SPRINGS AS INDICATORS OF DROUGHT: PHYSICAL AND GEOCHEMICAL ANALYSES IN THE MIDDLE VERDE RIVER WATERSHED, ARIZONA

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ABSTRACT

SPRINGS AS INDICATORS OF DROUGHT: PHYSICAL AND GEOCHEMICAL ANALYSES IN THE MIDDLE VERDE RIVER WATERSHED, ARIZONA

STEVEN E. RICE

In the western U.S., the worry of drought conditions affecting current and future water use and supply plans has been coupled with the rapid population growth over the past decade to push water resource management into the spotlight, particularly in rural areas. In this study, drought indicators and triggers based on springs were developed to augment the State of Arizona's existing set of indicators and triggers primarily based on precipitation and streamflow data. The objectives of the study were to determine if physical and geochemical data from springs could be used to create a viable correlation with drought conditions. Spring discharge, water-quality parameters, and isotope and anion data were collected from sixteen springs in the Middle Verde River watershed between July 2005 and June 2006. These data were compiled with discharge data from the same set of springs from November 2002 to October 2003. Additionally, data from biological inventories conducted at many of the spring locations were compared to the physical and geochemical findings.

The stable isotope (δ^2H and $\delta^{18}O$) data indicate that winter precipitation is the dominant source of recharge in the study area for all springs studied. Radioactive isotopes (^3H and ^{14}C) provided estimates of aquifer residence times, and the geochemical

data combined with regression fits of spring discharge hydrographs led to a refinement of the designation of springs classified as "regional" or "local". The concept of a continuum between regional and local end members was developed, and this assisted in the evaluation of how these springs responded to climate variability. Ultimately, drought trigger levels were calculated from spring discharge data in a manner similar to that used by the State in the generation of their drought levels.

Although drought levels based on the springs did not agree well with the State's drought levels, the springs do provide a different indication of the status of the watershed. Drought levels based on springs data fluctuated less than the State-generated ones; a pattern that seems to reflect that springs in general are less sensitive to the types of climate perturbations that drive the current drought-level designations. While the indices and drought trigger levels used by the State in the study area may reflect an availability of water, the trigger levels designated by spring discharge may be more of a reflection of the status of groundwater storage in the watershed.

ACKNOWLEDGEMENTS

I would like to begin by thanking my committee for all of their support during the data analysis and writing processes. Abe was instrumental in getting the research off the ground, locating funding sources, as well as providing me opportunities to work on a number of other interesting projects which have benefited my scientific thought process substantially. James is an invaluable source of knowledge, a very comprehensive editor, and broad thinker. Ron's intimate and almost photographic knowledge of the geology of the region is a luxury most are not afforded. Funding sources which made this research possible include the Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA) group at the University of Arizona, the Geological Society of America (GSA), Salt River Project (SRP), and of course the Friday Lunch Clubbe. The broad, encompassing nature of this work required a great deal of assistance from a number of people including (but not limited to) Gregg Garfin of CLIMAS at U of A, Phil Turk in the NAU statistics department, Andy Fisher at ADWR, Bob Sejkora at AZ State Parks, Don Dufek at NAU transportation for those great 4Runners, and Chris Eastoe at the U of A Laboratory of Isotope Geochemistry. Thanks also to Steve Flora, who laid the groundwork for this study with his research, Larry Stevens and Emily Omana for their work on the biology, and Kyle Blasch at USGS for proofing my draft and for all his great work on the Middle Verde.

I cannot forget all of my fellow grad students who I have made wonderful friendships with and who helped show me that grad school is not all lab time and journal reading. The camping, skiing, climbing, boating, exploring, etc. trips we took were just as important to my development as the formal education was. The Thursday crew of Corey, Daniel, Megan, Sheena, Tim, et al. (alphabetical order, no favoritism, OK?) have become my closest friends. Many thanks as well to all of the other friends I have made in Flagstaff. It's a special place with many special people.

Finally, I do not have the words to express thanks to my parents, whose never-ending support made this all possible. Remarkable people.

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CHAPTER 1 – INTRODUCTION

1.1 BACKGROUND

Water resource management has been pushed into the spotlight in response to the rapid population growth in the western U.S. over the past decade. Seasonal variations in climate over this period have exacerbated the issue as the worry of drought conditions affects current and future use and supply plans, particularly in rural areas (Arizona Drought Preparedness Plan (ADPP), 2004) and issues concerning water resource management have become paramount. In response, several states and local entities in the Southwest have formed organizations, panels, and groups to prepare for the potential impact of drought conditions. In 2004, the State of Arizona formed the Governor's Drought Task Force and issued the Arizona Drought Preparedness Plan. This plan outlines the responses the state will have to varying drought conditions. These responses are based on a set of indicators and triggers that have been developed by the Task Force's Monitoring Technical Committee based on "analysis of climatic and impact data" such as the Standard Precipitation Index (SPI) and streamflow data and act to "provide early detection and warning of impending drought conditions" (ADPP, 2004).

1.1.1 Defining Drought

Drought conditions can be divided into three components: severity, magnitude, and duration. The severity is described as the cumulative deficiency below normal, magnitude as the average deficiency below normal, and duration as the number of years below normal (Paulson, 1985). This duration is highly subjective depending on the location where the drought potential is quantified and what is considered "normal" for that area. For example, a period of six days without rain in Bali is considered the onset of drought conditions, while in Libya drought onset is not noted until no rain has fallen for two years (Dracup, 1980). Adding to both the complexity of indicating the beginning or end of drought conditions is the fact that droughts are cumulative; the effects are felt long after climatic conditions return to "normal". Additionally, not only do droughts decrease the amount of available water, they also degrade the quality of the remaining water. Increases in the concentrations of salts, inorganic compounds, turbidity, nutrients, and microbes are seen as drought conditions continue (ADPP, 2004).

An indicator is defined as a variable used to describe drought conditions (e.g. precipitation, groundwater levels) and a trigger is defined as a specific value of the indicator that can be used to designate the beginning and end of a drought status level. Data sources used currently to develop these drought indicators and triggers in Arizona include precipitation, streamflow, reservoir levels, and groundwater levels from well data. In this study, a set of indicators and trigger levels based on spring hydrology were developed to quantify drought status. Discharge, water-quality and geochemical data from springs located in the Middle Verde River watershed were used to develop a set of drought indicators and triggers that can be used to correlate and/or refine the existing indices used by the State. These indicators will allow for more effective actions to implemented prior to the onset of drought. The advanced warning of these drought classifications can be used to mitigate impacts to the affected areas and help develop tools to reduce drought vulnerability.

The American Meteorological Society (AMS) defines drought as a "period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrologic imbalance" (AMS, 1997). A problem with this definition is that the spatial and temporal distribution of these conditions, as well as the increased water demand from human use (agriculture, industry, etc.) are not accounted for, and it is therefore difficult to develop and successfully manage a singular definition of drought (Heim, 2002). Additionally, drought not only affects the amount of water available for consumptive use, but also impacts the natural ecological systems within the watershed including riparian areas, which need to be managed and protected in conjunction with the need to preserve water supplies.

1.1.2 Historical Significance

Drought is a recurring phenomenon that has negatively affected societies throughout recorded history (Heim, 2002). Records of prehistoric droughts in the Southwest can be reconstructed using dendrochronological (tree-ring dating) techniques. Data show a strong correlation (r=0.80) between tree-ring growth and precipitation (Meredith, et al., 1998), which has allowed the Laboratory of Tree-Ring Research at the University of Arizona to reconstruct a 2,000-year precipitation record for the Southwest from trees in northern New Mexico (approximately 300km from the study area) (Meredith, 2001). A graphical representation of the cool season (November-April) precipitation record for the last 1,000 years for the study area based on tree-ring data was reproduced from Ni, et al., 2002 (Figure 1). Several "mega-droughts" are recorded in the tree-ring data, the most recent in the latter half of the 16^{th} century. Another major

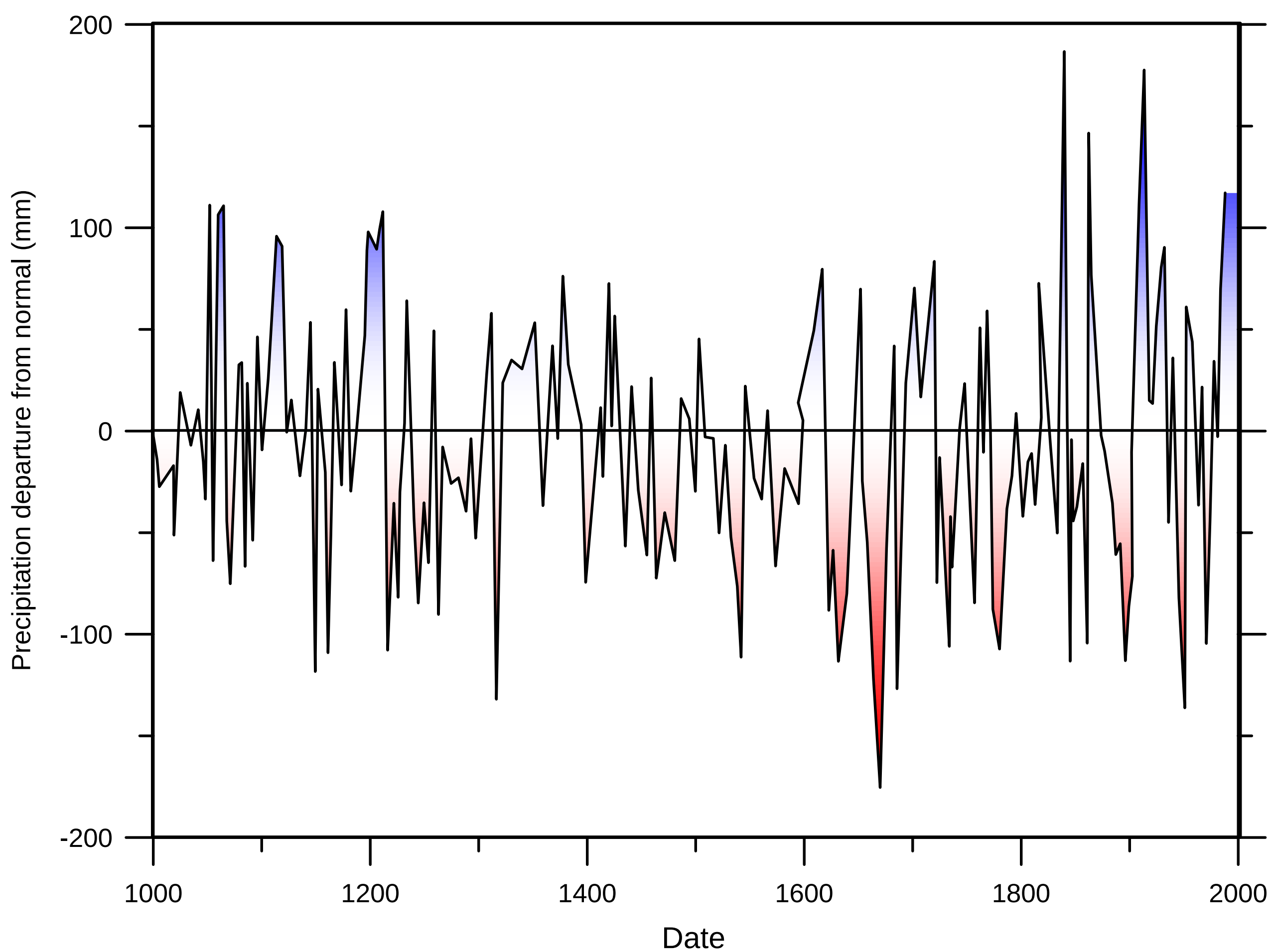


Figure 1. 1,000-year cool-season (November-April) precipitation record for the study area (NOAA Arizona Climate Division 3) based on tree-ring reconstructions. Plot was created with data from Ni, et al., 2002. Increased red and blue shading represent increasingly dry and wet periods, respectively.

drought period in the 13th century may be responsible for the abandonment of the Anasazi culture (Woodhouse and Overpeck, 2000). In addition to temporally locating historical drought periods, the tree-ring record has also given insight into the cyclical nature of past climate change, including the existence of the El Niño-Southern Oscillation (ENSO) (Swetnam and Betancourt, 1992). Tree-ring data have also assisted in creating reconstructions of past flows on the Colorado River (Hidalgo, et al., 2000).

In a historic context, Arizona and much of the Southwest have been in drought conditions for over a decade (ADPP, 2004). These years of drought have depleted the Colorado River reservoirs of Lake Mead and Lake Powell to some of the lowest levels since the dams were built and the reservoirs filled. Between January 2000 and 2004, the levels of Lake Mead declined more than 23 meters, a volume that represents approximately three years of Colorado River water allocation to the State of California, and the level of Lake Powell declined to a historically low 40 % capacity (Piechota, et al., 2004). Steam discharge of the Verde River at Camp Verde has decreased at an average of 2,000 acre-feet per year (2.46×10^6 m^3/yr) since 1994 (Blasch, et al., 2006). Still, much of Arizona's metropolitan areas are regarded as having an overall reliable water supply due to augmentation of local surface-water and groundwater sources with water imported from the Colorado River. Rural areas of the state, on the other hand, are more vulnerable to drought conditions due to their reliance on locally sourced water.

In Arizona, 2002 was recorded as one of the driest years in the last 100 years. Streamflow records in the State indicate that the drought years of 1999-2004 were the most severe since the early 1940s and perhaps earlier (Phillips and Blakemore, 2005). Precipitation records for the 20th century indicate wetter than average years from the start of the century to 1940, dry years from 1940 to 1977, wetter again from 1977 to 1994, and dry from 1994 to the present. This cyclicity has led to the postulation that the current drought could last for at least another decade (Blasch, et al., 2006).

1.1.3 Societal Relevance

The extreme drought year of 2002 led to the development of the Arizona Drought Task Force and an increased visibility to the drought problem in general. Following the exceptionally wet winter of 2004-2005, many concerns were assuaged as to the severity and duration of the ongoing drought conditions. The winter and spring of 2005-2006, however, were historically dry and reinforced the fact that Arizona's drought has not ended, and responses to the effects of this drought are increasing as the potential magnitude of the lack of water is beginning to be understood (Figure 2). In early February, 2006, the Governor of Arizona called for an emergency meeting of the Drought Council to discuss the situation at hand. The forest fire season started months earlier than usual and several damaging and costly fires occurred in the spring and summer months. Several national forests restricted access because of the increased fire risks, which has a negative impact on the economies of these areas supported by forest-related tourism.

Future estimates of drought conditions in the West based on past events as well as future scenario modeling indicate that conditions similar to those during prehistoric "mega-droughts" will most likely occur again, and the effects may be exacerbated due to expanded human land use and the effects of global warming (Woodhouse and Overpeck, 1998). This may be especially true in the Southwest, where already marginally

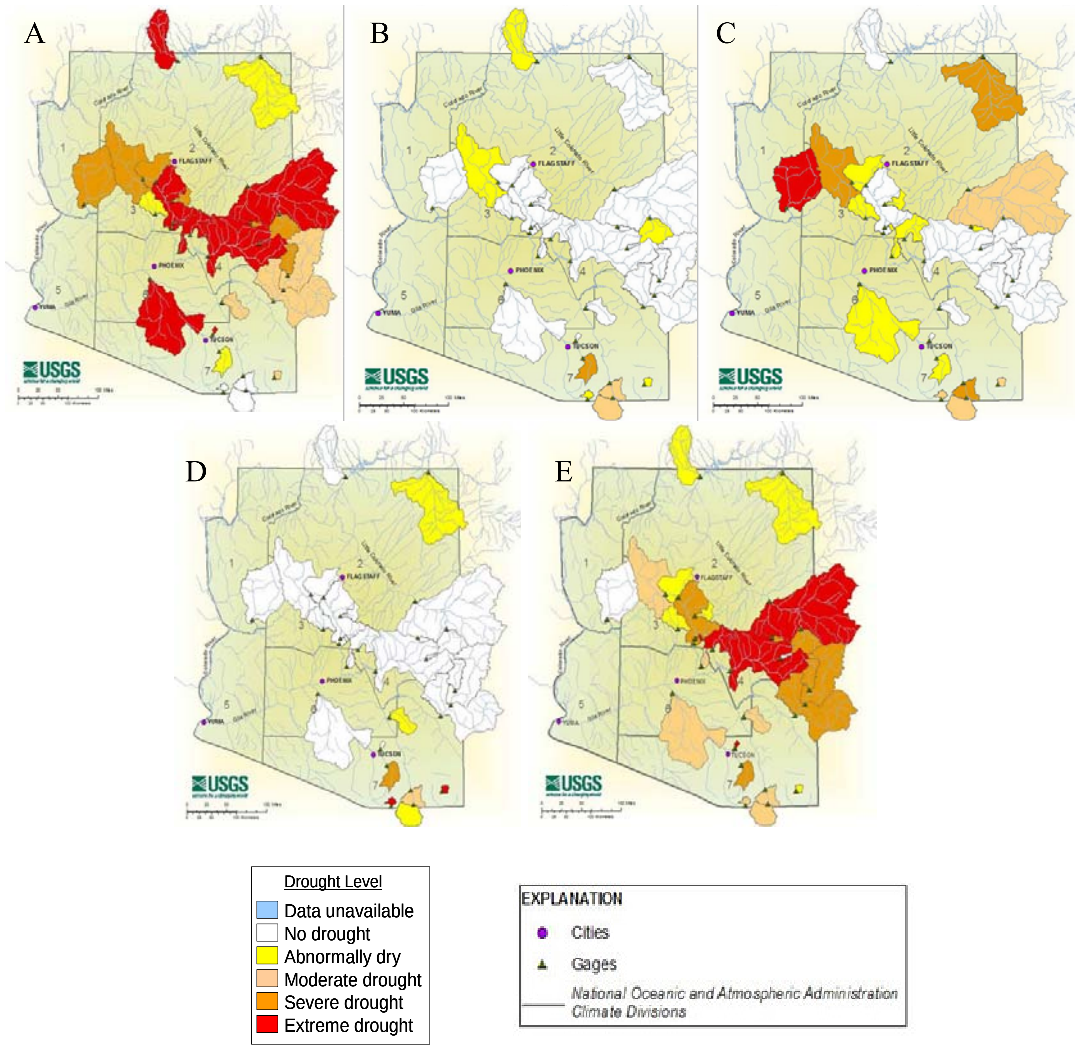


Figure 2. Statewide drought levels based on streamflow data for the month of March, A) 2002, B) 2003, C) 2004, D) 2005, E) 2006. 2002 was the year of the original spring inventory of the study area (Flora, 2004) and was one of the driest years on record in Arizona. 2005 was the start of the most recent spring survey, and began after a historically wet winter. The end of 2005 and the beginning of 2006, however, were also quite dry, and streamflow and some springs reflected this change. Data from USGS Arizona Water Science Center, http://az.water.usgs.gov.

acceptable lands are being irrigated for agricultural purposes and water usage is increasing with the expanding population.

1.2 PURPOSE AND OBJECTIVES

In this study, a new set of drought indicators and triggers were developed to augment the State's existing set of indicators and triggers. The objectives of the study were to determine if physical and geochemical data from springs could be used to create a viable correlation with drought conditions. Hydrologic data from springs in the Middle Verde River watershed were used to develop indicators and triggers that can be used to correlate and/or refine the existing ones used by the State. Geochemical data were interpreted in a variety of ways to characterize the behaviors of the springs and their supplying aquifers. Additionally, data from biological inventories conducted at many of the springs locations were utilized to support the physical and geochemical findings and strengthen the viability of the springs indicators and triggers.

It has been noted that trigger systems based on singular indices have not been able to adequately capture the intensity and severity of a drought and its potential impacts on the human and ecological systems involved (Heim, 2002), indicating the need of a drought quantification system based on a number of reliable indices. A successful set of drought triggers based on these indices can help identify the onset or increased severity of a drought and therefore assist in the initiation of drought response measures in a timely manner (U.S. Corps of Engineers, 1991).

Two problems encountered when trying to apply drought indicator and triggers in the semiarid West are that data recording locations such as weather stations and stream gages are more spatially separated than elsewhere, and that the historical record is often not extensive as in other areas. Long-term data that can be used as drought indicators are even less available in rural areas. Using well levels and/or streamflow data as drought indicators and triggers can be problematic, as the data are often influenced by pumping or storm-related discharge peaks, respectively, and therefore may not reveal an accurate assessment of overall hydrologic conditions. For example, a change in stream baseflow can indicate a change in aquifer storage, but it is unknown whether this change is a result of recharge rate change due to climate variability or from groundwater pumping (Bills, et al., 2007). Springs, because of their wide distribution and location in undeveloped areas, can act as an unbiased measure of response of the hydrologic system to climatic conditions.

