of the groundwater flow model. His master's thesis contains a detailed description of the structural geology associated with the Sevier Fault.

On the reservation, the Navajo aquifer is more than 200 feet thick in places and includes the saturated portion of the Navajo Sandstone and the sandstone in the upper 25 feet of the Kayenta Formation. The aquifer is underlain by the silty facies of the Kayenta Formation, which acts as a relatively impermeable confining layer and is continuous across the area (Sabol, 2005). There are a few minor water-bearing units lower in the Kayenta Formation and underlying geologic formations, but for the most part, these rocks do not yield groundwater to wells in sufficient quantity or quality to warrant construction of deep wells. The Navajo aquifer is the only groundwater source for the area.

Downward movement of the rock units on the west side of the fault has created a small synclinal trough that parallels the traces of the faults from Pipe Spring National Monument to just north of the Tribal irrigation wells. Groundwater flow from north to south in the synclinal trough is enhanced by fracturing of the rock by movement along the fault zone. The fracture zone is about 1000-1600 feet wide (Figure 8).

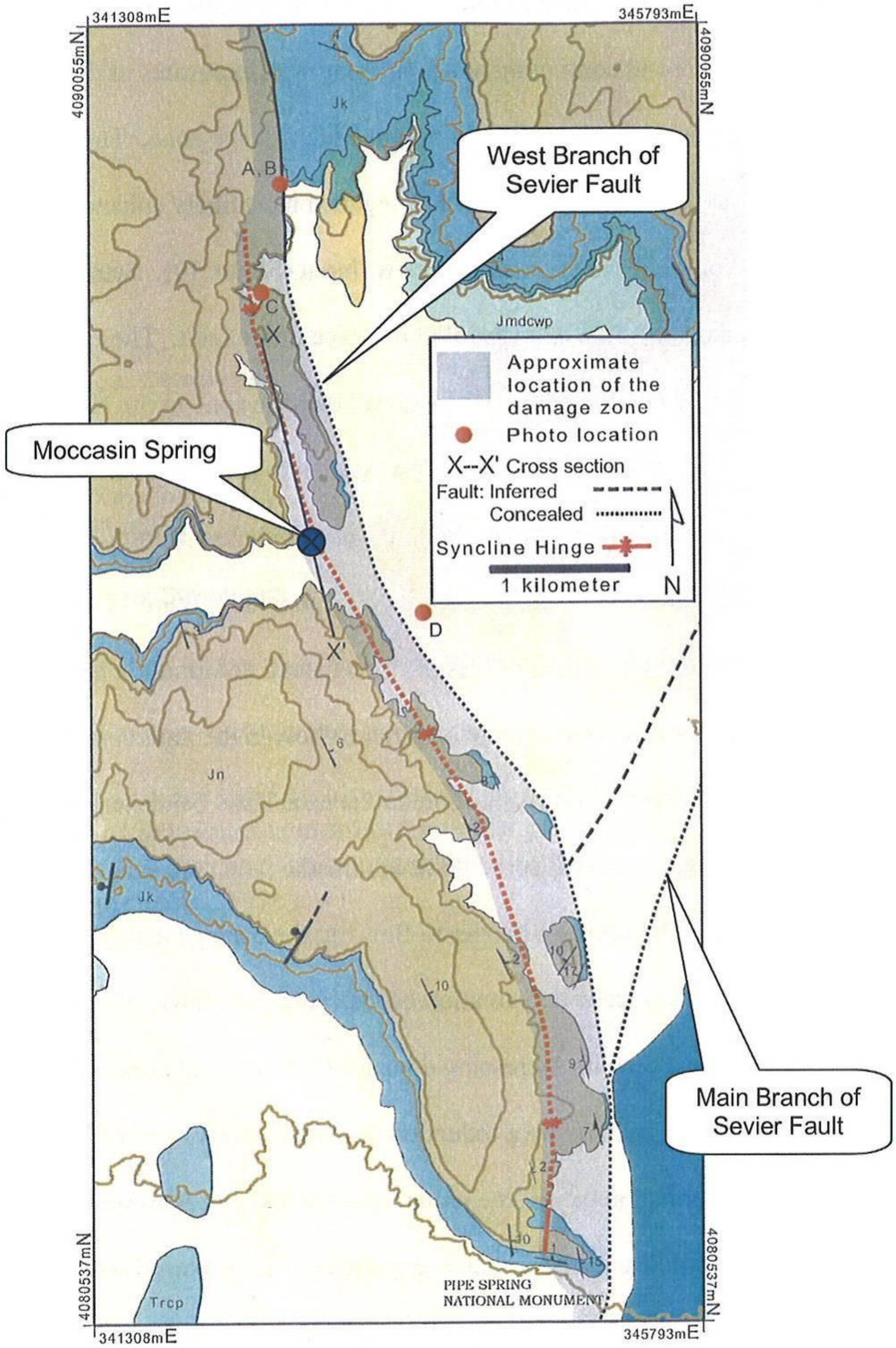

Figure 8. Location of fracture zone associated with the West Branch of the Sevier Fault, Figure 19 in Sabol (2005).

Geomorphology and geology play important roles in the groundwater flow system. Moccasin Canyon separates the Navajo aquifer into two nearly separate systems north and south of the canyon. Where the synclinal trough associated with the West Branch of the Sevier Fault crosses Moccasin Wash, the wash and the alluvium filling the wash cuts across the saturated zone of the Navajo aquifer. The alluvium filling Moccasin Wash has a lower permeability than the fractured rocks of the Navajo aquifer and impedes groundwater flow from north to south along the fault zone, causing some of the water to discharge at Moccasin Spring on the north side of Moccasin Wash (Figures 9 and 10). Additionally, the nearly complete erosion of the Navajo Sandstone part of the aquifer greatly reduces the cross-sectional area of the groundwater trough creating a restriction to the flow of groundwater from north to south across the wash and forces some of the groundwater to emerge at Moccasin Spring. The alluvium in Moccasin Wash is partially saturated by infiltration of water from Moccasin Spring and underground flow from the Navajo aquifer directly into the alluvium. Much of the groundwater in the alluvium of Moccasin Wash flows downstream, to the east, and exits the groundwater flow system associated with the Sevier Fault. This water is no longer available to, or recoverable for, the springs at Pipe Spring National Monument.