Springs, which are located at the intersection of the groundwater flow system and land surface, provide a view into the aquifers supplying them. Additionally, spring discharge is often seen as a singular response to the hydrologic character of a much larger area in contrast to measurements such as precipitation, which are only a reliable measure of the conditions at that point. Using discharge rates as well as water-quality and geochemical data from a suite of springs located in several hydrostratigraphic units within the watershed (Table 1), statistical and trend analyses were compared with existing drought indicators such as precipitation, streamflow records, and reservoir levels to create a new set of indicators and triggers. A percentile ranking system similar to the one used by the State was used to rank the severity of the indicators and to trigger different levels of drought conditions. These methods could then be modified and extended to other semi-arid locations across the Southwest.

Table 1. Summary of 16 monthly monitored springs used in this study, including hydrostratigraphic information, location, and elevation.

Spring Name	Aquifer System	Discharge Unit	USGS Quad	UTM NAD83 N	UTM NAD83 E	Elevation (m)
Foster	Local	Tertiary Basalt	Stoneman Lake	3848090.57	453664.74	2,127
Campbell	Local	Tertiary Basalt/Kaibab Contact	Happy Jack	3845231.6	454572.54	2,099
Poison	Local	Tertiary Basalt	Garland Prairie	3888336.58	411144.83	2,034
Gray	Local	Tertiary Basalt	Garland Prairie	3887504	412306.73	2,040
Clover	Local	Kaibab Formation	Long Valley	3818313.75	466715.48	2,085
Pivot Rock	Local	Kaibab Formation	Pine	3816617.18	463428.26	2,131
Hackberry	Local	Tertiary Volcanic Alluvium	Hackberry Mountain	3810510	436791	1,246
Log	Local	Cherry Springs Granite	Cherry	3829390	401673	1,664
Grimes	Local	Payson Granite	North Peak	3785571.34	463697.54	1,361
Grapevine	Local	Payson Granite	North Peak	3785656.86	463229.44	1,302
Spring Creek	Regional	Verde Formation	Page Springs	3848591	415844	1,088
Russell	Regional	Verde Formation	Camp Verde	3831081.57	430313.11	1,092
Sterling	Regional	Coconino Sandstone	Mountainaire	3876069	432383	1,706
Pieper Hatchery	Regional	Schnebly Hill Formation	Kehl Ridge	3810436.1	476483.92	1,940
Tonto Bridge	Regional	Redwall/Naco Formations	Buckhead Mesa	3797928	458192	1,390
Summer	Regional	Lower Redwall	Sycamore Basin	3860325	402560.75	1,102

Expanding on the scope of this study, data and their interpretations will assist in the overall understanding of spring hydrology and will further current classification schemes of springs in the semiarid west, as with Springer, et al., (2006). Additionally, the data can be used for a better understanding of the riparian habitats supported by spring discharge. These areas are quite significant to the overall landscape, and these habitats often support a diversity of plant and animal species that is 100 to 500 times greater than surrounding areas (Grand Canyon Wildlands Council, 2004).

1.3 STUDY AREA

The Middle Verde River watershed is located in central Arizona (Figure 3). There are multiple definitions that describe the physical boundaries of the Middle Verde watershed to distinguish it from the Upper and Lower portions. The State of Arizona in the 2005 Arizona Revised Statutes defines the Middle Verde watershed as the area known as the Verde Valley, which runs from the USGS streamflow gage at Paulden to the streamflow gage below Camp Verde (Arizona State Legislature, 2005). The Arizona Department of Water Resources (ADWR) defines the Middle Verde watershed as the areas of the Verde Valley and Verde River canyon between the Paulden gauging station and the gauging station on the Verde River below Tangle Creek (ADWR, 2006). For the purposes of this study, the Middle Verde watershed is loosely defined as the portion of the watershed between the confluence of the Verde River and Sycamore Creek downstream to Horseshoe Reservoir (Figure 3). This description of the watershed will from here be referred to as the “study area”.

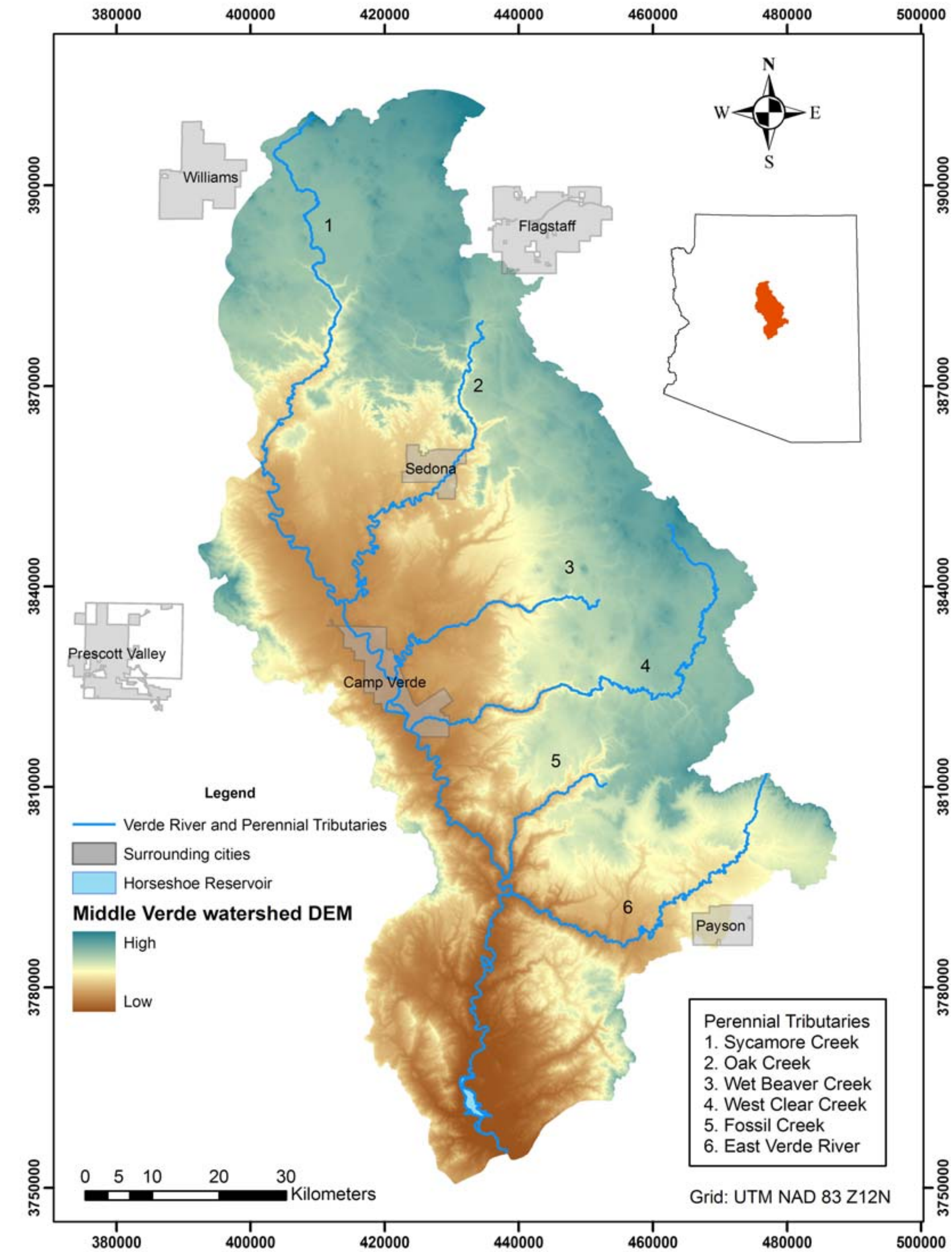


Figure 3. Study area map showing location of the study area within the state, elevation range within the watershed and the location of the Verde River and several perennial tributaries.

The study area encompasses more than 7,900 km^2 of central Arizona. The watershed is predominantly located in Yavapai County, which was the fastest growing rural county in the U.S. in 1999, with a population expected to more than double by 2050 (Woods and Poole Economics, 1999); smaller portions of the study area are located in Coconino, Gila, and Maricopa Counties. The area is primarily located in the Transition Zone physiographic province, a 60-100km-wide zone between the relatively stable Colorado Plateau and extensional Basin and Range physiographic provinces. Elevations in the watershed range from 2,812 meters above mean sea level (AMSL) near Hart Prairie on the western flank San Francisco Mountain northwest of Flagstaff to 610 meters AMSL along the Verde River above Horseshoe Dam near the Yavapai/Maricopa County line (extracted from a 10-meter Digital Elevation Model of the watershed). Other areas of higher elevation in the watershed include the Mogollon Rim of the Colorado Plateau, the Black Hills, and the Mazatzal Mountains. The Verde River has an average gradient between the confluence with Sycamore Creek and the Horseshoe Reservoir Dam (approximately the boundaries of the Middle Verde watershed) of 2.8 m/km (Flora, 2004).

Major tributaries of the Verde River within the study area include (from downriver to upriver) Tangle Creek (intermittent), East Verde River, Fossil Creek, West Clear Creek, Wet Beaver Creek, Oak Creek, and Sycamore Creek (Figure 3). With the exception of Tangle Creek, all of these tributaries originate on the higher elevations of the Coconino Plateau or the Mogollon Rim (Flora, 2004). The U.S. Geological Survey (USGS) operates stream gauging stations at all of these tributaries except Fossil and Sycamore Creeks. Stream gages are also located along the Verde River within the study area; one between Tangle Creek and Horseshoe Dam, one at Camp Verde, and one at Clarkdale (Figure 4) (USGS National Water Information System, 2006).

Two distinct precipitation periods occur within the study area. Winter precipitation of rain and snow accounts for the majority of the annual recharge (Bills, et al., 2007). Pacific Ocean-sourced frontal systems are the main source of this precipitation (Blasch, et al., 2006). During the summer, the monsoon season is the second major source of annual precipitation. The monsoon is the dominant climatological event in the Southwestern U.S. (Wright, et al., 2001). Low-level moisture is advected mostly from the northern Gulf of California and eastern Pacific Ocean, and to a lesser extent upper-level moisture is derived from the Gulf of Mexico. These two moisture sources are mixed over the Sierra Madre Occidental of Mexico before moving northward into the United States (Adams and Comrie, 1997). These storms are usually short but can be quite intense, and precipitation amounts have a high spatial variability due to the localized nature of the storms.

Monsoon (July-September) and winter (December-March) precipitation account for an average of 75% of the annual precipitation (Figure 5) from data collected for the study area from climate stations located on the Coconino Plateau, the Mogollon Rim, and the Verde Valley (Western Regional Climate Center, 2006 www.wrcc.dri.edu). Of the 75% of total precipitation throughout the year, proportions of winter (53%) and summer monsoon (47%) precipitation amounts are relatively similar. At the higher elevations of the Coconino Plateau, winter precipitation is a distinctly higher percentage than summer, with a distribution of approximately 60% and 40%, respectively (Bills, et al., 2007). Additionally, the effects of the cyclical ENSO can greatly influence the annual

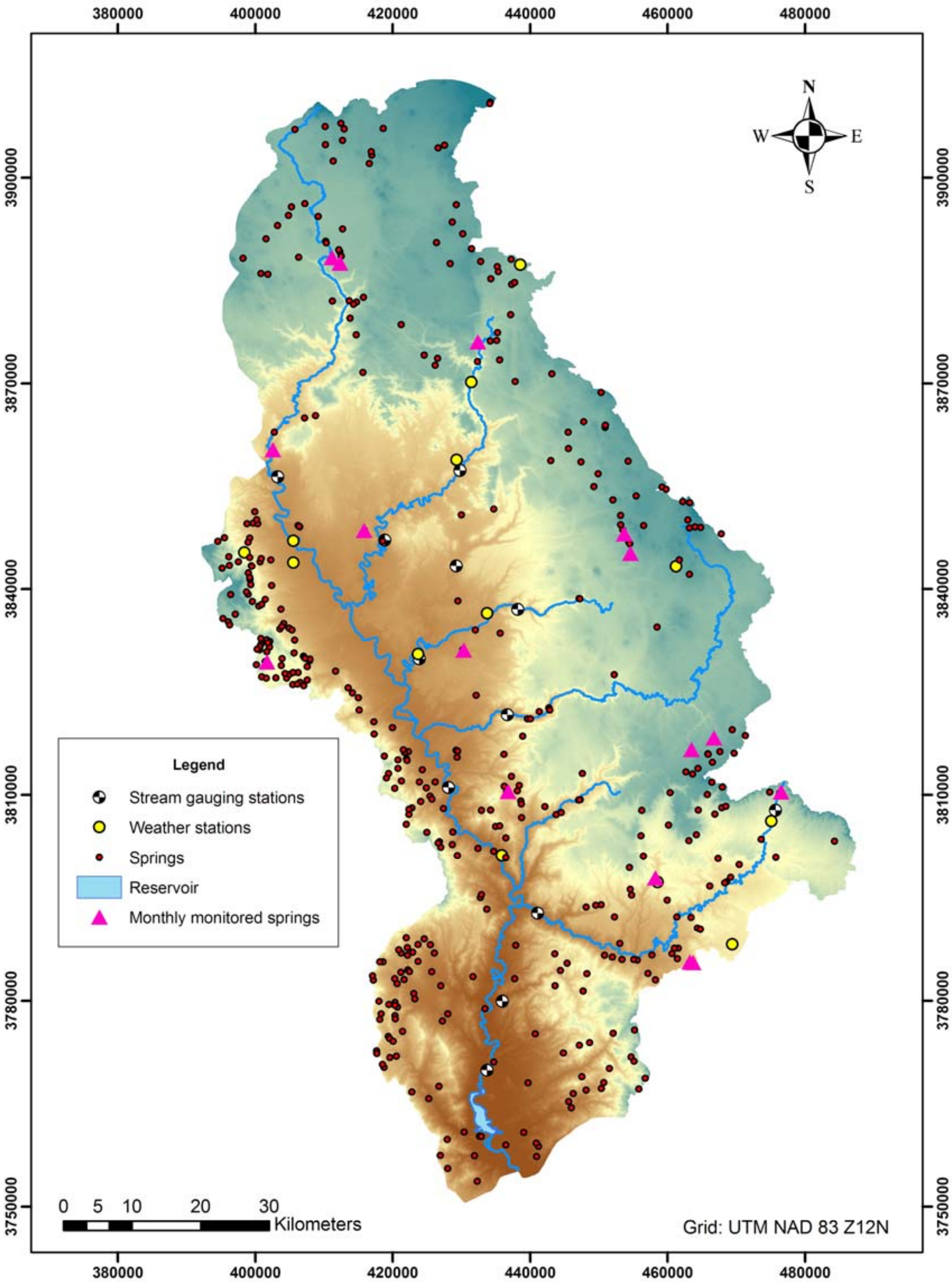


Figure 4. Study area with sources of hydrologic information including USGS stream gauging locations, weather stations, springs, and reservoirs.

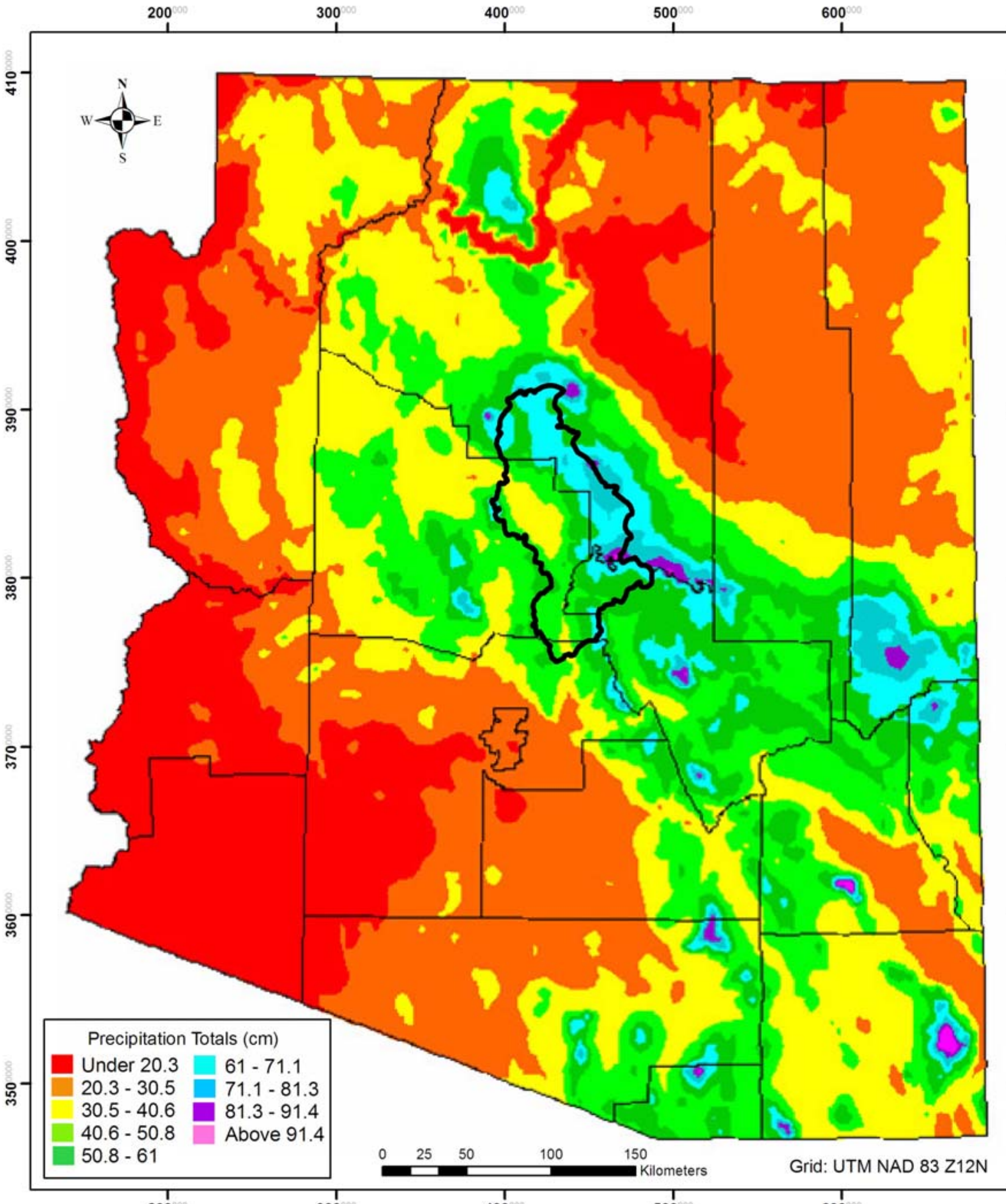


Figure 5. Average annual precipitation totals for Arizona. Study area is outlined. Modified from Daly (1998). 75% of the yearly precipitation in the study area occurs as winter rain and snow and summer monsoon storms. Of that, 53% is represented by winter precipitation and 47% as monsoon precipitation.

precipitation total (Figure 6). This cyclicity is often associated with drought/non-drought periods. Tree-ring records suggest that strong dry to wet precipitation reversals in the past 1,000 years might be linked to strong shifts from cold to warm ENSO oscillation events and from a negative to positive Pacific Decadal Oscillation (PDO) (Ni, et al., 2002).

1.4 GEOLOGY AND HYDROGEOLOGY

Geologic units in the study area range from Precambrian basement rocks and Paleozoic sedimentary rocks to Tertiary and Quaternary extrusive igneous rocks and alluvium (Figure 7), with scattered Mesozoic rocks of Triassic and Cretaceous age. This wide range of materials is also reflected in a wide range of spring types, discharge characteristics, and geochemical signatures throughout the study area. Much of the study area topography is controlled by the presence of numerous faults trending in a preferentially north-northwest direction (Parker et. al., 2004). The most prominent of these faults is the Verde Fault Zone, which creates the large valley between Clarkdale and Camp Verde (Figure 8). The Verde Fault has up to 1,829 meters of offset (Ranney, 1989), the largest offset in the study area. Along the Mogollon Rim and on the Colorado Plateau, the Paleozoic sedimentary sequence is the dominant exposure. Much of the southern Colorado Plateau within the study area is capped by Tertiary extrusive volcanic rocks (Figure 9).

1.4.1 Proterozoic / Cambrian Rocks

Rocks of Proterozoic age are found near Payson and in the Black Hills. These rocks are predominantly granitic and metamorphic in composition.

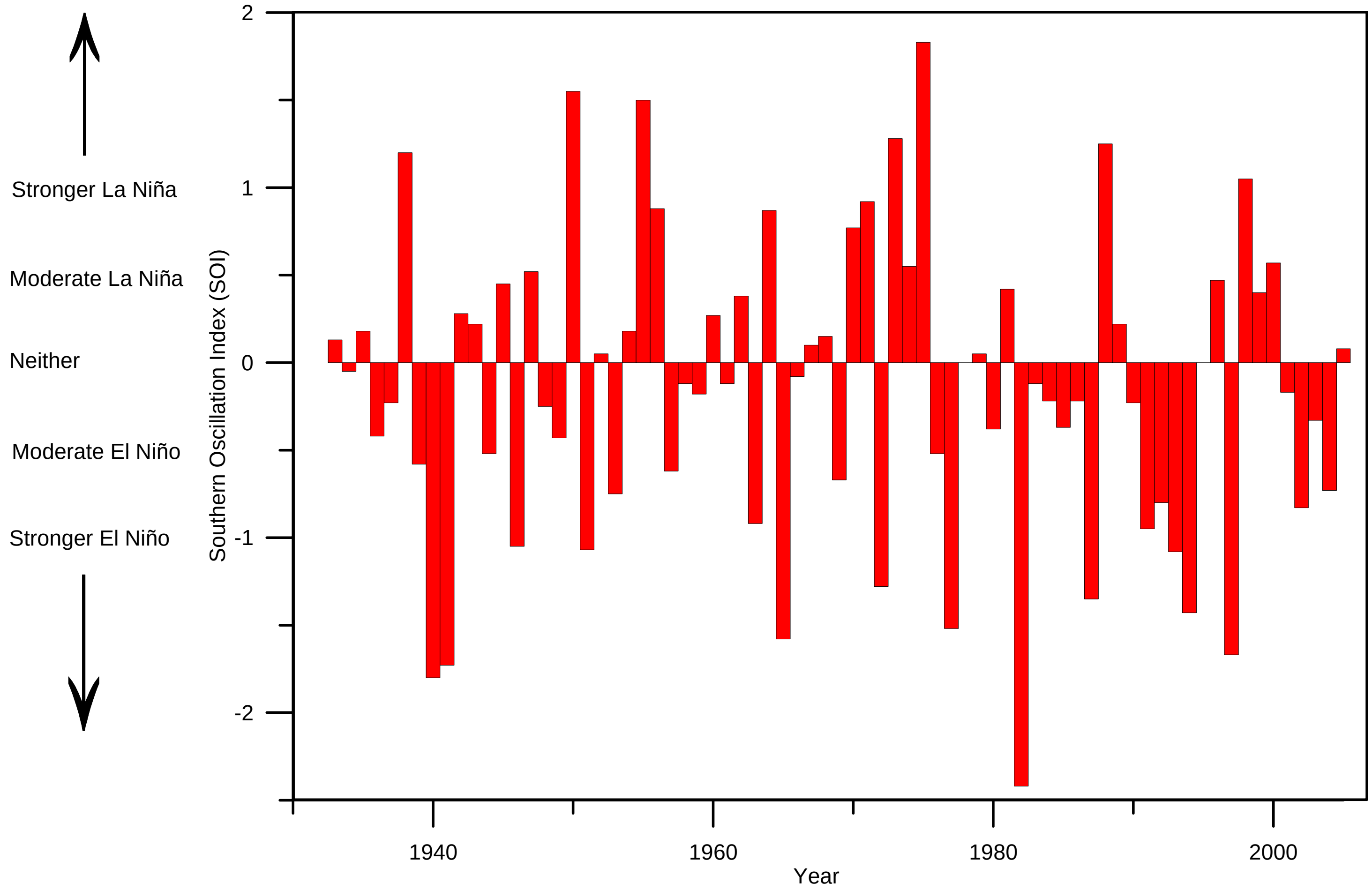


Figure 6. – Distribution of El Niño and La Niña years from 1933 to 2005 based on the Southern Oscillation Index (SOI). Data from the Western Regional Climate Center (2006), www.wrcc.dri.edu.

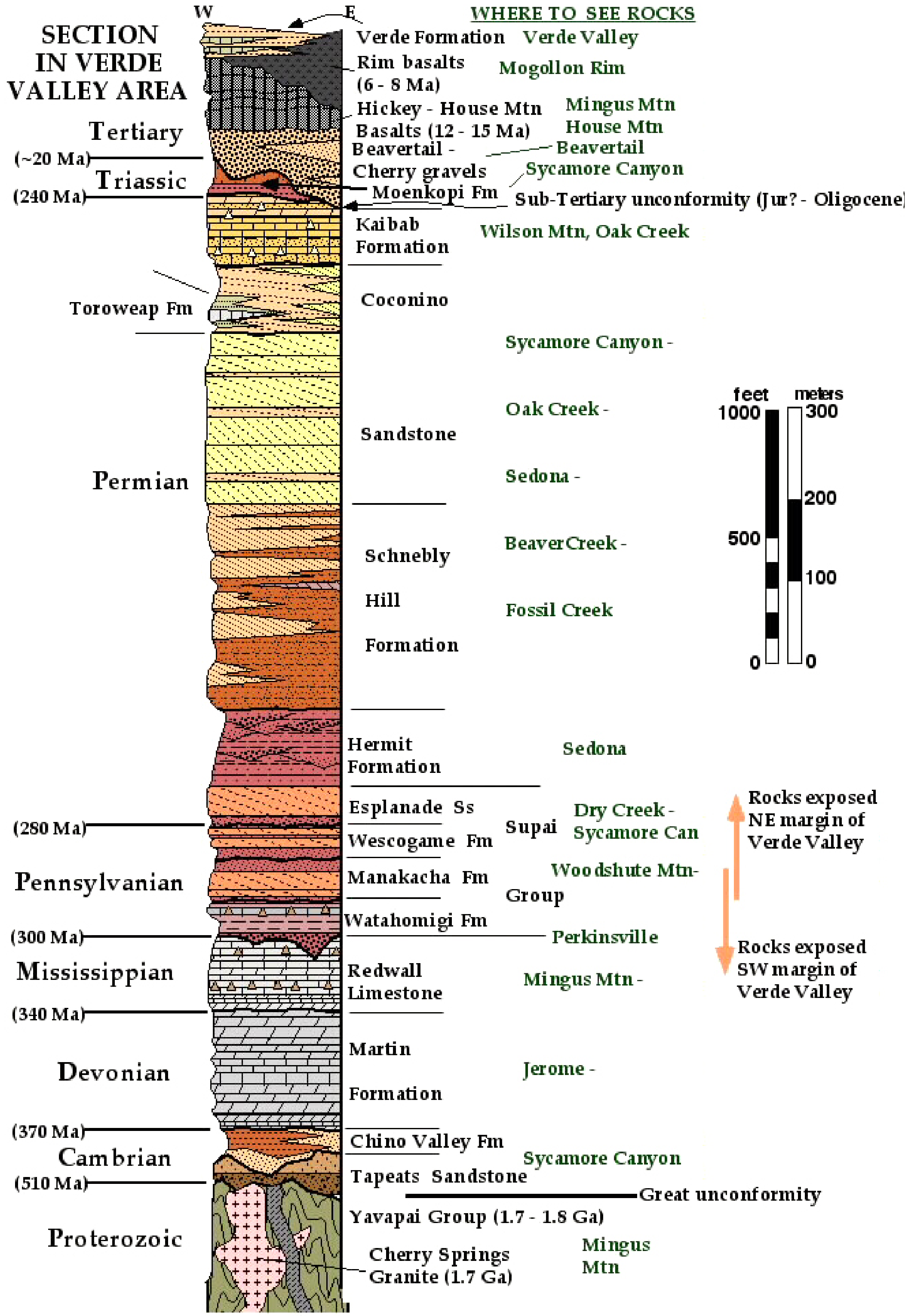


Figure 7. Generalized cross section in the Verde Valley, from R. Blakey, http://jan.ucc.nau.edu/~rcb7/Verde_col.jpg.

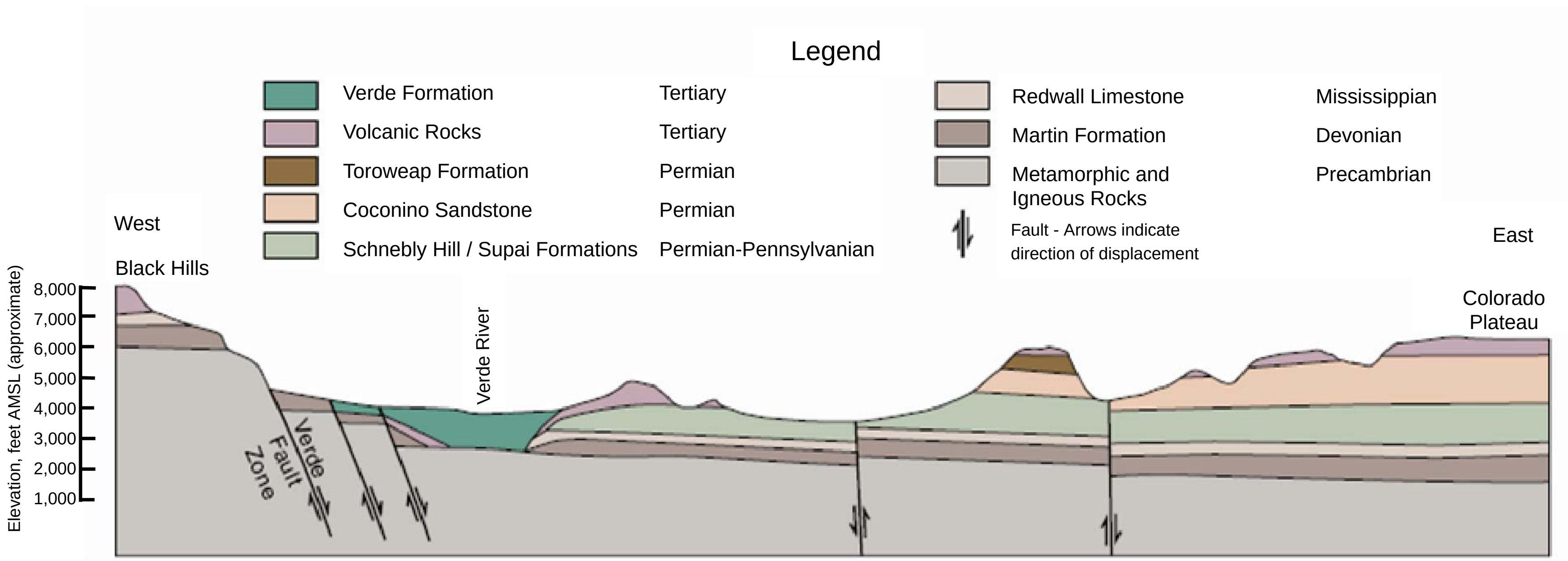


Figure 8. Generalized geologic cross-section of the Verde Valley from the Black Hills to the Colorado Plateau. Modified from Woodhouse, et al., 2002 (no vertical exaggeration).

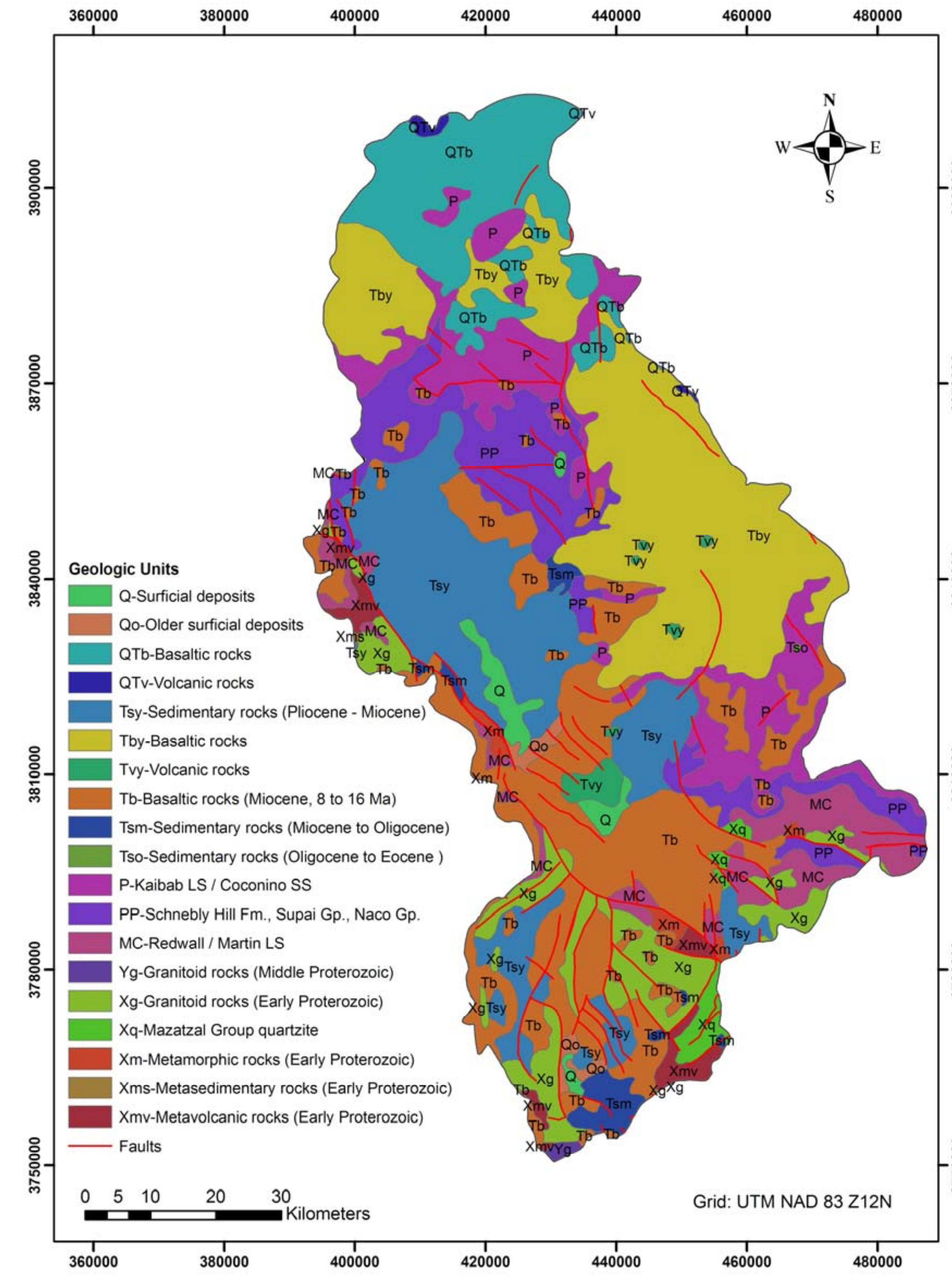


Figure 9. Geologic map of the study area. Geologic units from Arizona Land Resource Information System (ALRIS) metadata.

The Payson Granite is a tan to reddish potassium feldspathic (K-spar) granite dated to approximately 1.7 Ga (Parker et al., 2004). The Cherry Springs granite is located in the Black Hills and is part of a local batholith complex that is dated to approximately 1.74 to 1.80 Ga (Condie, 1982). Some Precambrian metamorphic schists and gneisses are found in the Yavapai Group near Jerome (Flora, 2004) and the Precambrian Mazatzal quartzite is also found near Payson. These units have an overall low permeability and springs found in these areas generally have low discharge volumes. High volume springs and productive wells do exist in these units when located within fracture zones (Parker, et al., 2004). The Cambrian Tapeats Sandstone, the lowermost unit of Paleozoic deposition in the study area, is composed mainly of a brown to reddish-brown medium to coarse-grained feldspathic sandstone (Bills, et al., 2007). Exposures of this unit are not abundant and are discontinuous in the region (Hereford, 1977), and an unconformity exists over the underlying Precambrian granitic rocks. Exposures occur in the upper portion of the Verde Valley as well as near Payson (Bills, et al., 2007).

1.4.2 Lower Paleozoic Carbonates

Two major limestone units located in the Verde River watershed are of lower Paleozoic age. The Martin Formation is of Devonian age and unconformably overlies the Cambrian Tapeats Sandstone (Ranney, 1989). This formation is exposed primarily in the northern portion of the watershed and along the Mogollon Rim near Payson and in the Black Hills. It is composed of a gray dolomitic limestone with interbeds of shaly mudstone. The lower Becker Butte member is up to 50 meters thick but is missing in most areas. The upper Jerome member is less than 30 meters thick northeast of the

Mogollon Rim but is nearly 120 meters thick at Tonto Natural Bridge State Park (Parker, et al., 2004).

The Mississippian Redwall Formation overlies the Martin Formation and is composed of a reddish-gray limestone and is commonly highly fractured and cavernous due to long periods of surface exposure in Late Mississippian time that led to karst development (Parker et al., 2004). The Redwall Formation ranges from less than 15 meters thick, to over 30 meters at Fossil Creek, and up to 150 meters northwest of Pine (Parker, et al., 2004). The Redwall and Martin formations formed in shallow marine depositional environments.

1.4.3 Upper Paleozoic Limestone and Sandstone

The Naco Formation (Pennsylvanian) is present above an unconformity with the underlying Redwall Formation limestone, and is only in the eastern portion of the Mogollon Rim from Fossil Creek eastward (Blakey, 1990). It is composed of limestone and mudstone beds. The transition from limestone to mudstone represents the changing position of the coastline at that time (Parker et. al., 2004). The formation ranges in thickness from 100m at Fossil Creek to over 200m in the Fort Apache area (east of the study area) (Blakey, 1990).

The Supai Group (Pennsylvanian/Permian) is composed of red sandstone, siltstone, and gray limestone and overlies an unconformity above the Redwall Limestone or the Naco Formation where present (Blakey, 1990). It is up to 200 meters thick near Sedona but averages approximately 90 meters thick (Blakey, 1990). The overlying Hermit Formation (Permian) is composed of sandy mudstone and siltstone. These two units are poor aquifers in the study area and springs sourced in these units generally have low discharge rates. The Permian Schnebly Hill Formation overlies the Hermit Formation and is up to 600 meters thick near Holbrook, northeast of the study area but thins in all directions away from this basin (Blakey, 1990). It is mainly composed of thick reddish-orange sandstones with minor siltstone and mudstone. Deposition of this geologic unit occurred in response to rapid subsidence of the Holbrook Basin (Blakey, 1990). The Fort Apache Member of the Schnebly Hill consists of a 15-18 meter thick carbonate layer which is mostly limestone, but transitions to dolomite to the north (Parker, et al., 2004). Through most of its occurrence, the Schnebly Hill Formation lies unconformably on the Hermit Formation or the Supai Group. The formation thins quickly to the north and is not present in well cuttings from the Flagstaff area (Bills, et al., 2007).

The Permian Coconino Sandstone is approximately 200 meters thick and has a gradational/intertonguing contact with the underlying Schnebly Hill Formation (Blakey, 1990). The Coconino Sandstone is nearly nonexistent at Milk Ranch Point, and has a maximum thickness of approximately 370 meters near the headwaters of the East Verde River (Parker, et al., 2004). It is primarily composed of fine grained cross-bedded eolian sandstone. The lower portion of the unit is continuous throughout the study area along the Mogollon Rim, and the upper portion grades into the Toroweap Formation, a carbonate, sandstone, and red bed complex, along Sycamore Canyon near the northwestern extent of the study area (Blakey, 1990). The Coconino Sandstone has a relatively high porosity and is a principal regional groundwater source aquifer. The

Coconino Formation is particularly productive where secondary porosity is enhanced along fault and fracture zones.

The Permian Kaibab Formation is approximately 90 meters thick and consists of a fossiliferous gray to tan cherty fractured limestone with interbeds of mudstone and poorly cemented sandstone (Weisman, 1984). The unit has locally developed karst topography, producing high secondary permeability that enhances the production of springs found in the unit.

1.4.4 Tertiary Volcanic Rocks

Pliocene and Miocene age basaltic lava flows cap much of the Colorado Plateau within the study area (Figure 9). These deposits are commonly faulted and fractured, which leads to small local water supplies as perched aquifers (Flora, 2004). Additionally, tuff, agglomerates, and cinders are located within the Verde Valley between Camp Verde and Fossil Creek (Weisman, 1984).