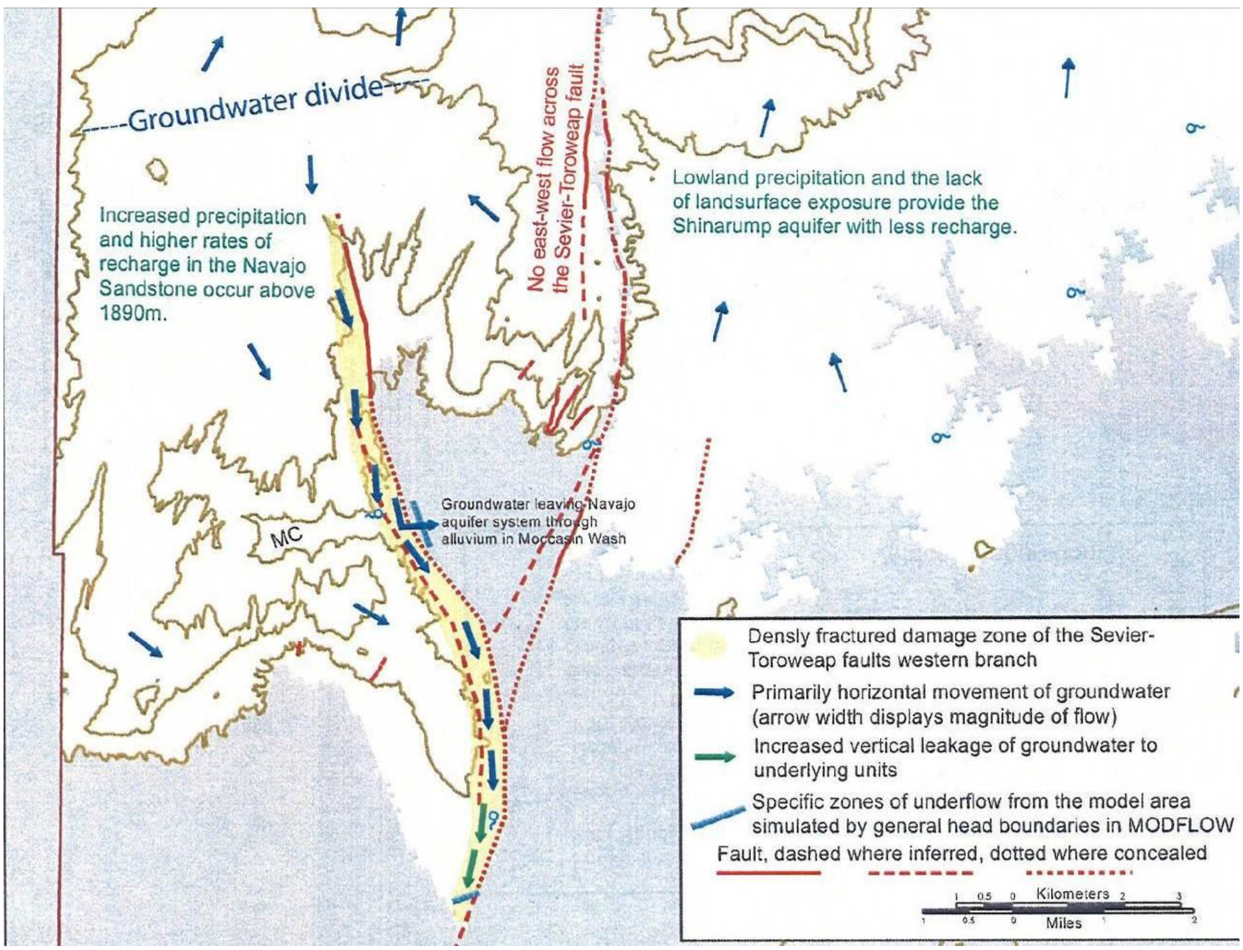

Figure 9. Conceptual model of groundwater flow showing north to south flow in the synclinal trough of fractured rock associated with the Sevier Fault. Also shown is the interception of groundwater by the alluvium in Moccasin Wash. Figure 21 in Sabol (2005).

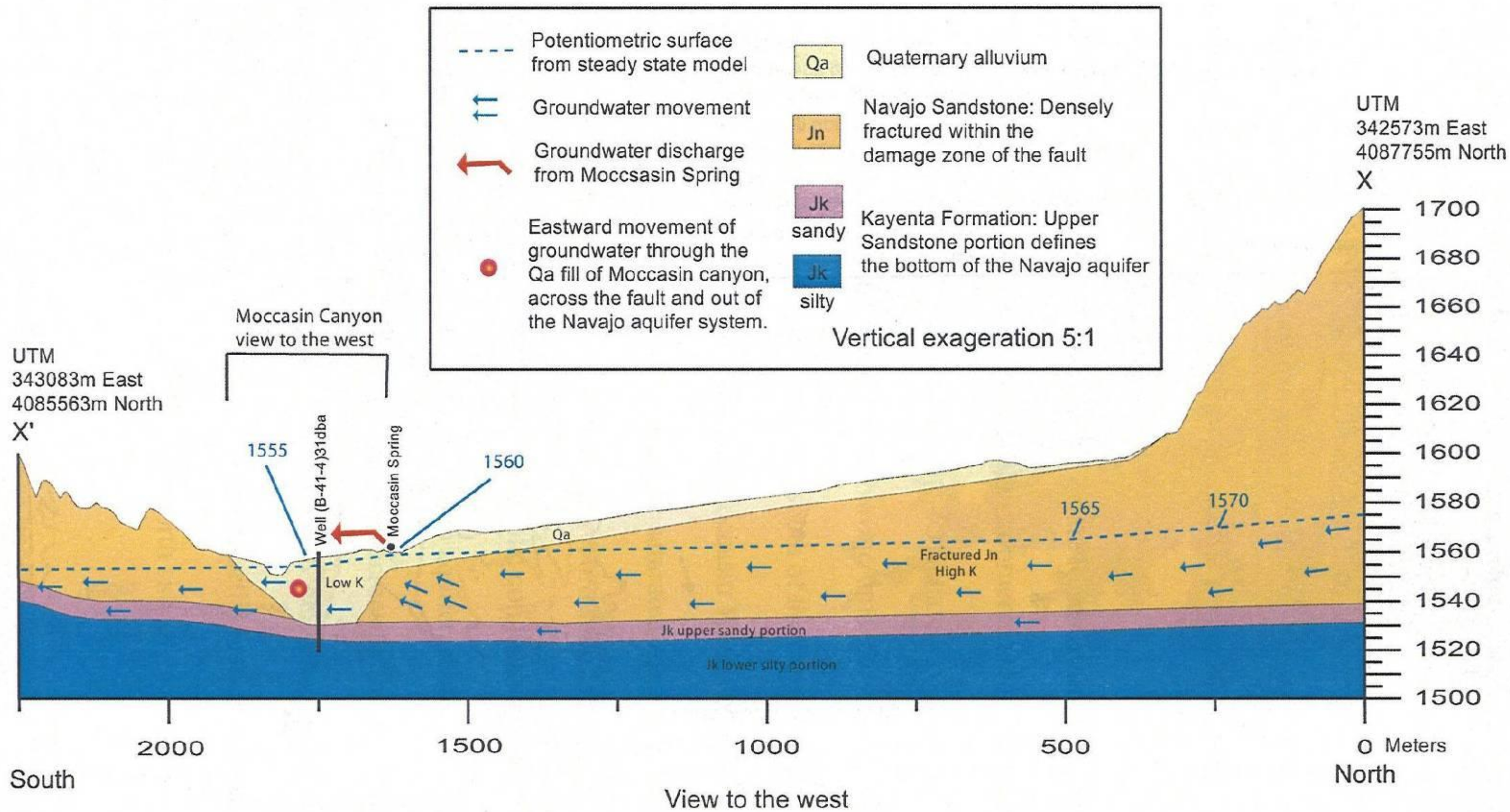

Figure 10. South to North cross section showing groundwater flow from north to south in the fractured rock associated with the Sevier Fault. Alluvial sediments filling Moccasin Wash impede the flow of groundwater, causing some of the groundwater to emerge at Moccasin Spring. Some of the groundwater is intercepted by the sediments filling Moccasin Wash and flows toward the east as underflow in Moccasin Wash. Some of the groundwater continues to flow south toward the NPS and Tribal potable supply wells and eventually Pipe Spring. Figure 22 from Sabol (2005).

Precipitation that infiltrates into the Navajo aquifer on Moccasin Mountain then flows easterly, following the dip of the geologic formation and is concentrated in the fractured rocks in the synclinal trough on the west side of the West Branch of the Sevier Fault. Additionally, the synclinal trough in the fractured rocks on the west side of the fault creates a preferential pathway for concentrating groundwater flow from north to south. At Pipe Spring National Monument, groundwater that is concentrated along the axis of the syncline either discharges at the springs or moves vertically downward into deeper bedrock formations.

The computer simulations of groundwater flow were able to mimic observed declines of spring flow from the time prior to groundwater pumping in the area to near present (1969-2002). The model showed that the major factor affecting spring discharge at Moccasin Spring and Pipe Spring is groundwater pumping from the fracture zone associated with the Sevier Fault. Computer modeling also showed that increases in groundwater pumping from the alluvium within Moccasin Wash or the Navajo aquifer north of the wash primarily affects only the spring flow from Moccasin Spring, while pumping from wells south of Moccasin Wash has a major impact on discharge from springs at Pipe Spring National Monument.

Forward and reverse particle tracking showed that while most of the groundwater in the Navajo aquifer south of Moccasin Wash originates as recharge on that area of Moccasin Mountain lying to the south of Moccasin Wash (Figure 11), there is some contribution of groundwater from north of Moccasin Wash. Groundwater south of Moccasin Wash is a mixture of both local recharge from Moccasin Mountain to the west and inflow of groundwater from north of Moccasin Wash that migrates south toward the NPS and Tribal potable supply wells and the springs at the monument.

Sabol attributed the observed decline of spring flow at Pipe Spring to groundwater pumping by all of the parties in the area: the National Park Service, the Kaibab Paiute Tribe, and residents of the Village of Moccasin. He recommended developing groundwater from the alluvium in Moccasin Wash to reduce the dependency on water from the Navajo aquifer and reduce the impact on spring flow.

Rymer, et al. (2005)

Rymer, Catchings, Goldman, Steedman, and Gandhok conducted seismic reflection and refraction surveys in 2002 in the area north of the monument to determine the subsurface orientation of the east and west branches of the Sevier Fault and to identify additional faults that may be buried by the local alluvium. They found that there are additional faults in the area buried beneath the surficial alluvium. These faults dip to the west and are listric at depth, meaning they curve toward a horizontal attitude with depth. They also determined that the locally prominent structural trough associated with the Moccasin monocline (mapped by Billingsley et al., 2004) has low seismic velocity (fractured rock has lower velocity than solid rock). This evidence provides further support for the theory of the structural trough as a conduit for groundwater flow from north to south. Other low velocity areas that were identified in this study are associated with the previously undetected faults, but they have limited area and are unlikely to contain much groundwater.