1.4.5 Verde Formation

The Miocene to Pliocene Verde Formation is up to 915 meters thick in the Verde Valley (Figure 9). This unit formed as the rapid subsidence of the valley caused the Verde River to be impounded. This allowed thick deposits of fluvial and lacustrine sediments to be preserved. Siliciclastic and shallow water carbonate deposits dominate the composition of the Verde Formation, but it also contains interbeddings of evaporites, conglomerates, and basalt flows. The Verde Formation makes up a large-area unconfined aquifer for the Verde Valley, and several large springs discharge from it.

1.4.6 General Hydrogeologic Characteristics

Perennial flow in the Verde River starts with the discharge of Big Chino Springs near Paulden, approximately 1.5 km south of Sullivan Lake. Source water to these springs has been identified as primarily the Big Chino Valley basin fill aquifer with a smaller percentage (up to 15%) from the regional limestone aquifer (Martin and Redwall Fms.) (Wirt and DeWitt, 2005, Fry, 2006). Substantial increases in the baseflow of the Verde River between Paulden and Clarkdale are attributed to spring discharges from the regional limestone aquifer (Bills, et al., 2007). The watershed as a whole receives most of its recharge during the winter, especially at higher elevations where snowpack accumulates and recharges the underlying aquifers. The Arizona Department of Water Resources (ADWR) estimated 2.31×10^8 m^3 (approximately 188,000 acre-feet) of annual recharge to the watershed between Paulden and Tangle Creek (ADWR, 2000). Blasch, et al. (2006) estimated 1.80×10^8 m^3 (approximately 146,000 acre-feet) of annual recharge to the Verde Valley sub-basin. Two regional aquifers have been identified for the watershed, a lower limestone aquifer made up of the Martin Formation, Redwall Formation, and (locally) Naco Formation ("R" aquifer) and an upper sandstone aquifer made up of the Schnebly Hill Formation and the Coconino Sandstone ("C" aquifer) (Flora, 2004). Where these units are saturated, the lower fine-grained units of the Supai Group act as an aquitard which reduces the hydrologic communication of the two aquifer systems (Blasch, et al., 2006), and the R-aquifer is confined for much of its occurrence with hydraulic heads up to several hundred feet above the top of the aquifer (Bills, et al., 2007). Communication between the two regional aquifers exists where faulting and fracturing of the aquitard exists. There are also smaller local aquifer systems represented by the Kaibab Formation and basalt flow aquifers, and the Verde Formation, which is predominantly fed from the regional aquifers as they discharge into the Verde Valley. Groundwater movement within the study area is predominantly south from the Flagstaff area, southwest from the Mormon Mountain monocline on the Mogollon Rim, northeast from the Black Hills, and southeast from the headwaters area near Big Chino Valley (Blasch, et al., 2006) (Figure 10). Groundwater divides exist west of Flagstaff near Bellemont (Figure 11), at the Mormon Mountain monocline and the Black Hills. The Verde River flows freely, with some agricultural diversions between Clarkdale and Camp Verde, until it reaches Horseshoe Reservoir near the Yavapai-Maricopa County line and it terminates at the confluence with the Salt River between Highway 87 (Beeline Highway) and the City of Mesa.

1.5 PREVIOUS STUDIES

1.5.1 Physical and Geochemical Investigations

One of the first hydrogeologic studies of the Verde River watershed was conducted by Twenter and Metzger (1963). This study included discharge data from 16 springs within the watershed but was a collection of point data not suitable for estimating average discharge rates for the springs. A later study was conducted by Owen-Joyce and Bell (1983) and included a survey of 97 springs in the Upper Verde River area. Discharges and a few selected parameters were reported for these springs, but once again these were singular measurements. The USGS has a database of over 300 springs that have been visited and had discharge and/or water sampling conducted (USGS, 2002).

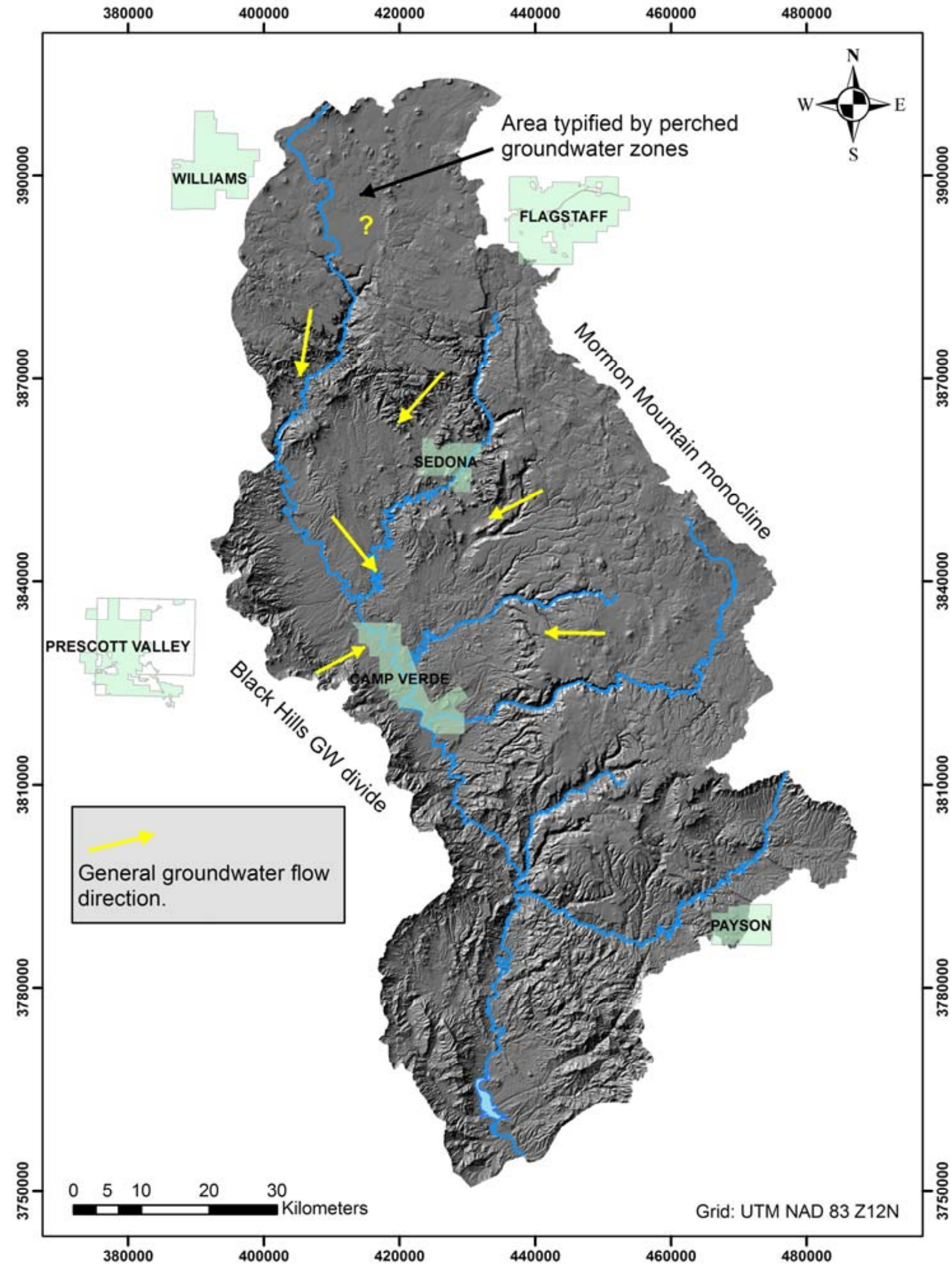


Figure 10. Generalized groundwater flow directions in the vicinity of three main groundwater divides located around the study area. Flow directions based on groundwater elevations in wells from Blasch, et al., (2006). The groundwater divide located near Bellemont between Flagstaff and Williams is associated with groundwater mounding due to recharge and its location changes in response to recharge rates and groundwater withdrawal in the area (Blasch, et al., 2006).

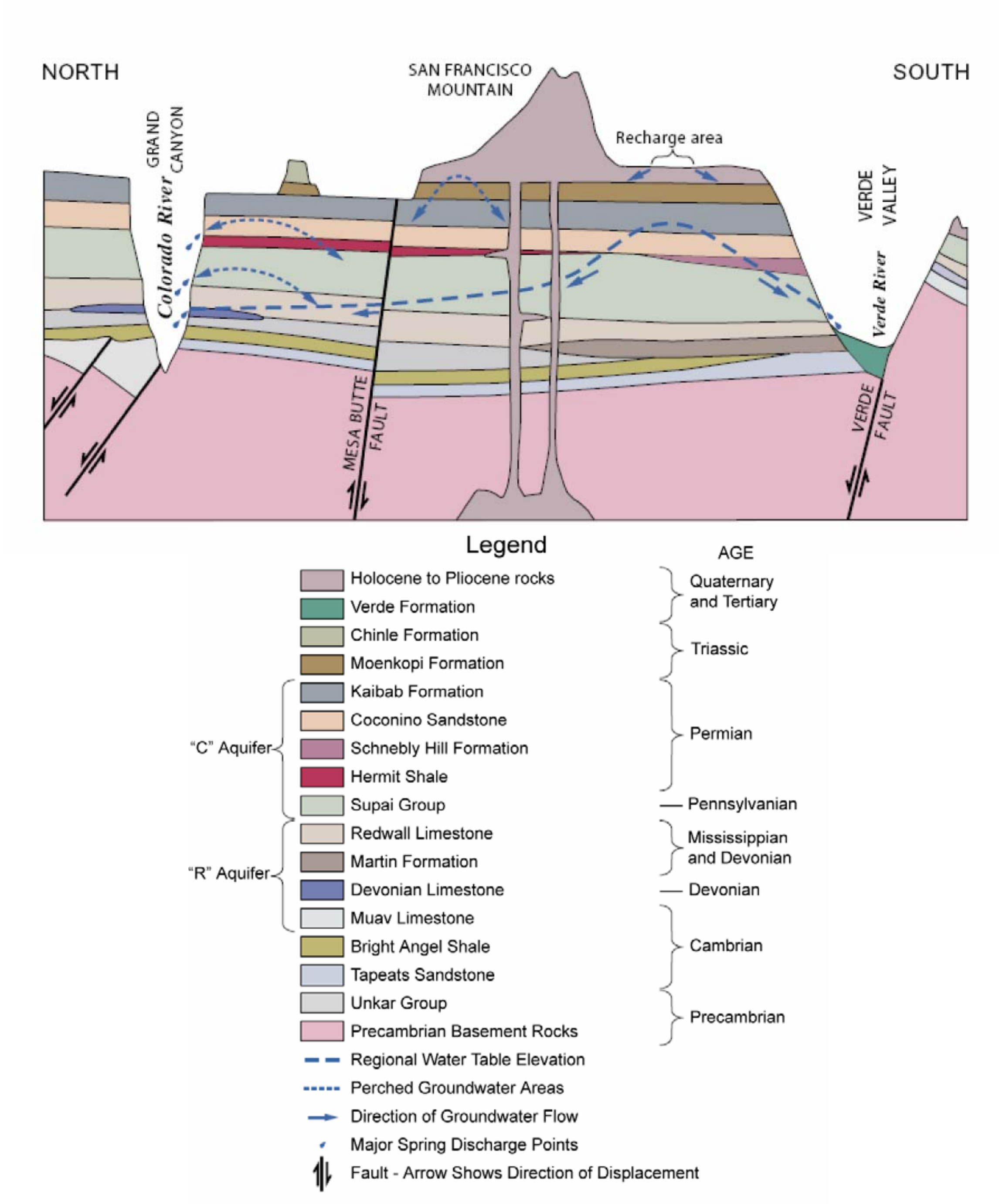


Figure 11. Generalized hydrogeologic cross-section from the Colorado River to the Verde River. One of the groundwater divides in the study area (Between Flagstaff and Williams) is shown near San Francisco Mountain. Modified from Flynn and Bills, 2002, from data from Breed and Beasley, 1975; not to scale.

These measurements were collected between 1950 and 2000. The U.S. Forest Service (USFS) also has a database of 160 springs (which were used for the 2002-2003 Flora inventories) in the study area between Sycamore Creek and the East Verde River (USFS, 2000). Information including location, elevation, geologic unit, and discharge were recorded. An investigation of the sources of the base flow to the Verde River headwaters using physical and geochemical data was conducted by Wirt and Hjalmarson (2000) and Wirt, et al. (2005) and a predominantly geochemical investigation of groundwater-surface water interactions in the same area was completed by Knauth and Greenbie (1997). A recent report on the hydrogeology of the Upper and Middle Verde watersheds was issued by Blasch, et al. (2006). The ADWR reports 335 springs in the study area, in a report summarizing the Arizona Land Resources Information Systems (ALRIS) (ADWR, 2000). Spring locations in that report were taken from the USGS NWIS database.

A comprehensive, synoptic study of 160 springs in the Middle Verde River watershed was conducted during the summer of 2002 by a previous Master's student at Northern Arizona University (NAU) (Flora, 2004). At each spring location, data describing discharge rate and water-quality parameters including pH, conductivity, and temperature as well as highly accurate GPS locations were collected. Additionally, information about the source geology, channel morphology, and ecological data including plants and animals present was collected. These data were compiled into a database and the physical, chemical, and ecological characteristics of the springs were used to develop a classification for springs in semi-arid landscapes (Flora, 2004).

A second phase to this initial spring inventory included selection of 16 springs representing the majority of hydrostratigraphic units within the study area for monthly monitoring over a one-year period. Three springs are located in Precambrian basement rocks, two in Devonian and Mississippian limestones, two in Permian sandstones, two in Permian karstic limestones, four in Tertiary basalt flows, and three in Quaternary deposits. Each month, discharge and water-quality parameters were collected and hydrographs were created to visualize the discharge trends throughout the year. Additionally, water samples were collected for laboratory analysis of oxygen and hydrogen isotopes ($\delta^{18}O$ and $\delta^{2}H$) at three seasonal intervals (December 2002, May 2003, and October 2003). These discharge and chemical data will be combined with the data collected in this study for the generation of drought indicators and triggers.

Studies of the Upper and Middle Verde watershed (Woodhouse, et al., 2002, Wirt, et al., 2005, and Blasch, et al., 2006), the Mogollon highlands (Parker and Flynn, 2000, Parker, et al., 2004), and the Coconino Plateau (Bills, et al., 2007, Flynn and Bills, 2002, Bills and Flynn, 2002, Bills, et al., 2000) were conducted through the USGS Arizona Rural Watershed Initiative (RWI). The information from these investigations will be used to develop numerical models that simulate the hydrogeologic system. These models will later be used to examine various development scenarios in the watershed.

Studies of the physical and geochemical characteristics of springs have been conducted in a variety of other locations that compliment the work being done in the Middle Verde watershed. Work done by Manga (1996, 1999, 2001) on flowpath and residence time of spring waters, Desmarais and Rojstaczer (2002) on source water investigations of karstic springs, the analysis of spring hydrographs and chemographs by

Grasso, et al. (2003), Padilla and Pulido-Bosch (1995) and Bonacci (1993), and the role of stable isotopes in spring water characterization by Ingraham, et al. (1991) are a few of the useful investigations whose methods and interpretations can be applied to the current study.

1.5.2 Drought Indicators and Triggers

The Arizona Drought Task Force's Monitoring Technical Committee has developed drought indicators and triggers using hydrologic data from the Middle Verde watershed, primarily the Standard Precipitation Index (SPI) and stream discharge records, as well as other statewide data (ADPP, 2004). Drought indicators and triggers have been developed in other parts of the country using a variety of hydrologic parameters such as streamflow (Rouhani and Cargile, 1989), groundwater levels (Schreffler, 1997), reservoir levels (Hoffman, 2003), and combinations of parameters such as precipitation, streamflow, and Palmer Hydrologic Index (Rao and Voeller, 1997). Many of the indices used to create drought triggers have shortcomings if used individually (Fisher and Palmer, 1997), which supports the need for multiple indices to create a more complete definitions of drought.

CHAPTER 2 - METHODS

2.1 EXISTING DATA COLLECTION

Information was gathered from a variety of sources which assisted in the evaluations and interpretations of the potential use of springs as drought indicators. Data sources included previous spring inventories by governmental agencies and a previous Master's thesis, climate and drought related data from a variety of local and regional collection sources, and Geographic Information System (GIS) data sets which allow the collected data to be visualized spatially.

2.1.1 Springs Data

Several previous investigations in the study area created databases of springs that were compiled for this study. A comprehensive inventory of 160 springs in the study springs was conducted in 2002-2003 by a Northern Arizona University (NAU) student (Flora, 2004). This thesis also incorporated information from investigations made by the USGS and the USFS. Data most relevant to this study from this database investigations included springs locations, geologic unit, elevation, and historic measurements of discharge, water-quality parameters and geochemical data.

2.1.2 Climate / Streamflow Data

Climate data, including monthly air temperature averages and precipitation totals, were obtained from three climate stations selected by the period of operation and location within the study area. To best represent the variability of climates due to the size of the study area and the large variation in elevations, one station was selected from the Colorado Plateau (Flagstaff Airport, high elevations), the Mogollon Rim (Town of Payson, intermediate elevations), and the Verde Valley (Tuzigoot National Monument, low elevations). Data from these stations were obtained by the Western Regional Climate Center (WRCC, 2006, www.wrcc.dri.edu). In addition to the climate data from these individual stations, regional summary data were obtained from the National Oceanic and Atmosphere Administration (NOAA) Climate Division Dataset. The majority of the study area is located in the Arizona Region 3 (North Central) climate division. Data on division-wide averages of temperature, precipitation and the Palmer Drought Severity Index (PDSI) were downloaded for the period of record, 1948 to present (2006). Monthly average streamflow data were obtained from the USGS stream gages located in the study area in the USGS NWIS Real-time Database for Arizona (USGS, 2006). The locations, periods of record, elevation (climate stations only) and drainage area (stream gages only) for the local climate and streamflow data used in this study were summarized (Table 2).

To compare the drought level designations generated from the springs data to those generated by the State for similar time periods using different climate data sets, the database of drought information and level designations as used by the State was acquired from the Arizona Department of Water Resources (ADWR). The ADWR holds the raw data and the calculated drought-level designations for a number of watersheds in the State. These drought level designations are calculated by the State's Monitoring Technical Committee (MTC) based on the percentile ranking system described in detail

Table 2. Location, period of record and other pertinent data for selected climate stations (A) and stream gages (B) in the study area.

A)

Station Name	Station ID	UTM NAD 83 N	UTM NAD 83 E	Period of record	Elevation (m)
Flagstaff Airport	23010	3887286.86	438556.75	1950-2006	2,137
Town of Payson	26323	3788214.25	469402.95	1940-2006	1,527
Tuzigoot National Monument	28904	3847061.83	405552.83	1977-2006	1,058

B)

Gaging Location	Gage ID	UTM NAD 83 N	UTM NAD 83 E	Period of record	Drainage Area km^2
Verde River at Clarkdale	9504000	3856428	403281.11	1915-2006	9,073
Oak Creek near Sedona	9504420	3857333.53	429813.18	1981-2006	603
Oak Creek near Cornville	9504500	3847182.07	418846.75	1940-2006	919
Wet Beaver Creek near Rimrock	9505200	3837040.12	438234.63	1961-2006	287
Dry Beaver Creek near Rimrock	9505350	3843378.84	429260.36	1960-2006	368
Beaver Creek near Lake Montezuma	9505400	3829839.25	423891.59	2004-2006	?
West Clear Creek near Camp Verde	9505800	3821736.7	436690.61	1964-2006	624
Verde River near Camp Verde	9506000	3811078.33	428127.89	1934-2006	12,973
East Verde River Diversion	9507580	3807752.88	475728.44	1965-2006	NA
East Verde River near Childs	9507980	3792792.79	441107.51	1961-2006	857
Wet Bottom Creek near Childs	9508300	3779988.93	435969.88	1967-2006	94
Verde River below Tangle Creek	9508500	433726.03	3769884.42	1945-2006	15,172

in the Arizona Drought Protection Plan (ADPP, 2004). Essentially, hydrologic data are converted to a percentile of historic averages of that data (highest precipitation being the 99th percentile, lowest precipitation the 1st percentile). The percentiles are then grouped and assigned a drought level based on a scale from 0 (no drought) to 4 (extreme drought). These assignments are explained in detail in section 2.5.6. Data used in the MTC database include discharge data from six USGS stream gages in the study area, as well as the Standardized Precipitation Index (SPI) for periods of 3, 6, 12, 24, 36, and 48 months. The 3, 6, and 12-month SPI data were used to calculate short-term drought conditions, while the 24, 36, and 48-month data were used to calculate long-term drought conditions. Drought level designations were then generated on a monthly basis based on the percentile ranking system for a period of record from January 1975 to October 2006.

2.1.3 Geographic Information Systems (GIS) Data

Much of the spatial information used to both visualize and perform analyses on the data collected in this study was obtained from outside sources. The Digital Elevation Model (DEM) files used to construct the 1/3 arc-second (10-meter) resolution DEM of the study area was obtained from the USGS Earth Resources Observation and Sciences (EROS) Data Center, part of the National Elevation Dataset (NED). Much of the remainder of the GIS data was provided in shapefile format from State agencies primarily provided by the Arizona Land Resource Information System (ALRIS), which is free upon request. Data files included information on cities, roads, towns, vegetation and watersheds, among others. The ADWR provided data on the geology and locations of faults and wells. Raster map files of georeferenced scans of USGS 7.5-minute quad sheets were downloaded from the Arizona Regional Image Archive (ARIA) at the University of Arizona. Finally, GPS locations of the 160 inventoried springs during the 2002-2003 survey were converted and imported (Flora, 2004). A summary of all the externally-acquired GIS data is provided in Table 3.

These shapefiles and rasters were organized into a Geodatabase using the ArcGIS suite of software (ESRI, Redlands, CA) to centrally locate and streamline data organization. Files were organized into similar “feature datasets” including geology, hydrology, springs, State data, and raster information. The data were projected to the Universal Transverse Mercator (UTM) system based on the 1983 North American Datum in Zone 12 North (Central Arizona) (UTM NAD83 Z12N). All externally-acquired GIS data were re-projected to this system for consistency purposes.

2.2 FIELD METHODS

Field methods for collection of discharge rates, water-quality parameters, and collection for geochemical analysis were similar to those employed by Flora (2004) during an investigation to the same selected set of 16 springs in 2002-2003. Discharge and water-quality parameter collection was resumed at this set of 16 springs in July 2005 and continued monthly through June 2006. The first set of geochemical samples was collected in October 2005 and continued on a seasonal basis thereafter.

2.2.1 Discharge Data Collection

Discharge was measured at each of the spring locations using a method most appropriate to the volume of water discharged as well as the morphology of the orifice

Table 3. Summary of GIS data and layers acquired and used in the study. Source locations are described in the footnotes.

Geodatabase Feature Class	Layer Data	Source Location
Geology	Geology	ADWR[1] (via ALRIS)
	Faults	ADWR
	Wells	ADWR
Hydrology	Reserviors	ALRIS[2]
	HUCS (hydrologic unit codes)	ALRIS
	Irrigation	ALRIS
	Lakes	ALRIS
	Riparian Areas	ALRIS
	Streams	ALRIS
Infrastructure	Interstates	ALRIS
	Towns	ALRIS
	Cities	ALRIS
	Counties	ALRIS
Springs	160 inventoried springs (2002-2003)	GPS data (Flora, 2004)
	16 monthly inventoried springs	GPS data (Flora, 2004)
	All springs (432)	ALRIS
State Data	Indian Reservations	ALRIS
	Mines	ALRIS
	Native Vegetaion	ALRIS
	USGS 7.5' Quad Grid	ALRIS
	State Outline	ALRIS
	Wilderness Areas	ALRIS
Raster Files	Watershed DEM[3]	USGS EROS[4] Data Center
	Buckhead Mesa DRG[5]	ARIA[6]
	Cherry DRG	ARIA
	Camp Verde DRG	ARIA
	Happy Jack DRG	ARIA
	Hackberry Mountain DRG	ARIA
	Kehl Ridge DRG	ARIA
	Long Valley DRG	ARIA
	Mountainaire DRG	ARIA
	North Peak DRG	ARIA
	Page Springs DRG	ARIA
	Pine DRG	ARIA
	Stoneman Lake DRG	ARIA
	Sycamore Canyon DRG	ARIA
	Wing Mountain DRG	ARIA

[1] Arizona Department of Water Resources (www.azwater.gov/)
[2] Arizona Land Resource Information System (www.land.state.az.us/alris/)
[3] Digital Elevation Model
[4] Earth Resources Observation and Sciences (edc.usgs.gov/)
[5] Digital Raster Graphic
[6] Arizona Regional Image Archive (aria.arizona.edu/)

and channel (if present) as well as the substrate at the site. Discharge rates in this study are presented as liters per second (L/sec), or cubic meters per second (m^3/sec) when referring to large discharge rates or streamflow rates. For low discharge springs with an easily captured discharge, a volumetric container was used to calculate the volume per unit time flow rate. Where springs did not have an easily captured discharge and a soft channel substrate, a weir plate was used. A 45° weir plate was used for all applicable measurements in this study (Figure 12). The weir plate was useful for measuring discharge rates between approximately 0.008 and 0.63 L/sec. For springs with an intermediate discharge and a defined channel, a flume was used to measure flow. The flume was a portable cutthroat variety manufactured by Baski, Inc. (Denver, CO). The flume can be assembled with a 1-inch or 8-inch throat depending on the magnitude of the discharge (Figure 13). Large discharge springs (over approximately 32 L/sec) require the use of a flow meter. A Swoffer 3000, manufactured by Swoffer Instruments, Inc. (Seattle, WA) was used for all high discharge measurements. For the flow-metering data collection method, the discharge channel was subdivided into equal-area cross-sections that were multiplied by the velocity of the discharge in that area at a depth of 60% of the total depth of flow. This velocity multiplied by the cross-sectional area of the channel section results in a volume per unit time value (m^3/sec). The monitored springs that required a flow meter to measure discharge were Summer Spring and on occasion based on discharge rate Sterling Spring as well.

Figure 12. Discharge measurement using a 45° weir plate, Campbell Spring (Tertiary basalt), December 2005.

A

B

Figure 13. Examples of discharge measurement using the portable cutthroat flume. The 8-inch throat (A) at Clover Spring (Permian Kaibab Fm.), August 2005. The 1-inch throat is shown (B) at Russell Spring (Tertiary Verde Fm.), October 2005.

2.2.2 *Water-quality Parameter Collection*

A Troll9000 multi-parameter sensor, manufactured by In-Situ, Inc. (Fort Collins, CO), was used to collect field water-quality parameters during each site visit. The unit measured temperature (°C), pH, specific conductance (µS/cm), and dissolved oxygen concentrations (mg/L) simultaneously. The data were stored on a rugged handheld computer taken into the field with the sensor. Figure 14 shows this unit in use in the field.

2.2.3 *Seasonal Wet/Dry Springs Inventory*

In addition to the monthly monitoring of the 16 selected springs in the study area, a large number of other springs were visited throughout the study area to investigate the response of springs to seasonal (short-term) climate changes. Half of the springs visited in the study area (80 of 160) during the initial survey during the summer of 2002 were dry (no measurable discharge) (Flora, 2004). The first task was to assess the response of a number of springs to the wet winter of 2004-2005. In July and August 2005, 57 of the 80 springs that were dry in 2002 were revisited. Then, after a remarkably dry winter of 2005-2006, the springs that had reactivated the year before were revisited once again and their responses were noted. When available, discharge rates and water-quality parameters were collected at each of these springs. Additionally, data on the geologic unit and elevation of the spring orifice were documented.

Using the field-collected data from the inventories of the reactivated and deactivated springs in 2005 and 2006, as well as previously collected data, investigations were made into the relations of these factors to the occurrence of reactivation and

Figure 14. Water-quality parameters being collected with the Troll9000 (In-situ, Inc.) and a rugged handheld computer, Grapevine Spring (Precambrian granitic rocks).

deactivation over time. Reactivations and deactivations of springs were compared to the geologic unit supplying the spring, the elevation of the spring discharge point, and whether the springs were being fed from local a or regional aquifer source. Patterns seen in these investigations shed light on what most affects the susceptibility of a spring to go dry, which reflects that aquifer system's resistance to drought conditions, especially on a short-term (recent climate variability) basis. These results also help assess the potential of instrumenting these spring locations or others like them for continual discharge measurements.

2.2.4 Biological Inventories

Biological inventories of the 16 monthly monitored springs were conducted in October 2006. Inventory data were collected in accordance to the protocols of Springer, et al., (2006) and included solar energy budget, vegetation diversity, invertebrate assemblage, and vertebrate assemblage characterizations, as well as a description of human impacts (Stevens and Omana, 2007). The results of this investigation were compared to the physical and geochemical findings.

2.3 ANALTICAL METHODS

2.3.1 Field Sample Collection

Spring water samples for geochemical analysis were collected at three seasonal intervals during the year of monitoring. Samples were collected in October 2005 (post-monsoon), February 2006 (winter) and May 2006 (spring/post-snowmelt). Springs are an ideal source for sampling groundwater because the water is constantly being expelled from the aquifer system and dissolved constituents are continuously being flushed (Clark and Fritz, 1997). The October 2005 sampling event was the most comprehensive, with analyses of anions and both stable ($\delta^{18}O$, $\delta^{2}H$ and $\delta^{34}S$) and radioactive (^{3}H and ^{14}C) isotopes conducted. The February and May 2006 samples were only analyzed for stable ($\delta^{18}O$ and $\delta^{2}H$) isotopes and anions, due to the cost-prohibitive nature of the radioactive isotope analyses.

Oxygen and hydrogen isotope samples were collected in 60mL glass bottles with a cap insert to eliminate headspace in the bottle. Anion samples were collected in a pre-cleaned 125mL high-density polyethylene (HDPE) bottle and were filtered through 0.45 micron (μm) membrane filter inserted into a Pall® 47mm in-line filter holder. A syringe was used to push the water through the filter and into the sample bottle. ^{3}H (tritium) samples were collected in 500mL Pyrex® bottles. These bottles were oven-heated to volatilize any compounds that may have existed in the bottle prior to sample collection. Carbon isotope samples were collected in 1L HDPE bottles. All sample bottles were rinsed three times with water from the spring prior to collection. Additionally, water-quality parameters were monitored and recorded during the sampling process.

Each sample location was given a unique sample ID for consistency and to keep the sample locations blind to the analytical laboratory. Sample IDs began with the prefix SP followed by the sample number for that day then the date in MMDDYY format (ex. SP-001-092905). Duplicate samples were also collected in a manner blind to the analytical laboratory to ensure results were reproducible. All samples were shipped on ice to the Laboratory of Isotope Geochemistry at the University of Arizona for analysis.

2.3.2 Analytical Laboratory Procedures

Measurements for $\delta^{18}O$ and $\delta^{2}H$ were made on a gas-source Finnigan Delta S™ Isotope Ratio Mass Spectrometer (IRMS). For $\delta^{2}H$, the samples were reacted with Cr metal at 750°C (Gehre et al., 1996). For $\delta^{18}O$, the samples were equilibrated with CO_2 gas at 15°C (Craig, 1957). Data were reported in standard δ notation as a per-mil (‰) variation of the Vienna Standard Mean Ocean Water (VSMOW), where:

$$\delta\ (^{2}H,\ ^{18}O)\ ‰ = [(R_{SAMPLE}-R_{VSMOW}) / R_{VSMOW}] \times 1000 \qquad \text{(Eq.1)}$$

R= $^{2}H/^{1}H$ or $^{18}O/^{16}O$ (Ingraham, et al., 2001)

The laboratory uncertainty of these analyses is approximately 0.8 per mil for $\delta^{18}O$ and 0.9 per mil for $\delta^{2}H$. Samples were analyzed for a set of seven anions (F^-, Cl^-, NO_2^-, Br^-, NO_3^-, SO_4^{2-}, and PO_4^{3-}) using a Dionex Ion Chromatograph (IC). Analytes were separated using an AS17 analytical column and a KOH gradient created by an EG50 eluent generator and a GS50 gradient pump. The KOH eluent was removed using an ASRS suppressor column. The anion concentrations were then calculated using a CD25 conductivity detector. Detection limits for all anions were 0.025 mg/L except for PO_4^{3-}, which had a detection limit of 0.10 mg/L.

^{3}H samples were distilled to remove non-volatile solutes, then electrolytically enriched by a factor of nine. This results in a detection limit of 0.6 tritium units (TU). After enrichment, each sample was mixed one-to-one with Ultimagold Low Level Tritium® cocktail. Decay counting was performed by liquid scintillation for 1,500 minutes using an LBK Wallac Quantulus 1220™ and the NIST SRM 4361 B and C standards. Error (+/-) of the ^{3}H sample results ranged from 0.19 to 0.48 TU. $\delta^{34}S$ values were measured on a ThermoQuest Finnigan Delta PlusXL continuous-flow gas-ratio mass spectrometer. Samples were combusted with V_2O_5 using a Costech elemental analyzer coupled to the mass spectrometer. Carbon isotopes were measured on the same IRMS as the $\delta^{18}O$ and δ^2H samples. $\delta^{13}C$ was measured on a split of the CO_2 sample prepared for the ^{14}C analysis by HCl hydrolysis of dissolved inorganic carbon (DIC). ^{14}C was reported in percent modern carbon (pMC). Error on this analysis ranged from 0.20 to 0.40 pMC. $\delta^{13}C$ was reported in a per-mil notation relative to a standard (NBS19).

2.4 DATA ANALYSIS METHODS

2.4.1 Hydrograph and Chemograph Creation

Monthly discharge data from each of the measured springs were incorporated into hydrographs that were used to visualize the trends in discharge during seasonal variations and climatic events such as precipitation events, snowmelt, monsoon season storms, or extended periods of below-normal precipitation[1] (Figure 15). The hydrographs were also used to compare the response of springs in different geologic units to help determine which units have quicker responses to these climatic stimuli. Discharge hydrographs were generated with two distinct periods of record, from November 2002 through October 2003 (Flora, 2004), and again from July 2005 through June 2006. These data leave a data gap encompassing 20 months which needed to be accounted for in the analyses. Only one spring of the 16 monthly monitored springs has a fairly complete period of record. Clover Spring has a fairly well-represented discharge history from approximately late 1999 through 2006. The rest of the hydrographs were therefore

[1] The hydrographs and chemographs created for analysis and display are presented in a line-scatter format. It must be noted that this format does not infer that the data are continuous. The scatter points represent known data points, whereas the lines connecting them simply illustrate the general trend between points. This format was selected for ease of interpretation when multiple lines of data are compared together.

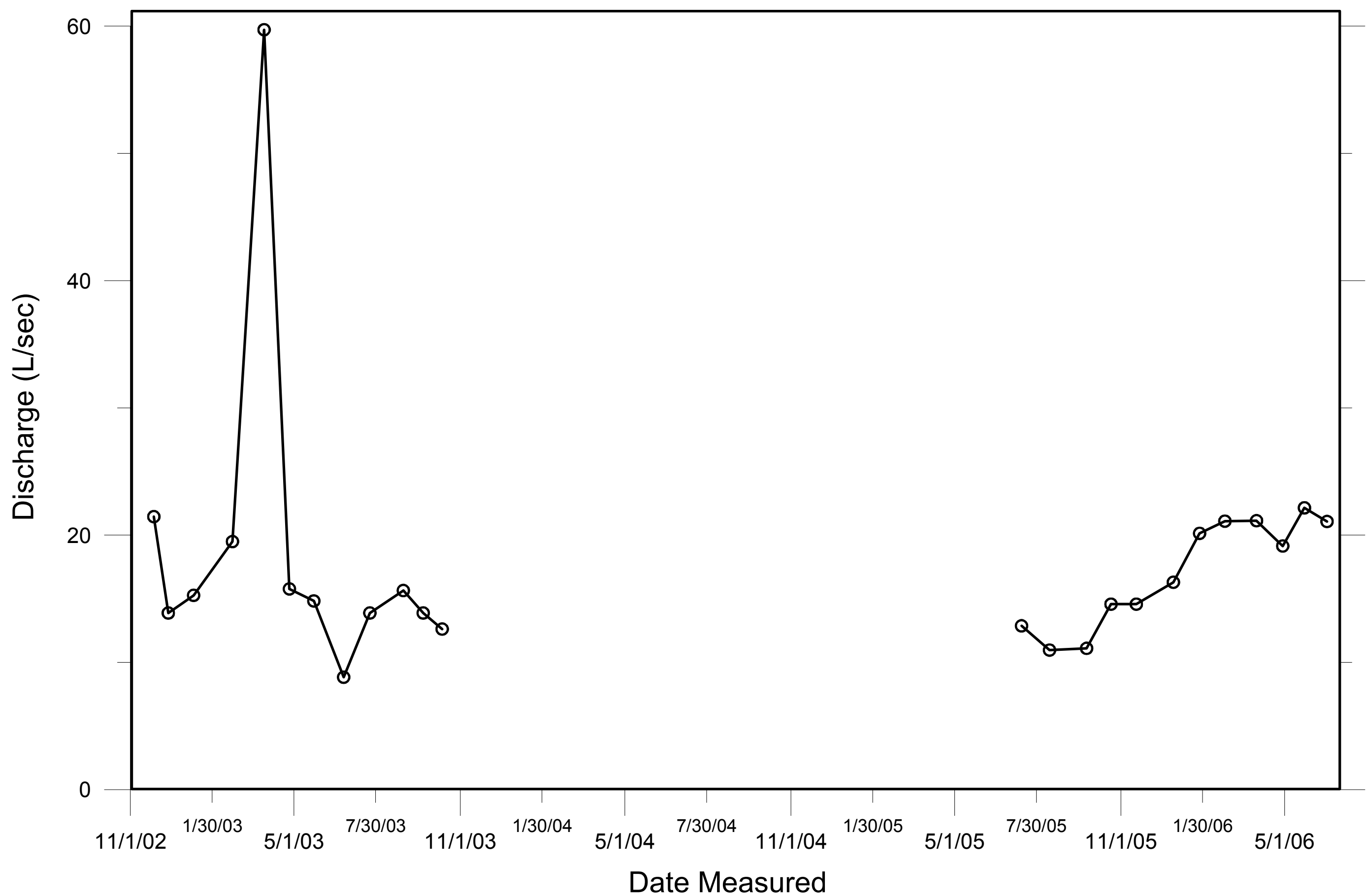


Figure 15. Example discharge hydrograph of Pieper Hatchery Spring (Permian Schnebly Hill Fm.). Date scales on all hydrographs and chemographs presented are limited to the investigation dates for the 2002-2003 and 2005-2006 investigations.

treated as two individual plots for much of the analyses, both physical and statistical, that were conducted in this study. The hydrographs were fitted to linear regression curves and coefficients of determinations (R^2, quantifications of how well the regression line fits the data) were calculated. Hydrographs are not only useful to visualize the trends in discharge over time, but also give insight into the sensitivity and varying responses of aquifer systems to climate change.

In addition to visualizing discharge rate over time, discharge data were compared to other data including climate data and a number of field-collected water-quality parameters. These plots were used to see relations between these parameters and discharge to look for patterns that can help explain the behavior of the aquifer systems supplying the springs. Figure 16 shows an example plot of discharge and electrical conductivity (EC). Data from the springs were also compared against climate data collected within the study area. Precipitation totals were compared with discharge data and air temperature was compared against spring water temperature. Examples of these plots are shown in Figures 17 and 18, respectively.

2.4.2 Interpretation of Recharge Elevation and Season Using Stable Isotopes

It has been known for some time that stable oxygen and hydrogen isotopes are partitioned by meteorological processes in a predictable manner (Craig, 1961). This isotopic fractionation occurs between the liquid and vapor phases of water and is largely a function of temperature with colder temperatures resulting in more negative isotopic values and warmer temperatures resulting in less negative values.

As a result, recharge water originating from higher latitudes, higher elevations or during winter season has more negative stable isotope values than water from lower latitudes, elevations or during the summer. These relations were used to help constrain both the season and elevation of the water that recharges the study area springs, and describe the relative importance of snowmelt versus monsoon precipitation to aquifer recharge. Figure 19 shows the general behavior of oxygen and hydrogen isotopes in response to factors including source latitude, elevation, and degree of evaporation.

To understand the changes in $\delta^{18}O$ and $\delta^{2}H$ throughout the study area as well as with time, the values were plotted against known linear relations of the stable isotopes including the Global Meteoric Water Line (GMWL) (Rozanski, et al., 1993), as well as local lines including for the South Rim of the Grand Canyon (Monroe, et al., 2005), Flagstaff precipitation from the International Atomic Energy Agency (IAEA), and a line created from data collected from springs across the Colorado Plateau (Springer, et al., 2006). Stable isotope values were also plotted against the elevation of the discharge point of the springs then compared against known summer and winter precipitation gradients with elevation in the study area (Blasch, et al., 2006).