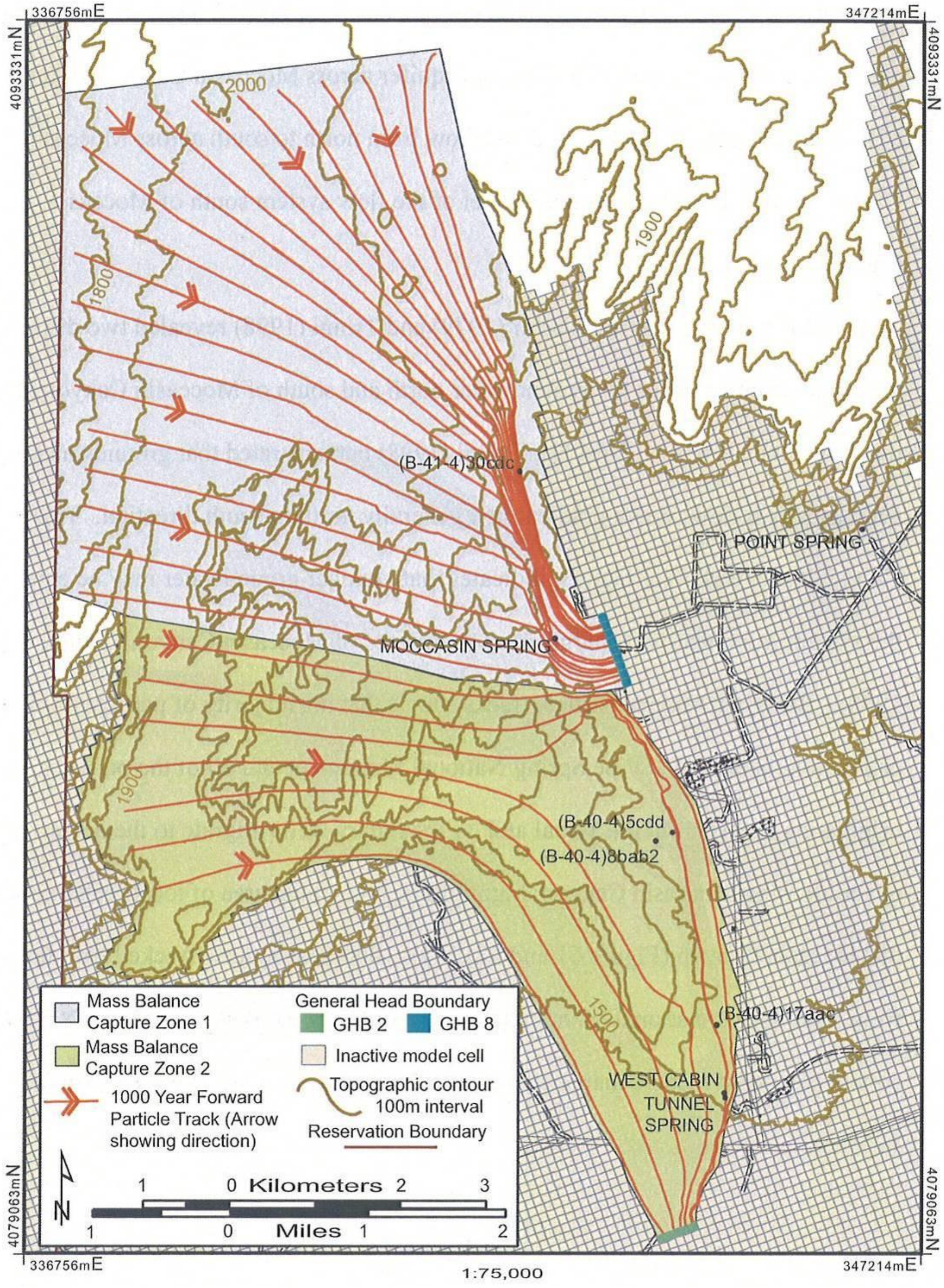

Figure 11. Capture zones for groundwater flow subsystems north and south of Moccasin Wash. Figure 60 from Sabol (2005).

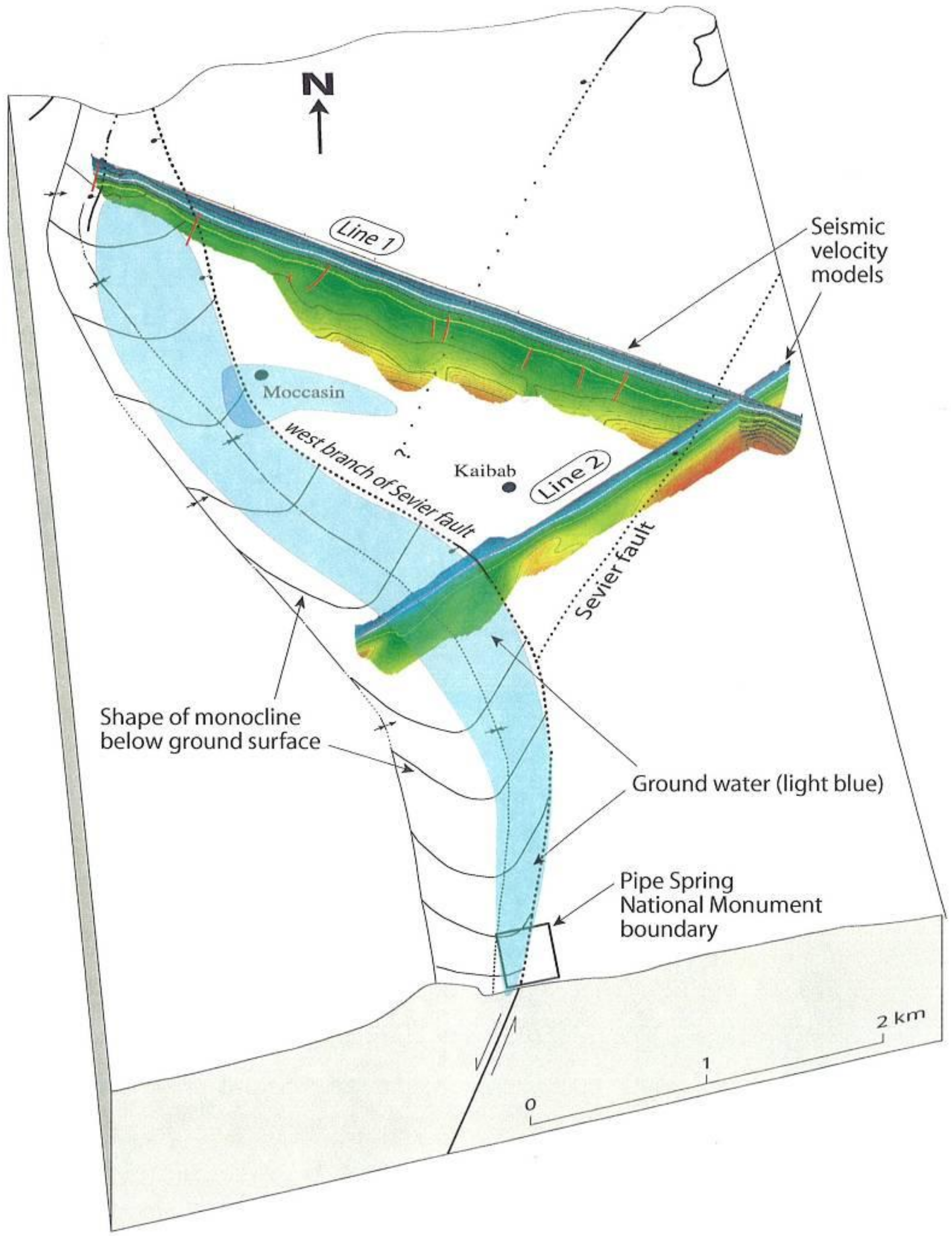

Figure 12. Geologic structure and hydrology, as determined from seismic profiling.
From Rymer et al., 2005

The high resolution reflection and refraction profiling, combined with the geologic mapping of Billingsley, allows production of a three-dimensional picture of where and how groundwater is constrained by geologic structure in the area (Figure 12). Rymer et al. (2005) also concluded that other geologic structures for groundwater storage and flow are not likely to occur in the area.

Monitoring Data

Spring flow data was presented and discussed in a preceding section of this report.

Groundwater Pumping

Groundwater pumping in the Pipe Spring area can be grouped into four categories; pumping from the NPS Well, pumping from the Tribal Well, pumping from private wells in the Moccasin area, and pumping from the Tribal irrigation wells north of Moccasin. The locations of these wells are shown on Figure 13.

The Tribal irrigation wells are located about a mile north of Moccasin and are completed in the fracture zone of the Navajo Sandstone associated with the West Branch of the Sevier Fault. Pumping from these wells has been intermittent; some years no water has been pumped. In the years when the wells are used to irrigate farmland, they are pumped nearly continuously at a high pumping rate for several months. This could have a large impact on the water supply of the local aquifer, but because the irrigation wells are located north of Moccasin Wash, the greatest impact is likely to be a decline of spring flow at Moccasin Spring. NPS has no data regarding the amount of water pumped from the Tribal irrigation wells.

The amount of groundwater pumping by private wells at Moccasin is unknown. There are 13 privately-owned wells in the Moccasin area that are registered with the Arizona Department of Water Resources (Table 2). Many of these wells are registered for stock and domestic use and might also be used to irrigate small garden plots and lawns. Some of the wells might be used to irrigate small fields. Some of these private wells are completed in the alluvial sediments of Moccasin Wash, and some of the wells are completed in the fracture zone associated with the West Branch of the Sevier Fault.

Large-scale farming and irrigation does not occur in the Moccasin area. Examination of orthophotography from the Mohave County Information Technology Department (http://gis.co.mohave.az.us) and the Arizona State Cartographer's Office (http://129.219.93.216/website/arizona) websites allow estimation of the amount of irrigated farm land in the area (Figure 14). At most, there are 70 acres of irrigated land on privately-owned land in Moccasin and 110 acres of irrigation on Tribal land northeast of Moccasin. All of the irrigated land is north of Moccasin Wash. Water for irrigation presumably comes from Moccasin Spring or irrigation wells north of Moccasin Wash.

The Tribal water supply well is completed in the fracture zone associated with the West Branch of the Sevier Fault. It is located about 700 feet southwest of the NPS Well. The Tribal Well is primarily used to supply water for residential use at Kaibab Village and Juniper Village; including the new Tribal Park and its irrigated ballfields and pow-wow grounds. NPS has no data regarding the amount of water pumped from this well.

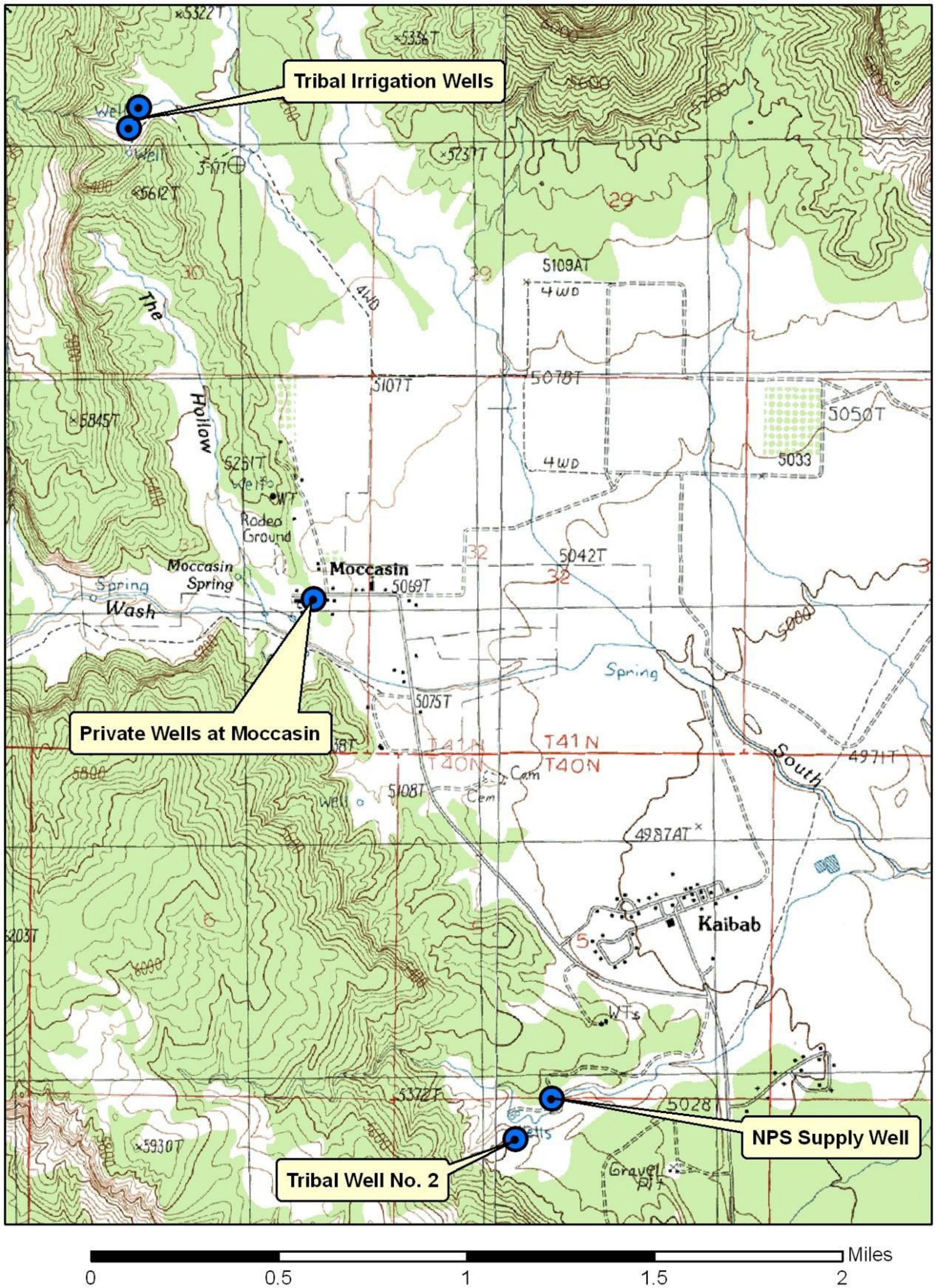

Figure 13. Location of water supply wells near Pipe Spring.

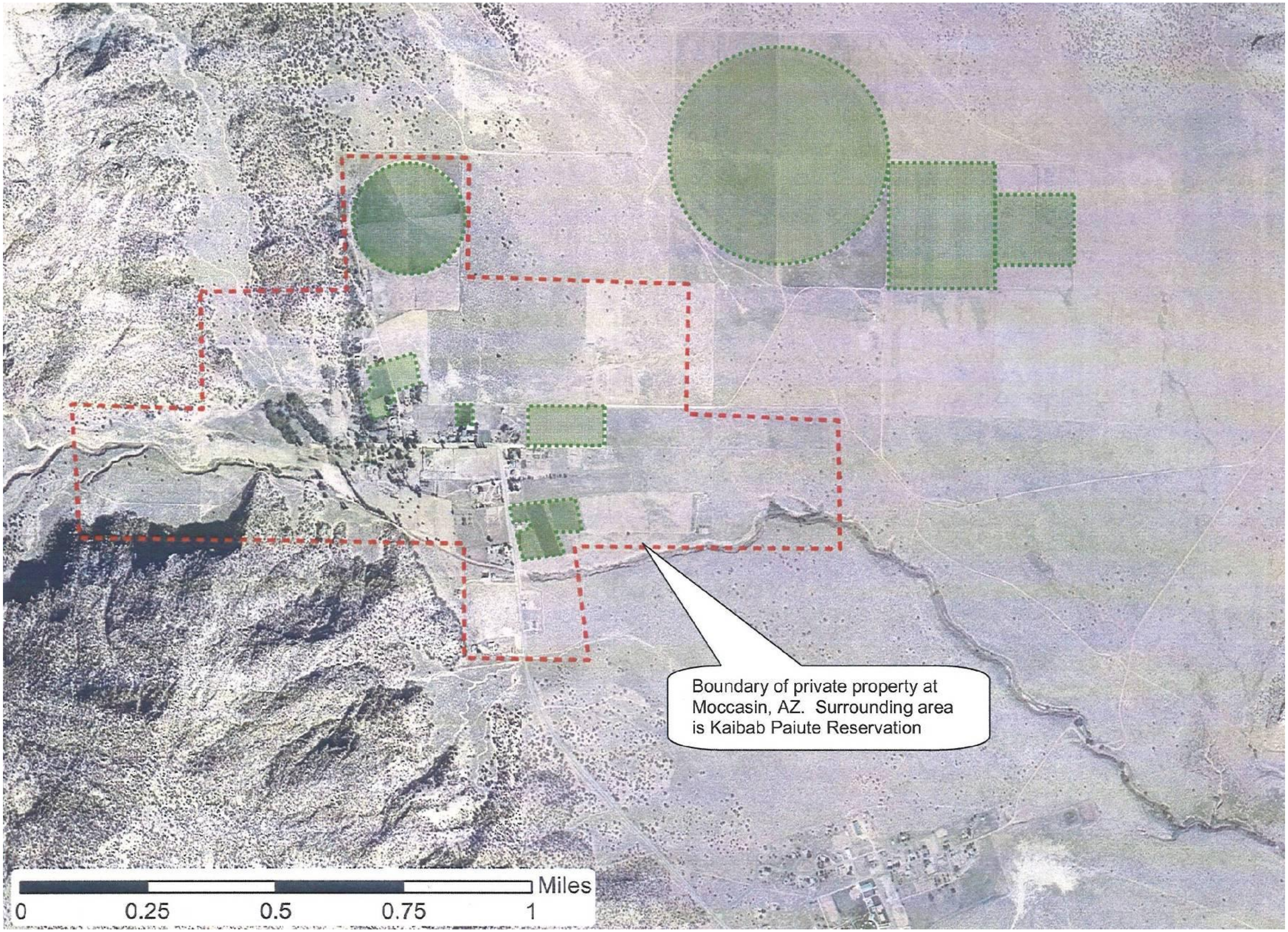

Figure 14. Probable extent of irrigated farm land in the Moccasin area. Green shaded areas are probably irrigated.