2.4.3 Interpretation of Residence Times Using Radioactive Isotopes

Radioactive isotopes were used to estimate groundwater age and aquifer residence times based on known decay rates of ^{3}H and ^{14}C. The half-life ($t_{1/2}$) of ^{14}C is 5,730 years and $t_{1/2}$ of ^{3}H has been calculated to be 4,500 ± 8 days (12.31-12.35 years) (Lucas and Unterweger, 2000). ^{14}C is seen as one of the most reliable chronometers for moderately old groundwater (approximately 5-30 kyr) (Clark, et al., 1998).

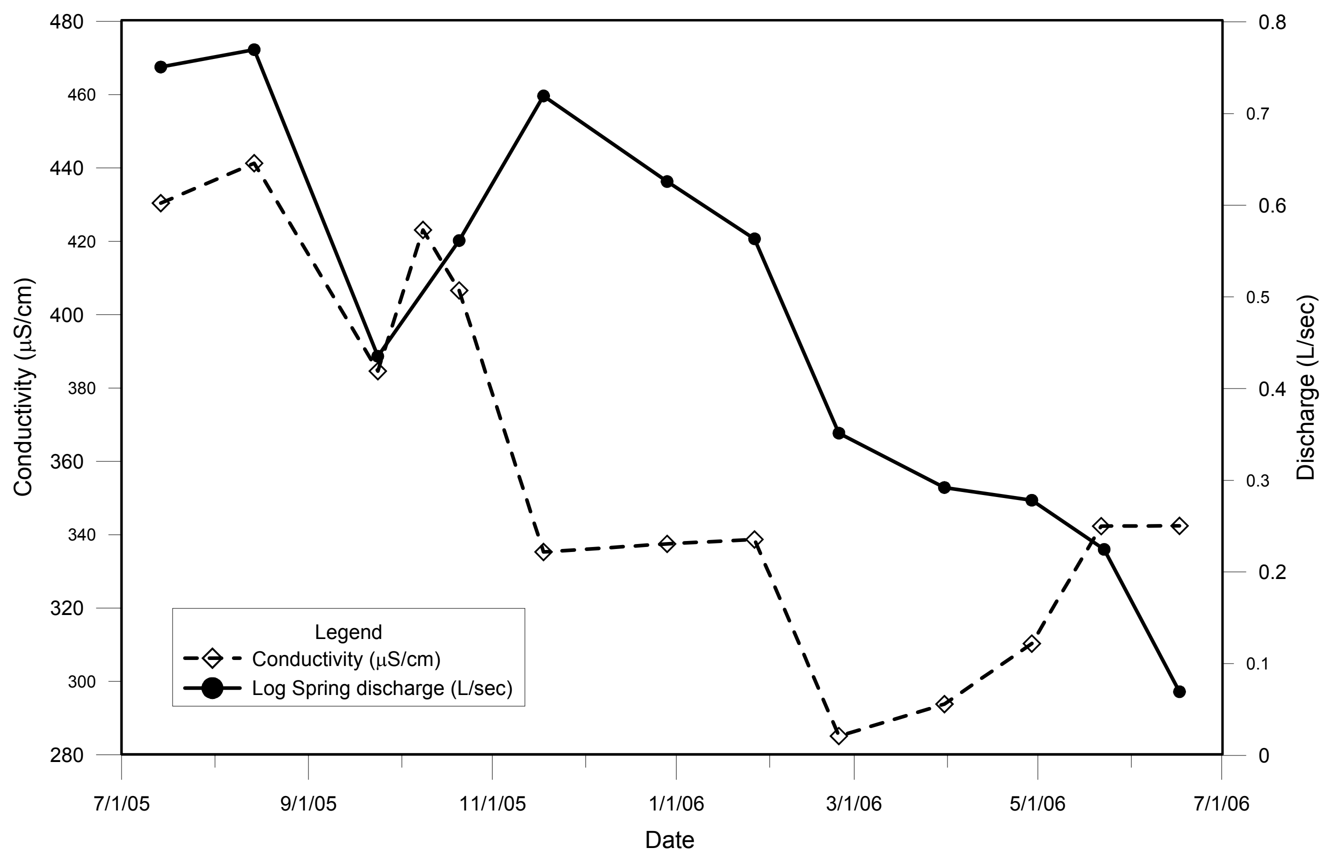


Figure 16. Example plot of spring discharge and electrical conductivity (EC) variability over time, Log Spring (Precambrian Cherry Springs Granite).

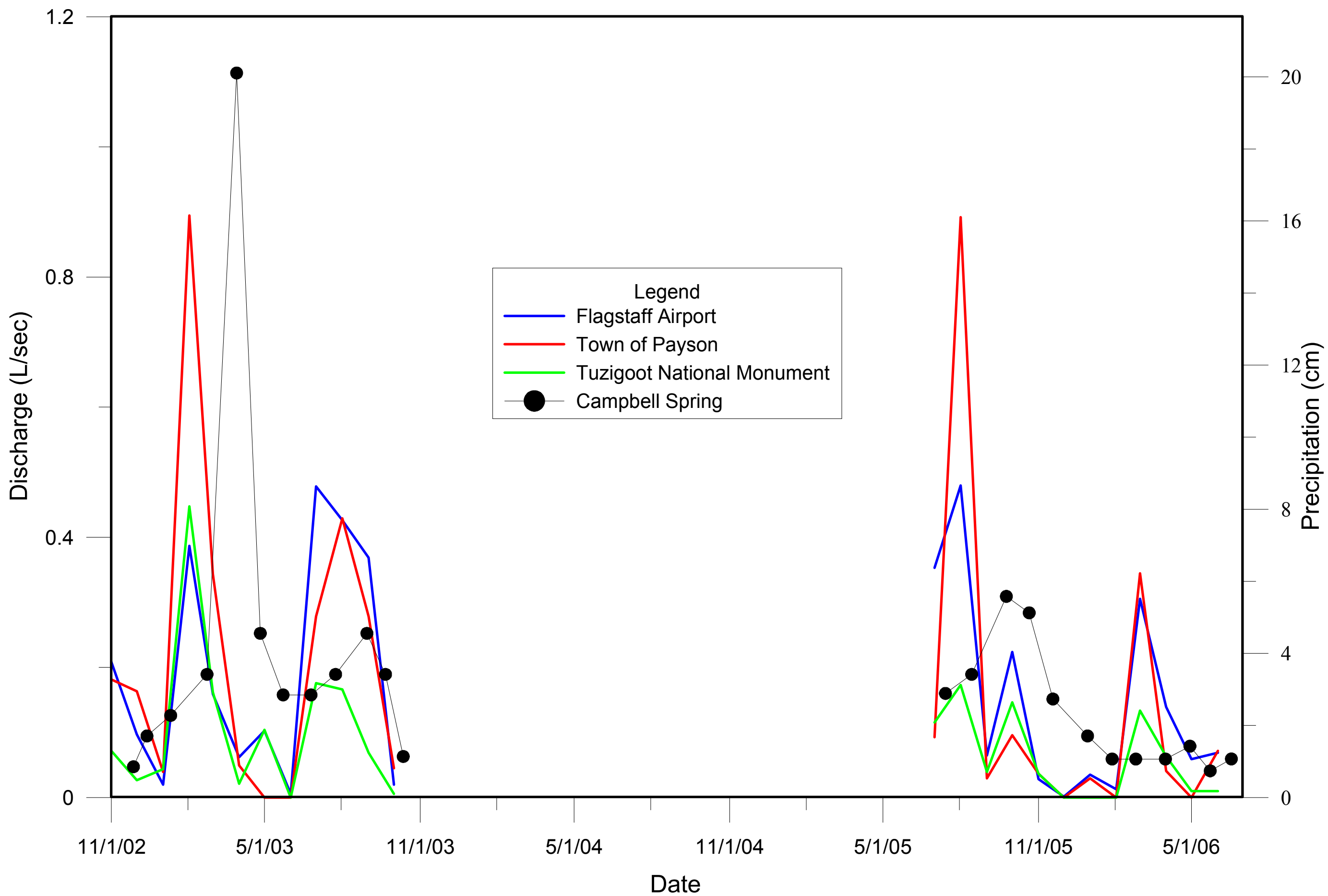


Figure 17. Example plot of precipitation versus spring discharge, Campbell Spring (Tertiary basalt). Precipitation amounts are represented by monthly totals for the climate stations mentioned in the legend.

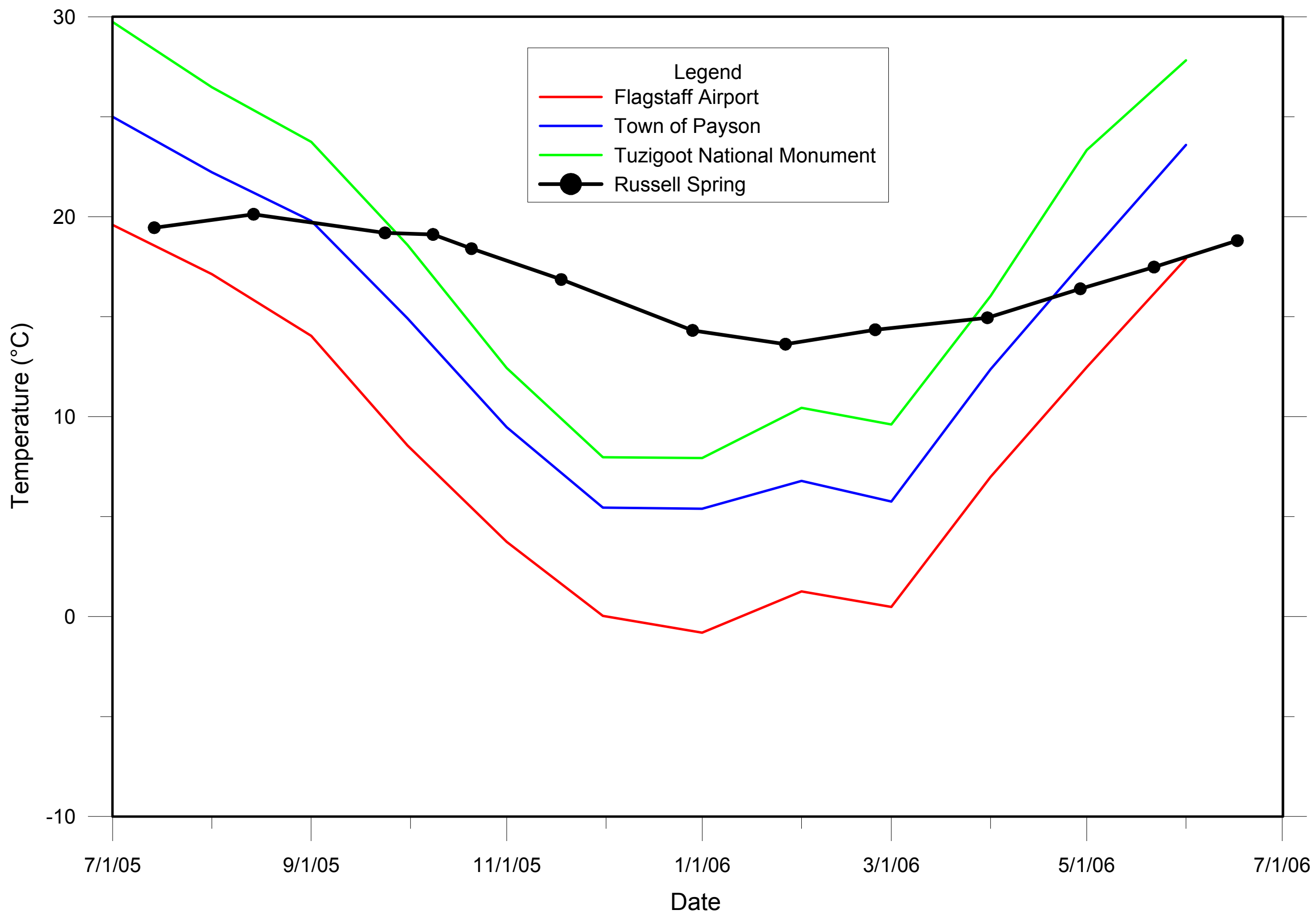


Figure 18. Example plot of air temperature vs. spring water temperature, Russell Spring (Tertiary Verde Fm.). Air temperatures are represented by monthly averages for the climate stations mentioned in the legend.

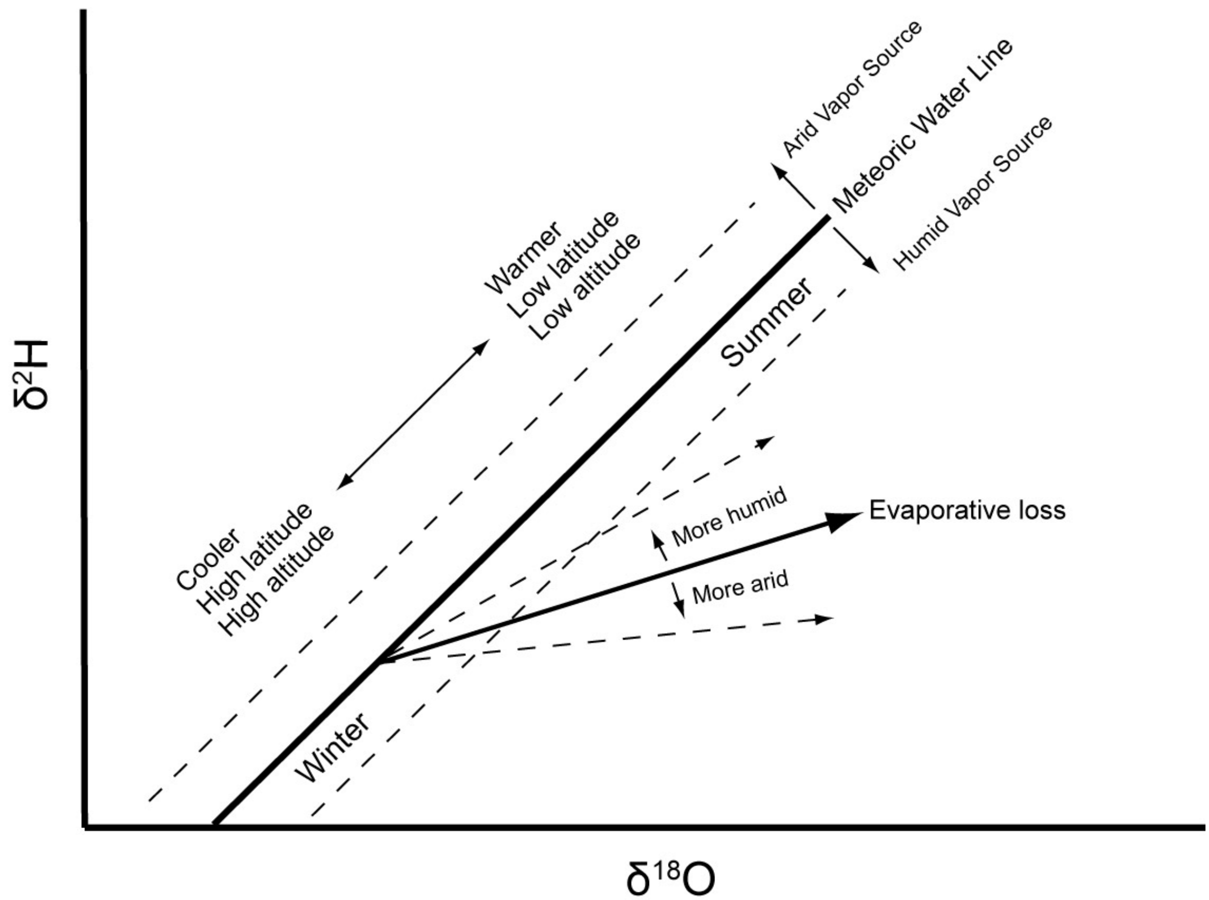


Figure 19. General behavior of oxygen and hydrogen isotopes in response to factors including source latitude, elevation, and degree of evaporation. Reproduced from the Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA) stable isotope website: http://www.sahra.arizona.edu/programs/isotopes/oxygen.html

However, corrections must be made to compensate for water-rock interactions, especially when groundwater is in contact with carbonate aquifers. For evaluations of ^{14}C-based groundwater ages, it is assumed that the natural activity in the atmosphere is 100 pMC. Anthropogenic (nuclear testing, etc.) activities have increased this value above 100 pMC, so for any sample with a ^{14}C value above 100 pMC it is assumed that the recharge occurred in the last 50 years (Clark and Fritz, 1997). Neglecting corrections required to accommodate water-rock interactions, the equation

$$t = -8267 \cdot ln(r) \qquad \text{(Eq.2)}$$

can estimate groundwater age based on the pMC value, with *t* equal to the apparent age in years, and *r* representing the decimal equivalent of the pMC value (ex., for 1 pMC, r=0.01). Dissolution of dolomite and calcite adds long-decayed C and dilutes the ^{14}C that was added at the time of recharge (Clark and Fritz, 1997). Ignoring these water-rock interactions, however, especially in carbonate environments such as limestone and dolomite can lead to overestimation of groundwater age.

Tritium data were also used to determine the relative age of the spring water. Without a complimentary analysis of the ^{3}H decay product ^{3}He, which cannot escape to the atmosphere after recharging past the unsaturated zone and quantifies the amount of ^{3}H decay (Solomon and Cook, 1999), the ^{3}H results allow for qualitative, not quantitative estimates of groundwater age. ^{3}He was not analyzed in this study due to the cost-prohibitive nature of the analysis. ^{3}H is continually generated in the upper atmosphere as a result of cosmic radiation. The base level of tritium content in the atmosphere (and consequently precipitation) increased exponentially during testing of thermonuclear devices primarily in the 1960s (Rademacher, et al., 2002). Based on the decay rate, it would take approximately 50 years for recharge water with an initial concentration of 10 TU to decay below laboratory detection limits (0.6 TU). Therefore, any recharge prior to the mid-1950s in the study area would have no detectable ^{3}H. Current amounts of tritium in rainwater in the Southwest are between 5 and 7 TU (Eastoe, et al., 2004). The radioactive isotope data for the springs were plotted by whether the spring was presumed to be sourced from a regional or local aquifer system and assisted in further defining this designation. Additionally, the residence time estimates assisted in the spring's climate response lag time determinations. These lag times were used in generating relations with other drought indicators (discussed in section 2.5.2).

2.4.4 Regional and Local Aquifer Distinctions Based on Isotopic Evidence

The geochemical data assists in refining classifications of which springs were sourced from regionally-extensive aquifers or local aquifers. These designations are paramount when the statistical analyses are conducted and lag times for spring responses are estimated. Most of the springs monitored during this study were easily identifiable as being supplied regionally or locally, based on either the depth of the aquifer, the geologic unit supplying the spring, or the size of the basin supplying the groundwater to the spring. These designations were later tested and confirmed based on isotopic evidence. Based on the findings of the geochemical investigation, springs discharging from regional and local aquifer systems should have distinct signatures which are compared to the designations based on the physical evidence.

2.4.5 GIS Analyses

The DEM of the study area was created by clipping the extent of the 10-meter resolution elevation data to the outline of the watershed boundary defined by the hydrologic unit code (HUC) polygon. The resulting study area DEM was shaded to show elevation changes clearly. From this high resolution elevation dataset, analyses such as sub-watershed basins representing localized recharge areas can be defined which help constrain the definition of a "local" versus "regional" aquifer system. This is best constrained for shallow aquifer systems, as the localized effect of smaller basins on the recharge of a deep aquifer is unknown in the study area. A hillshade was also conducted on the DEM which mimics the location of the sun to create shadow effects and better elucidate the details of elevation differences across the study area.

Several new shapefiles were created from the field-collected data and added to the Geodatabase of study area spatial data. GPS locations of the climate data stations and stream gages used in the study were converted to point files so they can be located and distances from known springs locations can be calculated. Point shapefiles were also created for each of the springs visited during the 2005 and 2006 field seasons, as well as the distribution of wet and dry springs for the years 2002, 2005, and 2006. Each of these files are linked to an attribute table giving information about the spring including name, geologic unit, elevation, and USGS quad sheet location. Each of these created files was added to the existing Geodatabase in the appropriate feature class. A summary of the created GIS data and their description and location within the Geodatabase is in Table 4.

Table 4. Summary of GIS layers and map files created during data analysis.