The NPS Supply Well is completed in the fracture zone associated with the West Branch of the Sevier Fault and is located about 2 miles north of the monument (Figure 18). The well supplies water for NPS facilities at the monument, the Tribal-NPS partnership visitor center, and Tribal facilities south of Juniper Village. These facilities include: the Tribal multi-purpose building, campground, NPS administrative offices, Tribal Court building, Red Hills Village, Red Cliffs gas station and convenience store, Tribal administration offices, and all facilities at the monument. The well has been in use since June 1973. Annual groundwater pumping from the NPS Well is shown on Figure 15. Over the past 10 years, water use for this system has ranged from about 12-14 million gallons per year (mgy). The midpoint of this demand, 13 mgy is equivalent to 25 gallons per minute (gpm).

From mid-April to mid-June 2006, the Tribal Supply Well was shut down for repairs. During this time the NPS Well supplied all of the demand of Tribal and NPS facilities, including Juniper and Kaibab Villages. During the early part of this period, the weather was cool and water demand was low. During the latter part of the period, water demand increased as the temperature rose, and more water was used for outdoor watering. Average daily use for all NPS and Tribal consumption during the two-month period was 88,400 gallons per day, or 60 gpm (Terry Strong, pers. comm.). Lacking more definitive data, this may be a good indicator of the average current combined use by NPS and the Tribe during that part of the year.

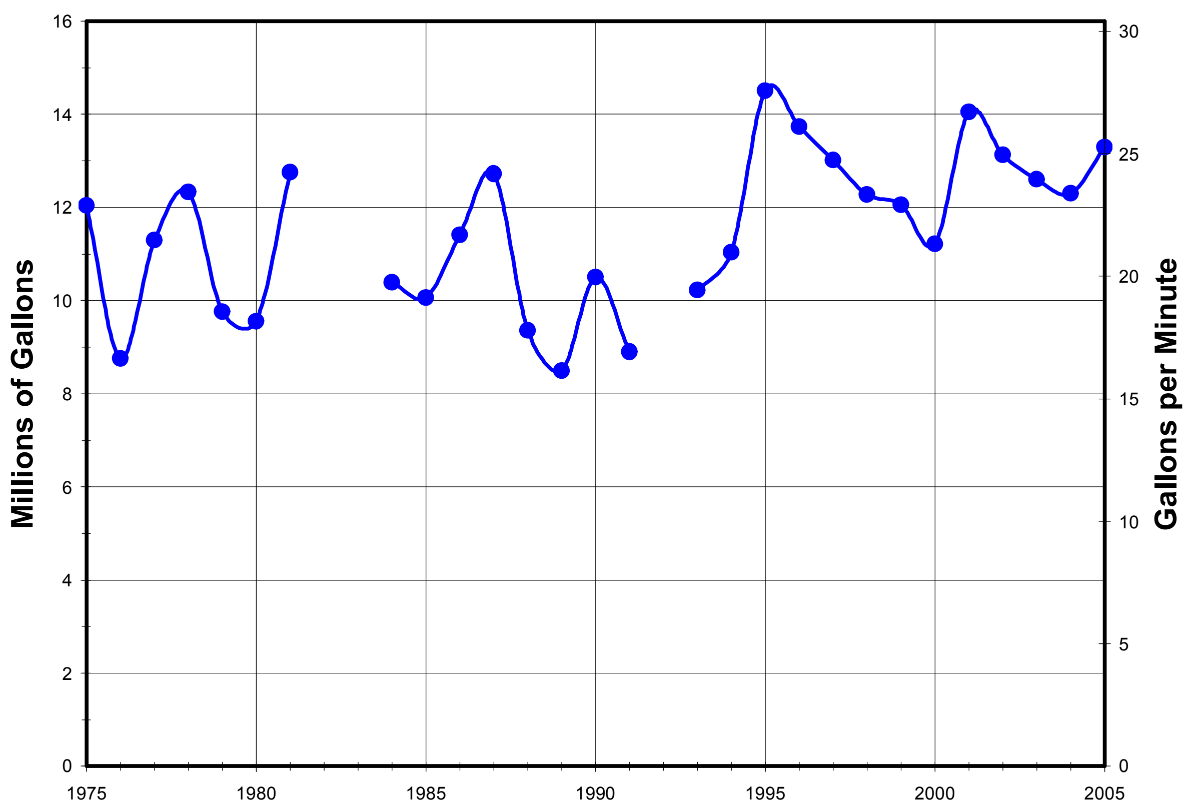

Figure 15. Annual groundwater pumping from the NPS supply well.

Precipitation and Drought

Precipitation has been measured daily at Pipe Spring National Monument since June 1963. Average annual precipitation for the 43-year period is a little less than 11 inches. Several periods of wetter than average conditions are apparent in the record, notably 1978-83 and 1992-95 (Figure 16). Total annual precipitation is a poor indicator of average hydrologic conditions as the total precipitation can be skewed by a few brief, but intense storms.

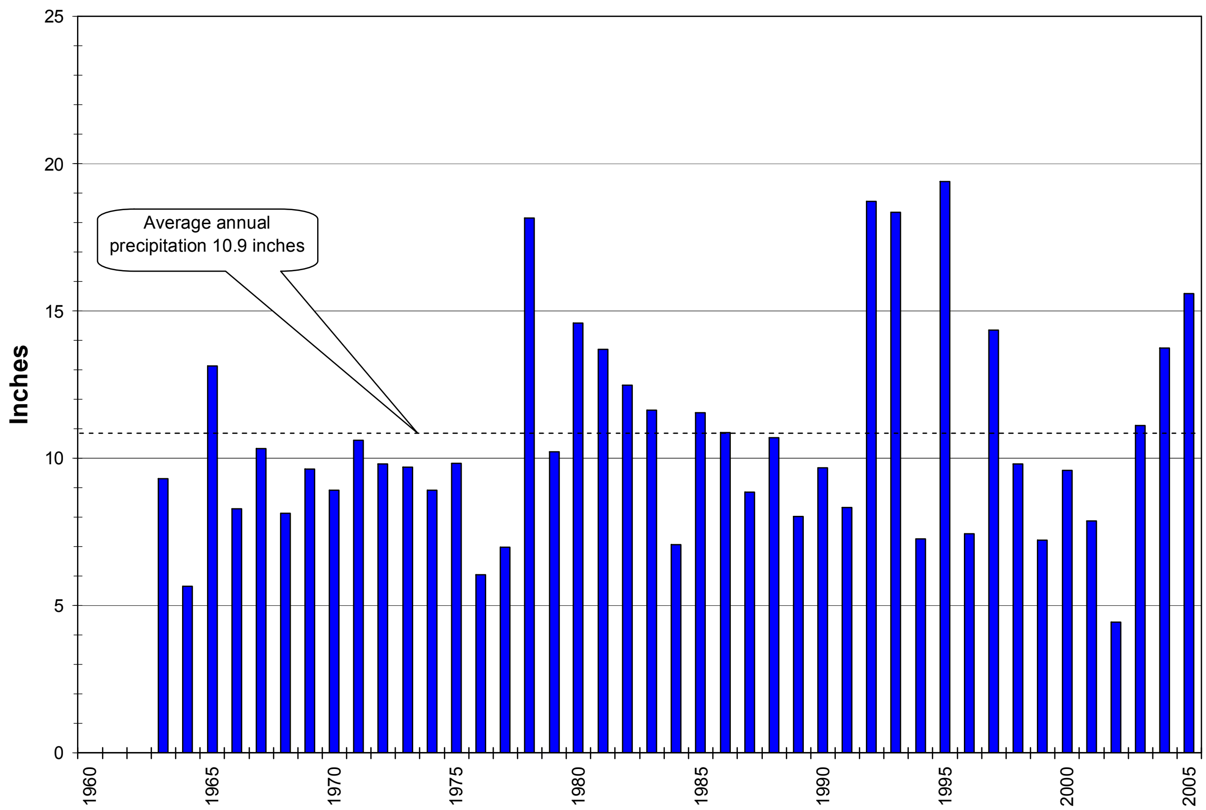

Figure 16. Annual precipitation at Pipe Spring National Monument.

A better indication of average annual hydrologic conditions is the Palmer Hydrological Drought Index (PHDI). The hydrological impacts of drought (e.g., reservoir levels, groundwater levels, etc.) take longer to develop and it takes longer to recover from them. The Palmer Hydrological Drought Index was developed to quantify these hydrological effects. The PHDI generally ranges from - 6 to +6, with negative values denoting dry spells and positive values indicating wet spells. PHDI values of -1.0 to - 2.0 indicate a mild drought, -2.0 to -3.0 indicate a moderate drought, -3.0 to -4.0 indicate a severe drought, and less than -4.0 indicate an extreme drought. Similar adjectives are attached to positive values of wet spells. The PHDI index for northern Arizona is shown in Figure 17.

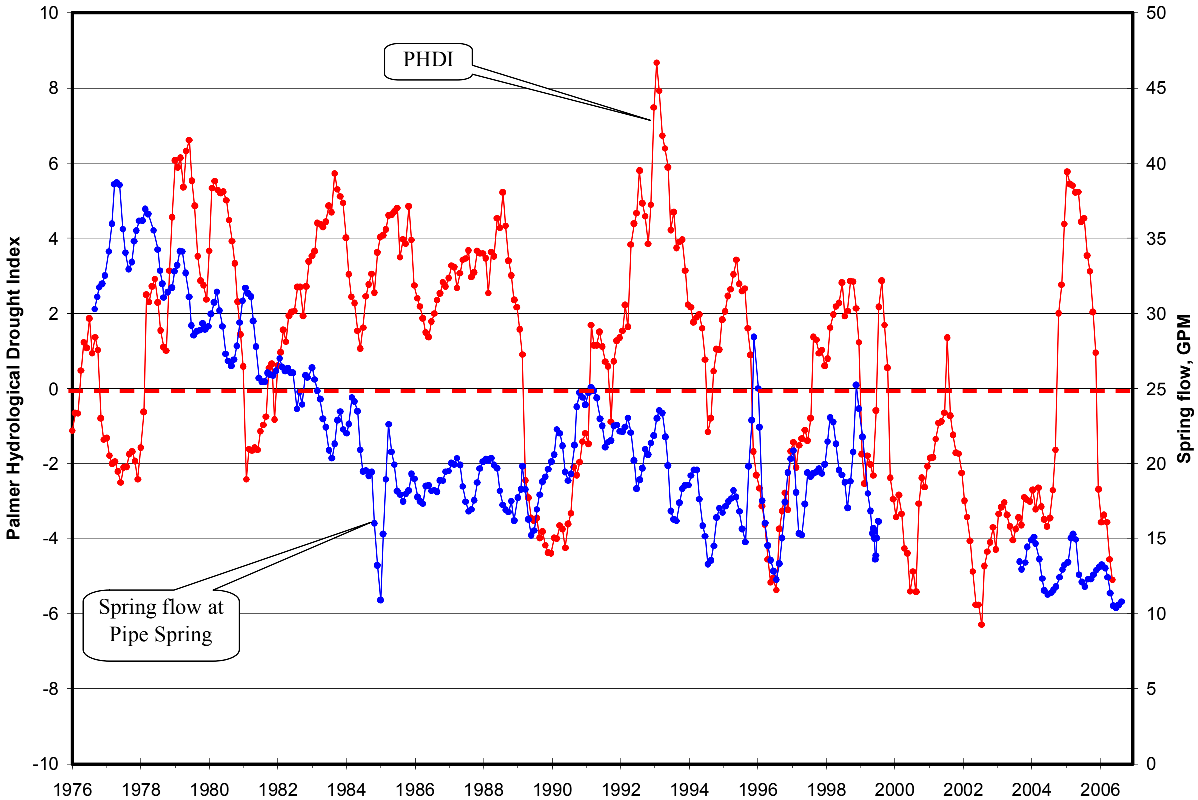

Figure 17. Comparison of Palmer Hydrological Drought Index and spring flow at Pipe Spring.

Comparison of the drought index and spring flow data shows poor correlation, leading to the conclusion that the observed spring flow decline at Pipe Spring National Monument is not a result of natural drought. For example, during much of the period from 1976-85, when the spring flow was declining at its highest rate, the drought index was positive, indicating wetter than average conditions. In 1989-90, when spring flow was increasing, the area was experiencing a severe drought. A wetter than normal period in 2005 had no apparent effect on spring flow.

Water Table Monitoring

Water levels in the Navajo Sandstone in the vicinity of the Tribal and NPS potable supply wells have been monitored regularly for many years. The USGS monitoring well is located about 1 mile northwest of the supply wells and about ½ mile south of the town of Moccasin (Figure 18). Water levels have been measured at the USGS monitoring well since 1976. The NPS monitoring well was constructed in 1989. It is located about a mile south of the supply wells and a mile north of the monument (Figure 18).

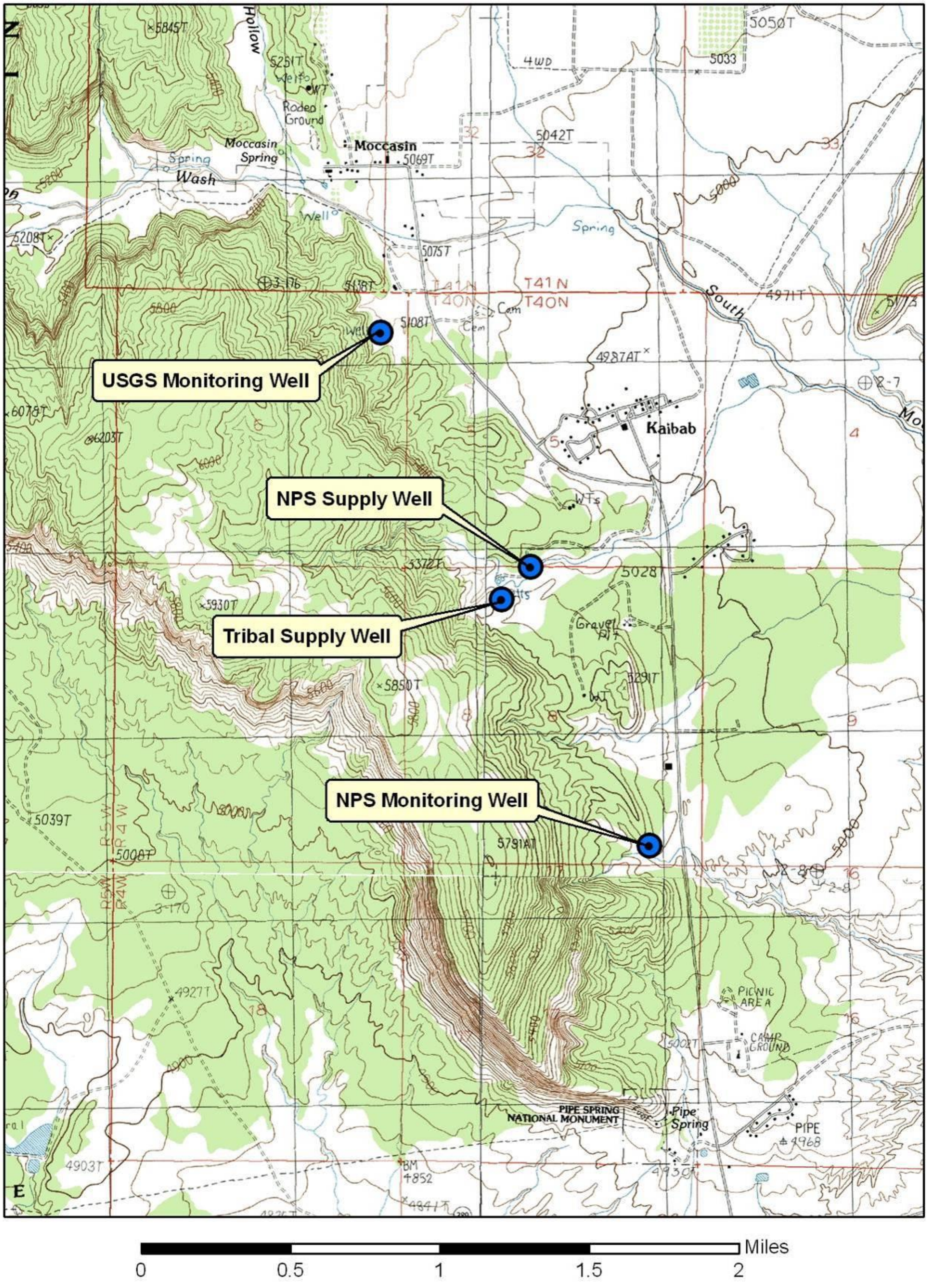

Figure 18. Location of water level monitoring wells and water supply wells near Pipe Spring.

Water levels in both monitoring wells show a general decline of about a third of a foot per year (Figure 19). Water levels in the immediate vicinity of the supply wells have not been regularly measured. The observed water table decline at the two monitoring wells, both about a mile from the supply wells, indicates a general decline of the water level in the aquifer encompassing a large area. This decline may be the cause of spring flow decline at Pipe Spring. As the water level in the aquifer is lowered, there is less of an elevation change between the water level in the aquifer and the springs, and therefore, it would be expected that discharge at the springs would decrease.