Geodatabase Feature Class	Layer Data	Description
Hydrology	Horseshoe Reservior	Only reservior in study area
	Stream Gauges	Location of USGS gauges in study area
	Weather Stations	Location of climate data sources in study area
Infrastructure	Surrounding Cities	Major cities in and around the study area
Springs	Dry Springs 2002	Dry springs from 2002-2003 inventory [1]
	Dry Springs 2005	Dry springs from 2005 inventory (dry in 2002)
	Dry Springs 2006	Dry springs from 2006 inventory (wet in 2005)
	Visited springs 2005	All springs visited in 2005 field season
	Visited springs 2006	All springs visited in 2006 field season
	$\delta^{18}O$, per mil	Distribution of $\delta^{18}O$ values for Feb 2006 samples
	Tritium	Distribution of tritium values, Oct 2005 samples
	Carbon-14, pMC	Distribution of ^{14}C values for Oct 2005 samples
	Fluoride	Fl concentrations, Feb 2006 samples
	Chloride	Cl concentrations, Feb 2006 samples
	Bromide	Br concentrations, Feb 2006 samples
	Nitrate	NO_3 concentrations, Feb 2006 samples
	Sulfate	SO_4 concentrations, Feb 2006 samples
	SO_4/Cl Ratios	SO_4/Cl ratio values for Feb 2006 samples
Raster Files	State Precipitation	Average annual precipitation in AZ (Figure 5)
	Hillshade	Hillshade of watershed DEM[2]

[1] Flora (2004)

[2] Digital Elevation Model

2.5 STATISTICAL ANALYSIS METHODS

Statistical analyses can provide a wealth of information regarding the behavior of springs and aquifer systems and their responses to climate variability, and which variables describing them are most closely related. On a yearly basis, three timescales have been observed to characterize the discharge of springs: the timing of peak discharge, the long-term response of the spring to temporal changes in recharge, and the mean residence time of the supplying aquifer (Manga, 1999). Small springs (short response times) can be excellent short-term drought indicators, whereas larger springs (longer response times) may be excellent indicators of long-term drought conditions. Analysis of hydrographs may be used to estimate aquifer properties such as specific yield and transmissivity, as they have been used in the past on well hydrographs (Shevenell, 1996). These were estimated from two karst aquifer springs in the monthly monitoring circuit (Clover and Pivot Rock) by Flora (2004) based on methods developed by Baedke and Krothe (2001). Simple data such as monthly temperature can also be used to give an idea of the volume and residence time of the aquifers supplying water to the springs. A more constant temperature generally reflects a larger aquifer volume and longer residence time (Manga, 1999). This in turn represents a spring that is more resistant to small-scale changes in climatic conditions.

Several statistical methods were employed to identify the relations between the physical and chemical responses of the springs to climate changes. First, simple descriptive statistics were calculated to describe central tendencies and variances of spring discharge. Then the discharge data were analyzed for variability using two different methods, and were plotted on hydrographs and fitted to linear regression equations, which allow for estimates of future discharge rate changes based on climate change such has been done by Paulson et al., (1985), and are related to the correlation coefficients described below.

Correlation coefficients were calculated between a number of measured and collected data including spring discharge, water and air temperature, precipitation totals and stream gage readings, and analyses of covariance between spring discharge and the State's short and long-term drought-level designations were performed. Tests for trend were also conducted to see if discharge rates were increasing or decreasing for each of the springs, a technique which has been used with groundwater levels in other locations to determine drought level designations (Schreffler, 1997). Finally, spring discharge data were centered and scaled to a common reference with the State's short and long-term drought level designations, which allow for visual inspection as well as regression line fitting to assess how well the discharge data and drought designations agree. Time-series analyses on the data were determined to be inappropriate for this study due to the period of record for the field data and the overall size of the data set.

2.5.1 Descriptive Statistics

Calculations of simple descriptive statistics were performed to quantify the tendencies, variations, and confidence intervals of the collected spring discharge data. Values for common statistical analyses including the mean, median, mode, standard deviation, and variance were calculated, and analyses of somewhat more involved statistical calculations including kurtosis and skewness were also conducted. Kurtosis simply characterizes the relative "peakedness" or "flatness" of a distribution compared to a normal distribution. A positive value indicates that the data set is relatively peaked, while a negative value represents a relatively flat data distribution. Skewness quantifies the degree of asymmetry of the distribution of data around its mean. A positive skewness value represents a distribution with a tail towards more positive values, while a negative value represents the opposite. Standard errors of kurtosis and skewness can be analyzed to assess whether the data are normally distributed or not, which may affect the results of other statistical analyses. The remaining descriptive statistical values can be studied for general trends and behaviors of the data and can focus future analyses and groupings of springs exhibiting similar characteristics. Some of the descriptive statistics (standard deviation, mean, etc.) are also used in other calculations discussed in later sections.

2.5.2 Discharge Variability – Coefficient of Variation

Methods for quantifying spring discharge variability include calculations of variation directly and calculation of a coefficient of variation. These two methods for analysis of variability were similar to those employed by Flora (2004) to allow for comparison of the 2005-2006 monthly discharge values with previous distinctions based on data from the 2002-2003 monitoring cycle. The methods for calculating spring discharge variability are as follows:

Method 1 – Variability

$$\text{Variability} = Q_{90}/Q_{10} \qquad \text{(Eq. 3)}$$

Where

Q_{90} = Discharge rate representing the 90th percentile, and
Q_{10} = Discharge rate representing the 10th percentile.

Variability Classes:	1.0 – 2.5	Steady,
	2.6 – 5.0	Well Balanced,
	5.1 – 7.5	Balanced,
	7.6 – 10.0	Unbalanced,
	> 10.0	Highly Unsteady, and
	Infinite	Ephemeral.

Method 2 – Coefficient of Variation

$$\text{Coefficient of Variation} = (\text{SD}/\text{Mean}) * 100 \qquad \text{(Eq. 4)}$$

Where
SD = Standard Deviation, and
Mean = Mean monthly spring discharge rate.

Variability Classes:	0-49	Low,
	50-99	Moderate,
	100-199	High, and
	>200	Very High.

2.5.3 Correlation and Covariance Analyses

Data both field-collected and obtained from outside sources for the study area were investigated to quantify how different variables were related. Data including spring discharge, water-quality parameters, precipitation, Palmer index, air temperature, and the stream discharge rates from seven USGS gages in the study area were examined to see how they all changed with respect to one another and correlation coefficients for each were generated. Analyses of covariance (ANCOVA) were also conducted to assess how spring discharge and the State's drought-level designations were related.

The correlation coefficient is a measure of the extent to which two variables vary together. The coefficient is scaled so the value is unchanged with changing units (such as gallons per minute to liters per second). The result is a number that varies between -1 (strong negative correlation) and +1 (strong positive correlation) with a value of zero signifying no correlation. The calculation of the correlation coefficient is:

$$r = \frac{\sum (X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum (X - \overline{X})^2 \sum (Y_i - \overline{Y})^2}} \qquad \text{(Eq. 5)}$$

and is expressed by Pearson's product moment coefficient (r) (Shaw, 2003). This calculation is fairly simple and the process is automated using the Microsoft Excel Data Analysis plug-in correlation tool. The square of this value, R^2 (the coefficient of determination) is advantageous in that it represents the proportion of the variance which is explained by the linear regression (Shaw, 2003), or how well the regression line approximates the real data. For example, an R^2 value of 0.72 indicates that 72% of the variance in the dependent variable can be explained by the regression equation, while the other 28% is unexplained. The analysis provides a "correlation matrix" with the r-values (which were later converted to R^2) for each possible permutation of variable combinations. An example of one of these matrices is shown as Table 5. In addition to a straight correlation between the variables, the spring discharge was lagged between one and six months for each of the springs designated originating from regional aquifer systems. Due to the longer residence times of these springs, changes in discharge resulting from climate change may not be reflected for some time at the discharge point.

Covariance is essentially the combination of regression analysis and analysis of variation (ANOVA) (Şenoğlu, 2007). Covariance is different from variance, which measures the variation within a data set of a single variable instead of multiple variables, which in this case were spring discharge and short and long-term drought-level designations. The formula which describes the ANCOVA analysis for a data pair is written:

$$Cov(X,Y) = \frac{\sum(x-\bar{x})(y-\bar{y})}{n} \qquad \text{(Eq. 6)}$$

where *n* is equal to the sample size. This analysis helps determine relations between datasets. In this case, the analysis was performed to assess the relations between spring discharge and the drought-level designations assigned by the State based on other hydrologic information. Unlike the correlation coefficient calculation, covariance is not scaled from -1 to +1, but has a similar output where a positive result indicates that when the value of one parameter increases (e.g. precipitation) the other (e.g. spring discharge) does as well. The opposite is true for a negative covariance value. A covariance of zero or near zero indicates that the two parameters are independent of one another.

2.5.4 Trend Analyses

Trend analyses were conducted to assess whether spring discharge trends were increasing or decreasing overall with time, and whether these trends were statistically significant. The data sets representing discharge did not have a continuous period of record robust enough to identify and therefore remove the effects of seasonality. The trend analysis selection was thus changed from Mann-Kendall seasonal trend to the Kendall-Theil method. The Kendall-Theil method is a non-parametric test that consists of two parts.

Table 5. Example correlation matrix for a number of variables for Log Spring. Calculated correlation values are represented by Pearson's product moment coefficient (r). Air temperature, precipitation totals, and Palmer Drought Severity indices represent monthly values for the study area (NOAA AZ Climate Division 3). Numbers 1-7 represent stream discharge data from USGS gages at the locations noted.

	Discharge	**Conductivity**	**W. Temp**	**Air Temp.**	**Palmer**	**Precip**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Discharge	1.00												
Conductivity	0.60	1.00											
Water Temperature	0.25	0.84	1.00										
Air Temperature	-0.03	0.70	0.90	1.00									
Palmer Drought Severity Index	0.90	0.75	0.45	0.19	1.00								
Precipitation	0.46	0.69	0.65	0.48	0.56	1.00							
Clarkdale (1)	0.72	0.02	-0.36	-0.64	0.50	0.11	1.00						
Oak Creek-Sedona (2)	0.61	-0.10	-0.37	-0.67	0.45	0.15	0.88	1.00					
Beaver Creek (3)	0.47	0.36	0.29	0.06	0.39	0.67	0.51	0.47	1.00				
West Clear Creek (4)	0.46	0.37	0.31	0.07	0.39	0.71	0.50	0.46	1.00	1.00			
Verde River at Camp Verde (5)	0.57	-0.05	-0.31	-0.59	0.37	0.26	0.92	0.87	0.74	0.73	1.00		
East Verde at Childs (6)	0.55	0.57	0.48	0.27	0.54	0.86	0.41	0.35	0.94	0.95	0.60	1.00	
Verde below Tangle Creek (7)	0.14	0.38	0.47	0.43	0.10	0.77	0.06	0.01	0.87	0.87	0.37	0.87	1.00

First, the method tests to see if there is an upward or downward (or stable) trend to the data. This method is not affected by the magnitude of the change in discharge from one reading to the next, just the general trending direction (Helsel and Hirsch, 1992). The analysis next determines the slope of the best-fit line (negative, positive, or none) as well as an s-value and p-value. The s-value is calculated by assigning each data pair possibility a value of -1, 0, or +1 for data that shows a decrease, no change, or increase, respectively, then summing the results (Figure 20). The possible s-values depend on the number of data points being analyzed. For example, with seven data points, s-values could range from -21 to +21. The p-value is calculated from the s-values and Kendall's tau statistics (Kendall, 1990). It represents the cumulative probability that a randomly fluctuating data set would yield a particular s-value. The Kendall-Theil method is seen as slightly less powerful as simple linear regression analyses when the data meet assumptions of normality. When the data are not normally distributed, however, this method provides a much more accurate estimate of the slope of the trend line (Helsel and Hirsch, 1992).

A Microsoft Excel macro developed by the Desert Research Institute (DRI) Causes of Haze Assessment (COHA) division (www.coha.dri.edu) was used to conduct the Kendall-Theil trend analyses. This macro, used by the United States Environmental Protection Agency (USEPA) to calculate trends in air quality, was used to perform the analyses (USEPA, 1998). The USEPA suggests that values under p=0.05 (5%) represents a trend that is statistically significant.

Month	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Discharge	93.4	83.1	92.5	87.8	93.6	94	86.2	93.1	91.9	90.2	94.5	91.6
Order 1	−	+	−	+	+	−	+	−	−	+	−	
Order 2	−	+	+	+	−	−	+	−	+	+		
Order 3	−	+	+	−	−	−	+	+	−			
Order 4	+	+	−	+	−	−	+	−				
Order 5	+	+	+	+	−	+	+					
Order 6	−	+	−	+	+	−						
Order 7	−	+	−	+	−							
Order 8	−	+	+	+								
Order 9	−	+	−									
Order 10	+	+										
Order 11	−											

Example: 3rd order comparisons, 87.8 is less than 93.4, so the sign is "-". The last row is the 11th order comparisons, 91.6 is less than 93.4, so the sign is "-". The number of negative and positive values is summed and the resulting number is the s-value (+6 in this example).

Figure 20. Example of trend analysis matrix on one year of data points.

2.5.5 Centered and Scaled Discharge vs. State Drought Levels

To compare graphically such data sets as spring discharge and the State's drought-level designations, the data must be transformed to a common reference. This can be achieved by centering and scaling the data. The calculation which performs the centering and scaling operation is:

$$(X - X_{mean}) / SD \qquad \text{(Eq. 7)}$$

The center and scaling calculation was performed using the statistical software program R, which was developed by the R Project for Statistical Computing (http://www.r-project.org). R is a collaborative effort between many institutions and individuals worldwide, and the source code can be downloaded and complied free of charge. Monthly discharge data from the sixteen monitored springs and monthly short and long-term drought-level designations were centered and scaled, and the resulting values were plotted to identify potential trends. A plot was generated for each of the 16 monthly monitored springs, with centered and scaled values for discharge and the short and long-term drought levels, for the months in 2002-2003 and 2005-2006 when the springs were monitored.

2.5.6 Generation of Drought-Level Designations Using Springs Data

Drought trigger levels were generated for each of the 16 monthly monitored springs based on the percentile ranking system used by the State's Monitoring Technical Committee in the ADPP. The divisions used by the State are as follows:

No Drought:	40.1th percentile or higher
Level 1:	25.1 to 40th percentile
Level 2:	15.1 to 25th percentile
Level 3:	5.1 to 15th percentile
Level 4:	0 to 5th percentile

Where determined to be necessary, the appropriate time lag on the spring data was incorporated in calculating the drought-level designations. Then, the drought designations based on spring data were compared against those calculated by the State for the same period using the climate data in their models (stream gage data, SPI, etc.) and the results were compared to see how well the spring's response to climate change matched the responses seen in the State's data set.

CHAPTER 3 – RESULTS

The large volume of data both gathered and collected during this study were employed in a variety of methods which directed interpretations of springs' sources, classifications, typical behaviors, responses to climate change, and viability of use as drought indicators. The results of these individual investigations were ultimately combined to generate an overview of spring response to recent climate changes within the study area.

3.1 GEOCHEMICAL RESULTS

Results of the geochemical analyses directed many of the physical and statistical analyses discussed later and are therefore presented first. To use springs as potential drought indicators, the flowpaths and mean residence times of the aquifers supplying the springs must be understood. The seasonal geochemical analyses provided information to better constrain the sources and pathways of the water supplying the springs, the most important season(s) for aquifer recharge, the definitions of regional and local aquifer systems, and aquifer residence times. A summary of the results of all the geochemical analyses from this study is provided in Appendix A.

3.1.1 Stable Isotopes

The stable isotopic compositions of waters collected during the three seasonal sampling rounds (October 2005, February 2006, and May 2006) as well as one round collected in October 2003 were compared to the global meteoric water line (GWML) and three local water lines (Figure 21). Of the existing lines, most of the springs fall closely to the line representing precipitation at the South Rim of the Grand Canyon (Monroe, et al., 2005) with a slope of 7.6. The results of the samples in this study fall on a calculated best-fit line with the equation:

$$\delta^2H = 5.25 + \delta^{18}O - 19.7 \qquad \text{(Eq. 10)}$$

with an R^2 value of 0.89. The range of stable isotope values for the springs were compared to data for areas surrounding and including the study area from other investigations (Blasch, et al., 2006 and Bills, et al., 2007), which examined groundwater stable isotope data from a set of wells and springs (Table 6). The minimum stable isotope values for the study area best compare to the northern Verde Valley, whereas the maximum values compare closely to samples from the southern Verde Valley. The average values, however, are more closely related to samples colleted from the Coconino Plateau and the northern Verde Valley. The standard deviations for the study area samples are significantly higher than those for the areas investigated by Blasch et al. (2006), but this is expected due to the substantially larger area this study encompasses than the other more spatially constrained locations. The study area also experiences much more dramatic variations in elevation than these other areas individually, as do the samples from the Flagstaff area (Bills, et al., 2007).

Minimal variability was observed in the stable isotopic values on a seasonal basis. Variability of the springs was generally within the analytical precision of the analysis of these isotopes (approximately 0.09 δ^2H ‰, 0.08 $\delta^{18}O$ ‰). Calculated variability (average of the deviations from the mean) showed that regional springs have a lower variability (0.26 and 2.16 for $\delta^{18}O$ and δ^2H, respectively) than local springs (0.73 and 3.66,

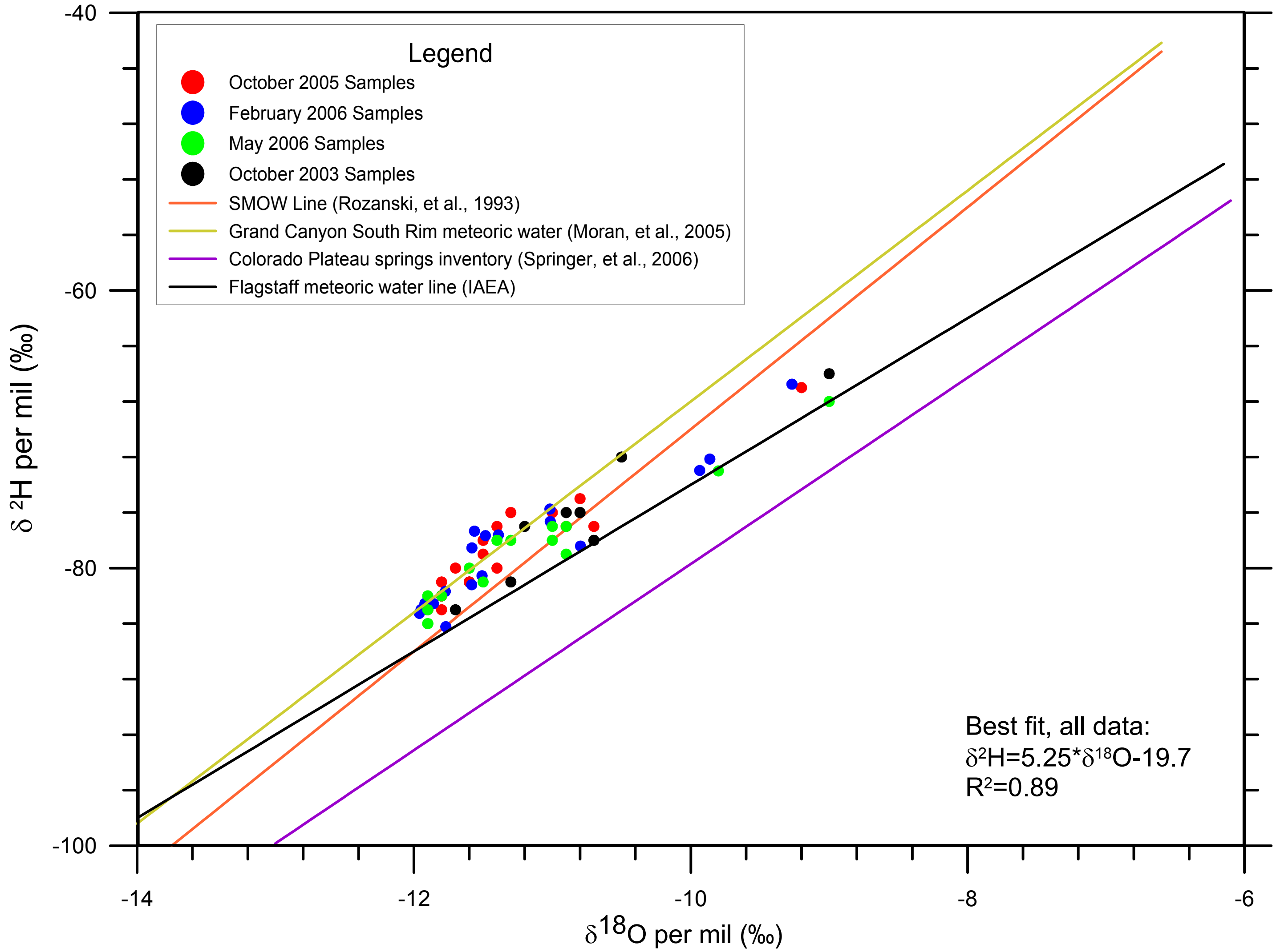


Figure 21. δ18O/δ2H plot for four seasonal sampling events with the global meteoric water line and three local water lines.