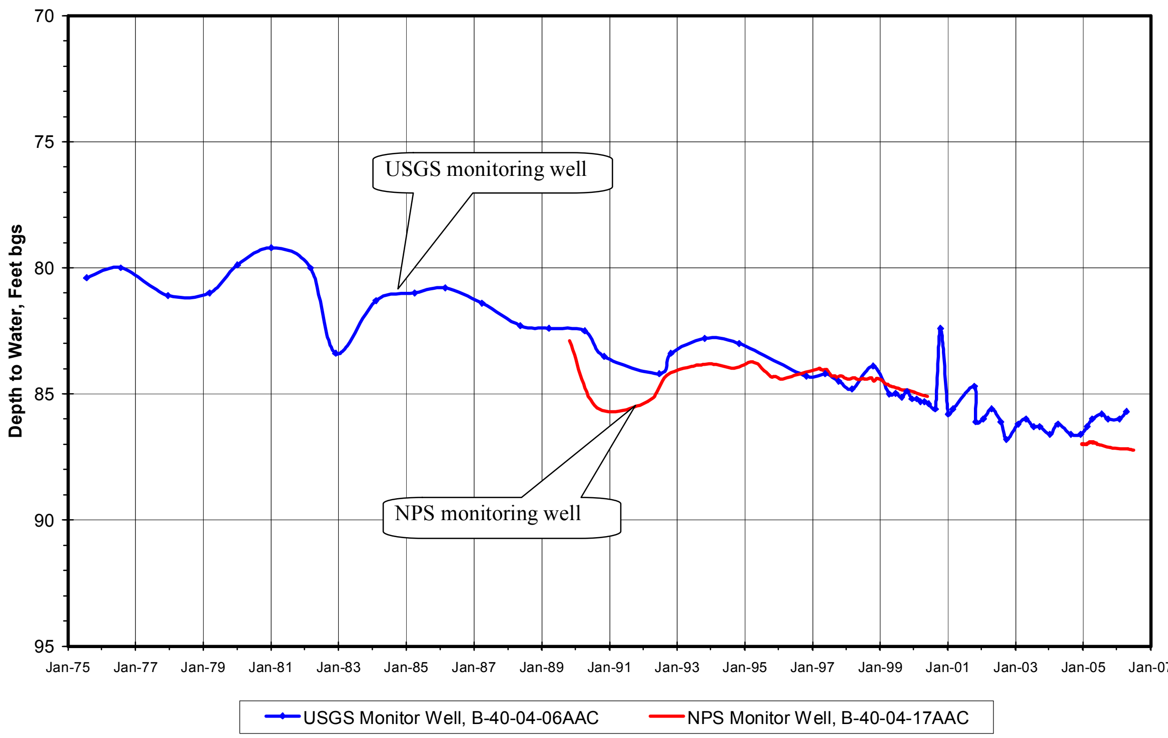

Figure 19. Water levels in monitoring wells north of Pipe Spring.

Water Budget

All hydrologic systems have a water budget. In simple terms;

$$\text{outflow} = \text{inflow} \pm \text{change in storage}$$

Sabol (2005) showed that the groundwater system supplying the springs at Pipe Spring is mostly limited to the area south of Moccasin Wash and west of the Sevier Fault. The majority of the groundwater flow to the springs occurs in the fractured rock in the synclinal structure associated with the fault.

Prior to construction of the NPS and Tribal potable supply wells, the only outflow from the local groundwater system occurred as spring flow at Pipe Springs. The pre-development flow of the springs was about 35-40 gpm, or 18-21 mgy.

One of the questions to be addressed is whether the pre-development water budget for the springs at Pipe Spring could be balanced using only recharge from south of Moccasin Wash. Mapping the potential recharge area to be approximately coincident with the outcrop of the Navajo Sandstone on that part of Moccasin Mountain that is south of Moccasin Wash and west of the fault shows the potential recharge area is greater than two square miles (Figure 20). I then assume that the recharge rate is 5% of the annual precipitation, well within the range of values reported for the Navajo Sandstone by other investigators. Multiplying the recharge rate by the area yields an annual recharge of 19 mgy to the local groundwater system (equivalent to 36 gpm). Thus it would appear that the entire predevelopment flow at Pipe Spring could be supplied by infiltration of a small percentage of precipitation on the east-facing slope of the mountain north and west of Pipe Spring and south of Moccasin Wash (Figure 20). Some additional inflow to the groundwater system likely occurs via the north-to-south flow of groundwater under Moccasin Wash from areas north of Moccasin.

Pumping groundwater from the Tribal and NPS potable supply wells is an additional outflow from the local groundwater system. This additional outflow must be balanced by: a decrease in outflow at the springs, increased inflow, or reducing the amount of water in storage. Increasing inflow or recharge to the system is not possible as the recharge rate is a function of the infiltration of precipitation. It is not possible to induce more infiltration. Reducing the amount of water in storage will result in lower water levels in the aquifer and, subsequently, less flow from the springs.

Groundwater pumping must eventually be balanced by reducing outflow at the springs by an equivalent amount. Records for pumping of the NPS Supply Well show the average pumping rate to be around 25 gpm. The average pumping rate for the Tribal Supply Well is not available to us. However, a limited amount of data from April-June 2006 suggests that the combined groundwater pumping from both the Tribal and NPS potable supply wells is approximately 60 gpm. This estimate of 60 gpm is based on data from for two months in one year. We don't know what the usage was during that short period, or whether there was significant irrigation or not. Thus, the figure of 60 gpm should be used with a great deal of caution.

If the combined annual average pumping rate for the NPS and Tribal Supply Wells is more than the predevelopment flow rate at the springs (about 40 gpm), then spring flow at Pipe Spring will probably continue to decline until it ceases entirely.

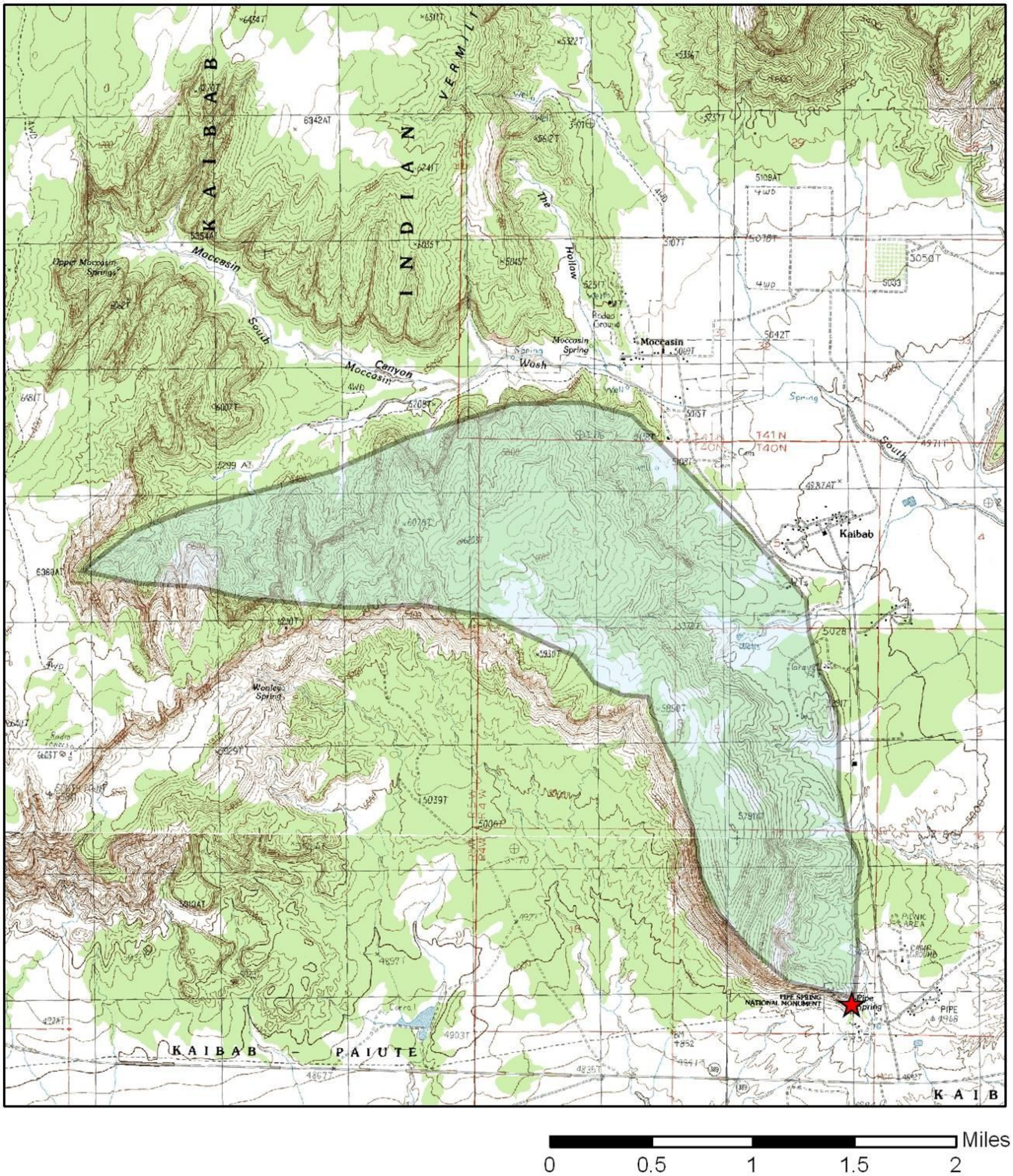

Figure 20. Possible recharge area for the springs at Pipe Spring National Monument (modified from Sabol, 2005).

Future Prospects for Spring Flow at Pipe Spring

The preponderance of evidence indicates the spring flow at Pipe Spring National Monument represents the outflow from a small, local groundwater system. Flow in this groundwater system occurs primarily in the fractured Navajo Sandstone in the synclinal structure along the west side of the West Branch of the Sevier Fault. It is essentially a trough of fractured rock. Most of the inflow to the groundwater system is from infiltration of precipitation on the east-facing slopes of the adjacent portion of Moccasin Mountain. Some inflow may occur from the continuation of the fault zone north of Moccasin Wash, but computer modeling and geochemical data suggest that most of the inflow is locally derived from the area south of Moccasin Wash.

Some of the wells in the Moccasin area may pump water from the northern part of this local groundwater flow system. The amount of groundwater pumping from these wells is unknown, but because of their distance from Pipe Spring and the geologic discontinuity (Moccasin Wash) of the fractured rock trough on the west side of the West Branch of the Sevier Fault, groundwater pumping from these wells is probably a minor causative agent of spring flow decline at Pipe Spring.

Wells in the Moccasin area that are completed in the alluvial sediments of Moccasin Wash are not likely to affect spring flow because they are completed in a different aquifer and primarily pump groundwater occurring as underflow in Moccasin Wash. Computer modeling of the groundwater flow system by Sabol (2005) indicates a strong likelihood of limited groundwater flow from the sediments in Moccasin Wash to the fractured bedrock along the Sevier Fault. Most of the groundwater in the alluvial sediments flows "downstream" in Moccasin Wash (to the east) as underflow.

Pumping from the Tribal irrigation wells north of Moccasin is unlikely to be a major factor contributing to the decline of spring flow at Pipe Spring. Computer modeling (Sabol (2005) suggests that groundwater flow in the fault zone north of Moccasin Wash is largely separated from groundwater flow south of the wash. There is some degree of uncertainty regarding how much, or how little, of the groundwater in the fault zone north of Moccasin Wash flows into the groundwater system in the fault zone south of Moccasin Wash. Moccasin Wash flows west-to-east, perpendicular to the fault. Downcutting and filling of the wash with lower permeability sediments may have created enough of a geologic discontinuity to block or intercept most of the north-to-south flow of groundwater along the fault zone. Alternatively, there may be significant groundwater flow from north-to-south in the deeper part of the trough of fractured rock associated with the fault zone underlying Moccasin Wash. However, erosion, downcutting, and sedimentation in Moccasin Wash has removed most of the thickness of the fractured rock in the "groundwater trough," creating a restriction to the north-to-south flow of groundwater across Moccasin Wash. The degree of the hydrologic discontinuity associated with Moccasin Wash is an important issue that needs better resolution.

Continued pumping from the NPS and Tribal potable supply wells is likely the major cause of spring flow decline at Pipe Spring. It is almost certain that spring flow will continue to decline and eventually cease unless the water supply wells are relocated north of Moccasin Wash or some alternative source of water is developed.

Perhaps nothing illustrates and summarizes the problem better than a graph showing the rate of decline of the water table and the rate of decline of spring flow at Pipe Spring (Figure 21). If we don't change anything, if the Tribe and NPS continue to pump groundwater at the current well sites, the water table will continue to decline and spring flow will continue to decline. Eventually the springs will cease flowing.

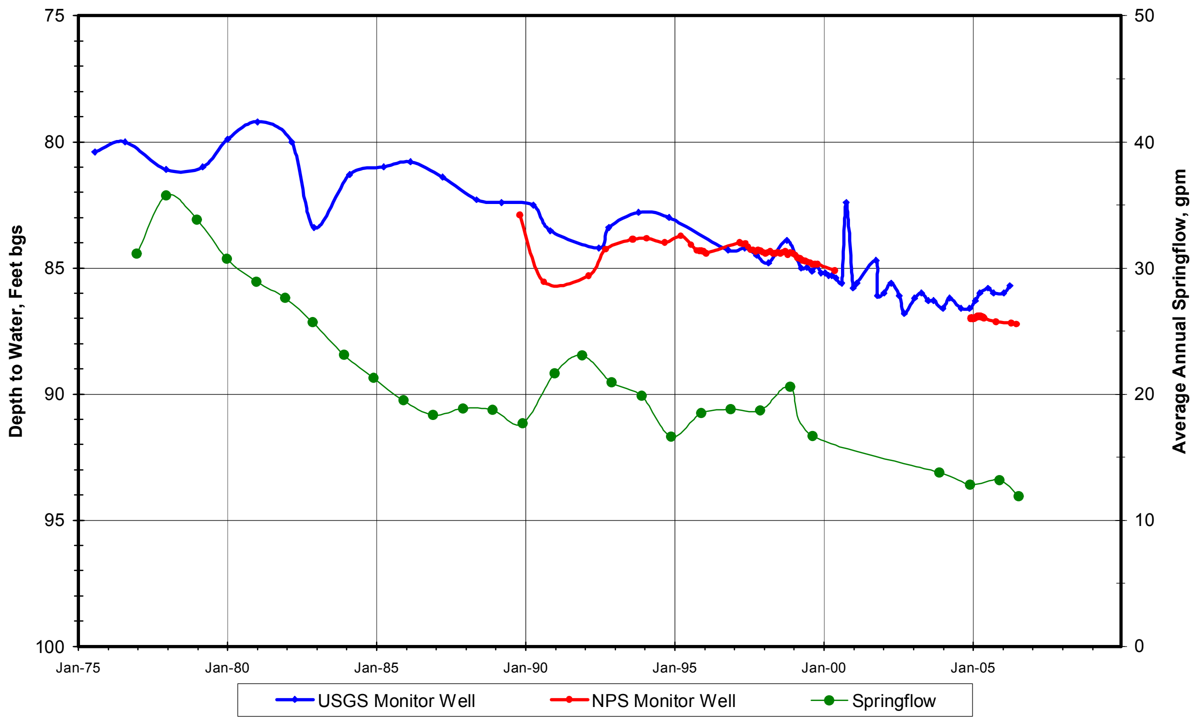

Figure 21. Graph showing water table decline and spring flow decline in the Pipe Spring area.

Recommendations for Future Studies

Additional geophysical studies are planned in the area for 2007. One investigation will evaluate the West Branch of the Sevier Fault in an area about 6 miles north of the monument to assess the continuation of the fault zone and possible connection to potential recharge areas at higher elevations to the north. Another investigation will be conducted on the monument, in the immediate vicinity of the springs to try to delineate discrete, separate fracture zones that may be pathways for groundwater flow to individual springs.

Perhaps the biggest remaining question with respect to groundwater flow in the area is how much groundwater flows from north to south across, or under, Moccasin Wash. Evaluation of this component of the hydrologic system will greatly aid in evaluating the cause of spring flow decline at Pipe Spring (i.e., determine whether the cause is almost entirely due to groundwater pumping from the NPS and Tribal supply wells or if groundwater pumping at Moccasin and north of Moccasin significantly contributes to the decline of spring flow). Resolution of the issue of groundwater flow across Moccasin Wash will also help identify the recharge area for the groundwater system feeding the spring (i.e., determine whether there is significant recharge from areas north of Moccasin Wash or if the recharge area is primarily limited to areas south of Moccasin Wash).

In addition to the currently planned geophysical studies, some additional geophysical work, along with geochemical sampling of groundwater, may be useful in determining the degree of separation or interconnection of groundwater in the fracture zone north and south of Moccasin Wash. This would be important information if there was serious consideration to relocating water supply wells to the area north of Moccasin. We would want some assurance that the relocated wells would have minimal impact on groundwater levels south of Moccasin Wash. Relocating the NPS and Tribal supply wells to north of Moccasin, or finding some other source of water, would probably allow recovery of water levels in the aquifer and an increase of flow from the springs at Pipe Spring National Monument.

Previous studies have provided a pretty clear understanding of the hydrogeology of the area and groundwater flow system feeding the springs at Pipe Spring National Monument. Geologic mapping and geophysical investigations provide a clear picture of the structural geology controlling groundwater flow in the area. Computer modeling of the groundwater flow systems show the groundwater flow paths and verify what should be intuitively obvious, that groundwater pumping from the fault zone causes spring flow to decline.

Spring flow will continue to decline unless groundwater pumping is curtailed. Spring flow will probably increase if groundwater pumping from the NPS and Tribal potable water supply wells ceases. That would require importing water to the area or developing new wells north of Moccasin Wash. Additional groundwater pumping north of Moccasin Wash is likely to cause additional spring flow decline at Moccasin Spring.

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