Table 6. Stable isotope values for the study area as well as surrounding areas from previous studies.

Study area location	Minimum		Maximum		Average		Standard deviation	
	$\delta^{2}H$ ‰	$\delta^{18}O$ ‰	$\delta^{2}H$ ‰	$\delta^{18}O$ ‰	$\delta^{2}H$ ‰	$\delta^{18}O$ ‰	$\delta^{2}H$ ‰	$\delta^{18}O$ ‰
Western Coconino Plateau [1]	-80	-10.6	-75	-10	-77	-10.4	1.4	0.15
Coconino Plateau near Flagstaff [2]	-90.7	-12.4	-72.3	-9.2	-77	-10.8	5.3	0.92
Verde Valley north [1]	-89	-12.3	-82	-11.3	-86	-11.9	1.8	0.22
Verde Valley south [1]	-74	-10.1	-70	-9	-72	-9.6	1.4	0.4
Middle Verde watershed samples [3] (2005-2006)	-84	-12	-67	-9	-78.7	-11.3	4.2	0.7

[1] Data from wells and springs in area noted (Blasch, et al., 2006)

[2] Data from wells and springs (Bills, et al., 2007)

[3] Data from springs only, this study

respectively). Stable isotope values from most springs were isotopically light, and values from several springs discharging from regional aquifers were lighter than the winter precipitation average for Flagstaff (-79.65 δ^2H, -10.92 δ^{18}O) (Blasch, et al., 2006). This indicates that winter precipitation is the dominant recharge event in the study area.

The stable isotopic values from local aquifer sources show a strong relation to elevation of the discharge point. Local springs' stable isotope values plot very closely to a known line of winter precipitation isotope values plotted versus change with elevation (Figure 22) (Blasch, et al., 2006). Values of δ^{18}O in winter precipitation decrease at a rate of 0.23 per mil for every 100 meters in elevation gained. The best-fit line representing water from local aquifer springs has a rate of 0.234 per mil for every 100 meters of elevation change with an R^2 value of 0.84. By comparison, δ^{18}O values for regional aquifer springs show no discernable pattern with elevation change (Figure 22). The isotopic data indicated that these regional springs are recharged from high elevation precipitation, but the spring discharge points are often located at lower elevations (Figure 23). These observations imply that at all elevations and for all springs, winter precipitation dominates and that the elevation of the recharge precipitation, more than the amount of winter versus summer precipitation, is the leading control on the isotopic composition of spring water.

In contrast to elevation of source area, there is no clear relation between isotopic composition and the geologic unit from which the spring discharges (Figure 24). Generally, the springs discharging from the regionally extensive Pennsylvanian-Permian sandstone and Mississippian-Devonian limestone aquifers have the lightest isotopic signatures, and the springs discharging from the Quaternary alluvium and low-elevation

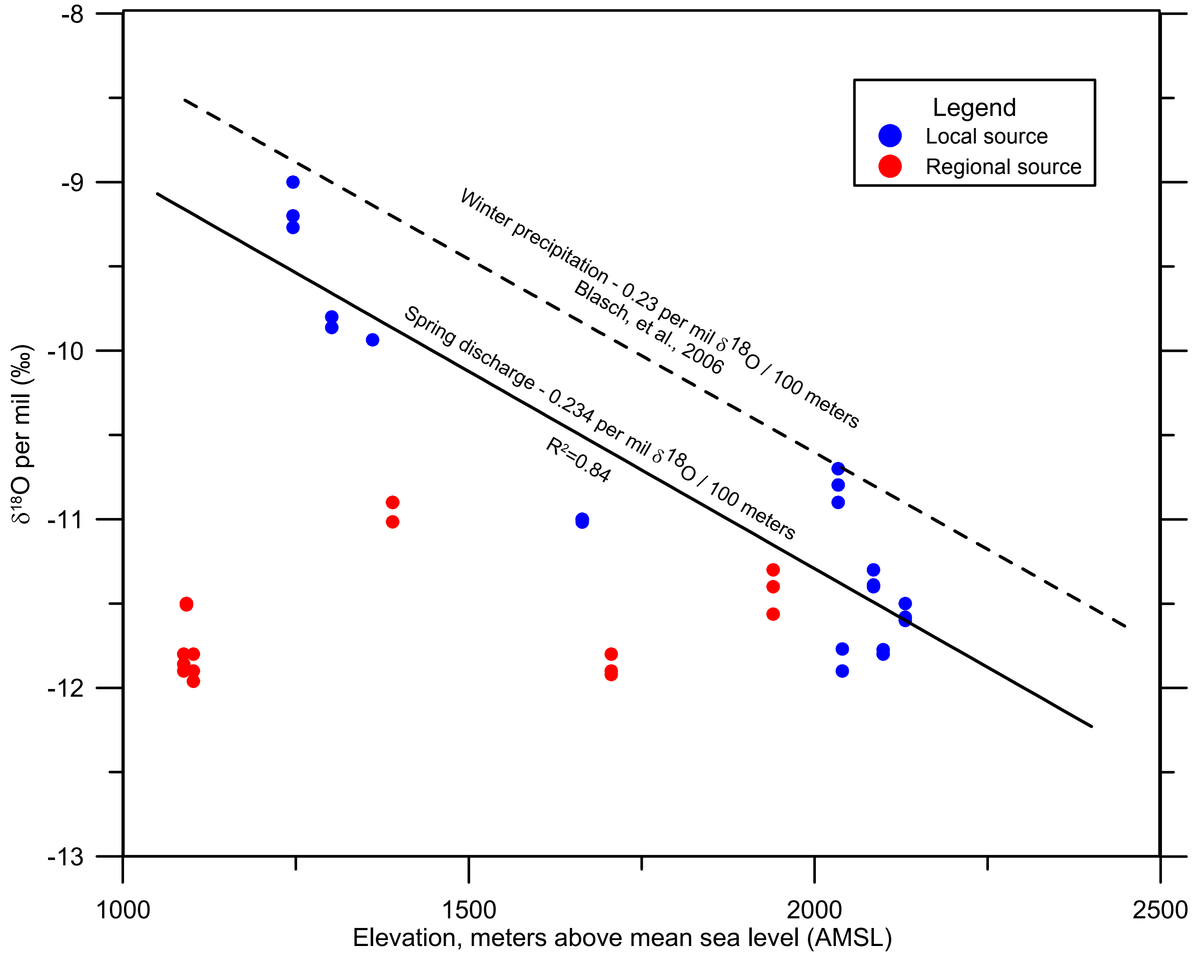


Figure 22. δ18O values for samples collected in the study area in October 2005, February 2006, and May 2006 plotted against elevation. Springs sourced from regional aquifers show little isotopic variation and no trend with elevation. In contrast, springs sourced from local aquifers show a strong correlation with elevation that mimics the best-fit line for winter precipitation in the study area (Blasch, et al., 2006).

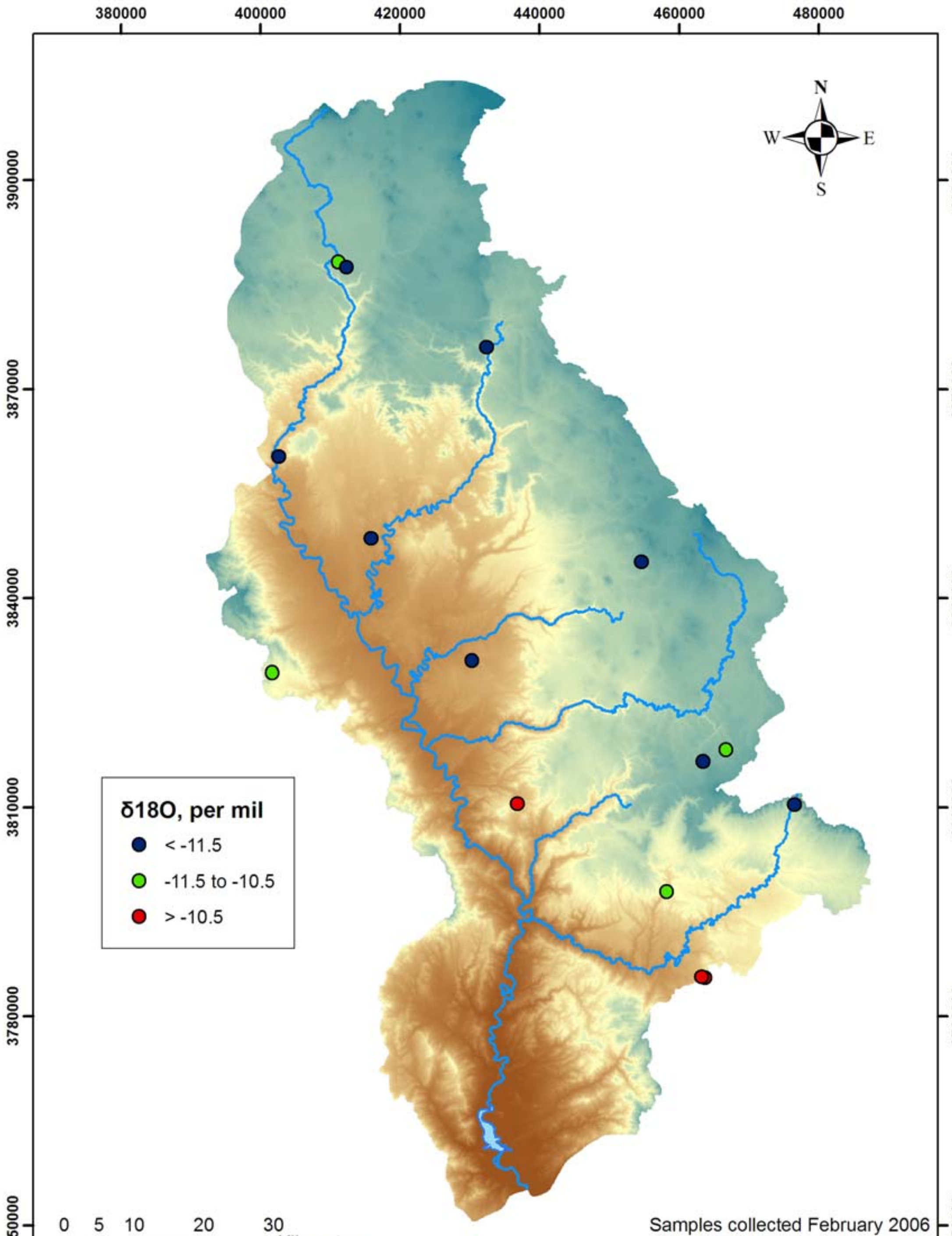


Figure 23. Spatial distribution of δ18O throughout the study area. Regional aquifer springs discharging at low elevation have similar lighter values than springs located at high elevations.

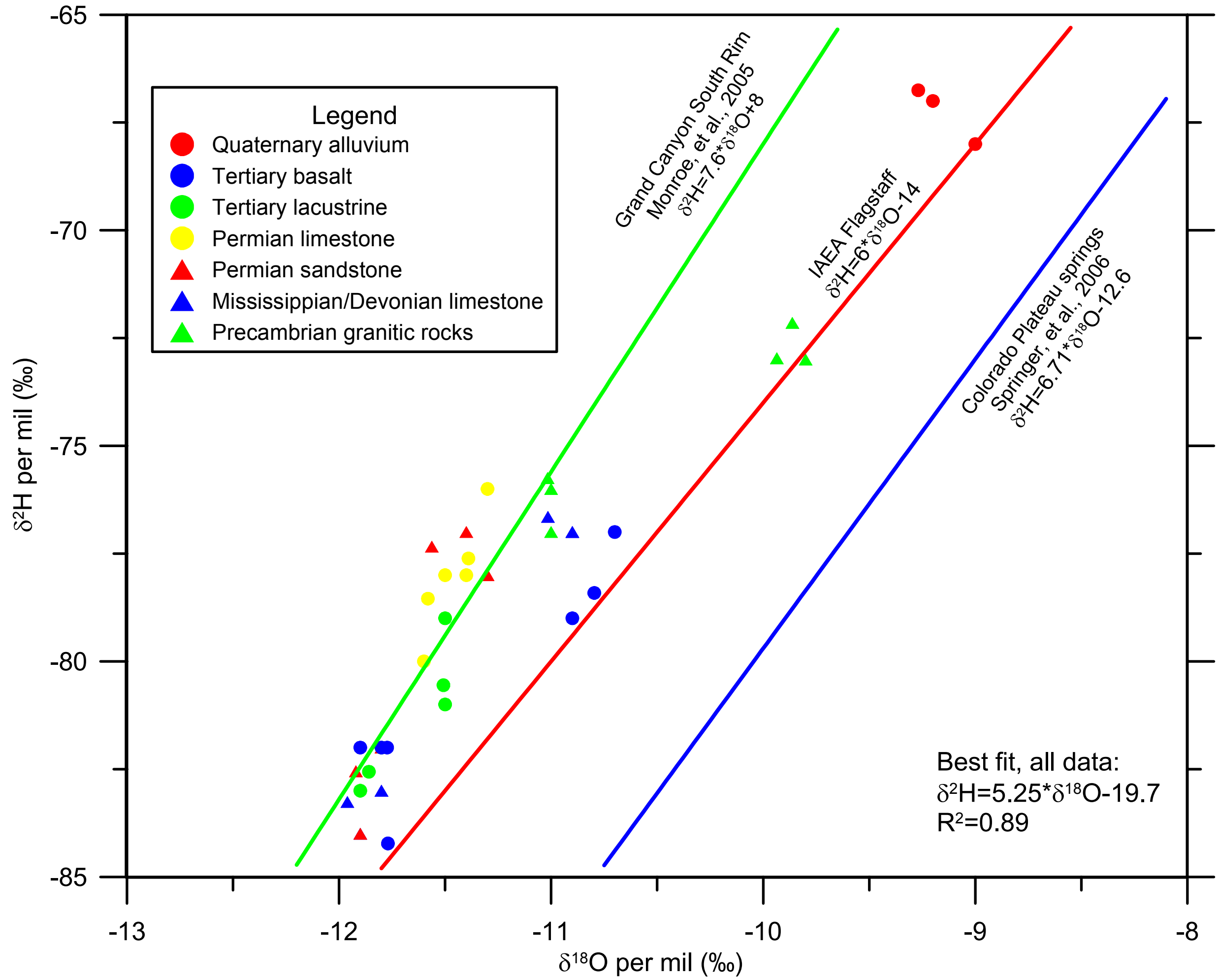


Figure 24. δ18O and δ2H values plotted by geologic unit from which the spring discharges. Values from samples collected in the study area in October 2005, February 2006, and May 2006. Three local water lines indicate that the springs correlate best with the meteoric water line for the South Rim of the Grand Canyon.

Precambrian granitic aquifers are the heaviest. The springs discharging from the alluvium and low-elevation granitic rocks fall more closely to a line representing winter precipitation at Flagstaff (IAEA). This line has a lower slope (6.0) which indicates that evaporation of the precipitation recharging these springs is potentially occurring and/or summer precipitation has a larger role in the overall recharge amount to these springs.

3.1.2 Radioactive isotopes

There were a wide range in values and spatial distribution of both ^{3}H and ^{14}C analyses (Figures 25, 26, and 27). Generally, values for both of these radioactive isotopes were highest in local aquifer springs, indicating a younger groundwater and shorter residence time than the lower values seen in the regional aquifer springs (Figure 25). Tritium values ranged from 0.5 to 6.5 TU (n=20), and ^{14}C values ranged from 25.1 to 103.8 pMC (n=5). Spatial distributions and values for ^{3}H and ^{14}C results in the study area are shown in Figures 26 and 27, respectively. One of the five ^{14}C samples collected came from a local aquifer spring (Pivot Rock, Permian karst limestone) and the pMC of 103.8 indicates that the spring discharge was recharged to the aquifer recently (less than 50 years); this is supported by a ^{3}H value of 4.4 TU. Some of the ^{14}C values from regional aquifers show both decayed ^{14}C as well as detectable ^{3}H concentrations. For example, samples from Fossil Springs have ^{14}C values of 25.1 pMC, but have ^{3}H values of between 1.1 and 2.5 TU (Appendix A). Based on the large difference in decay rates of these two isotopes, the presence of both at these levels indicates that the water supplying the spring is predominantly older, but with a significant input of recent recharge. Converting the pMC values to uncorrected groundwater ages using Equation 2 (Clark and

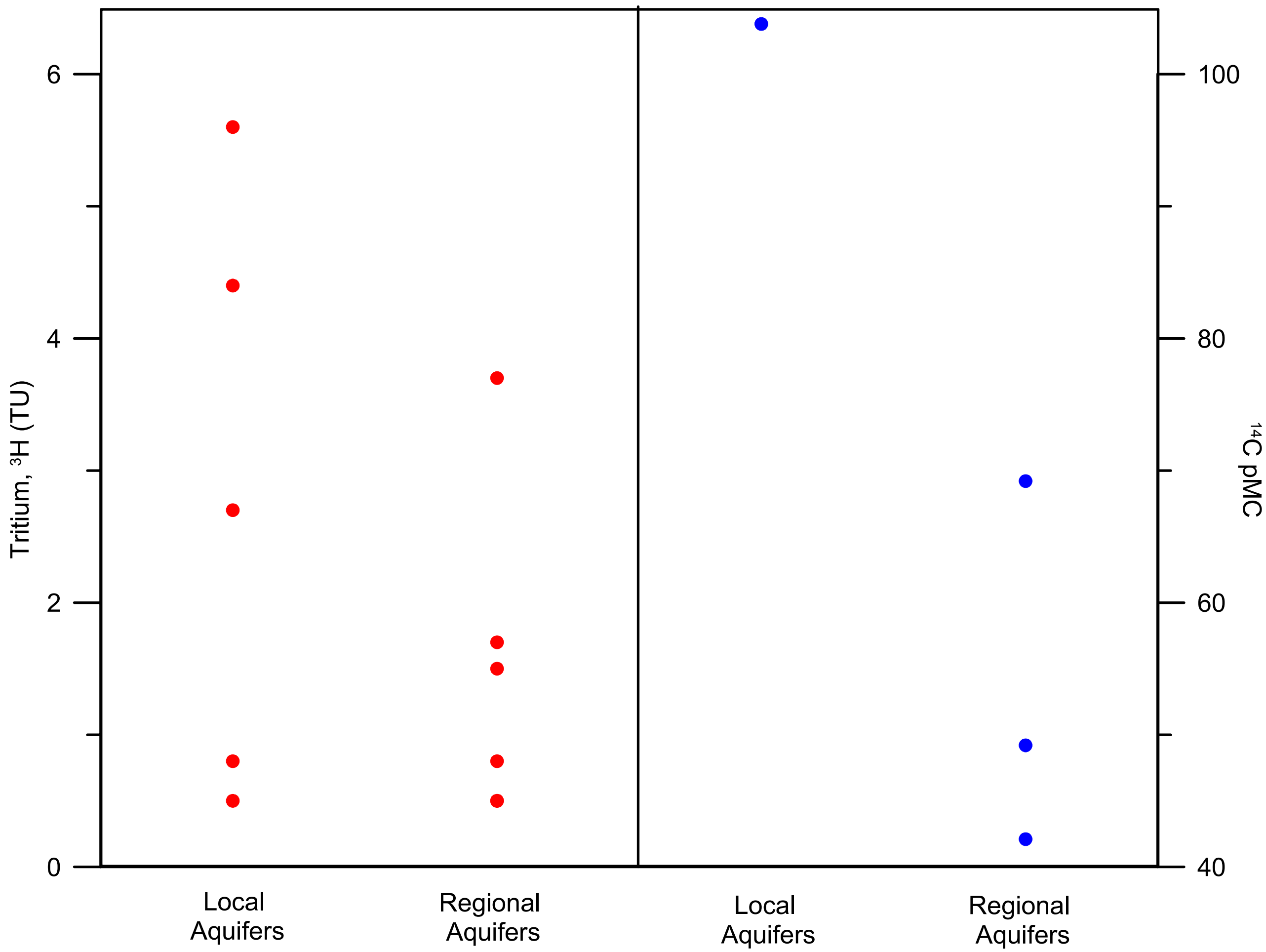


Figure 25. Radioactive isotope values for regional and local aquifer springs used in determining residence times. Local springs had the highest 3H values on average and the one 14C value for a local aquifer system indicated the water was modern. Regional aquifers with low 14C values and detectable 3H indicate the effect of recent local recharge. Samples were collected in October 2005.

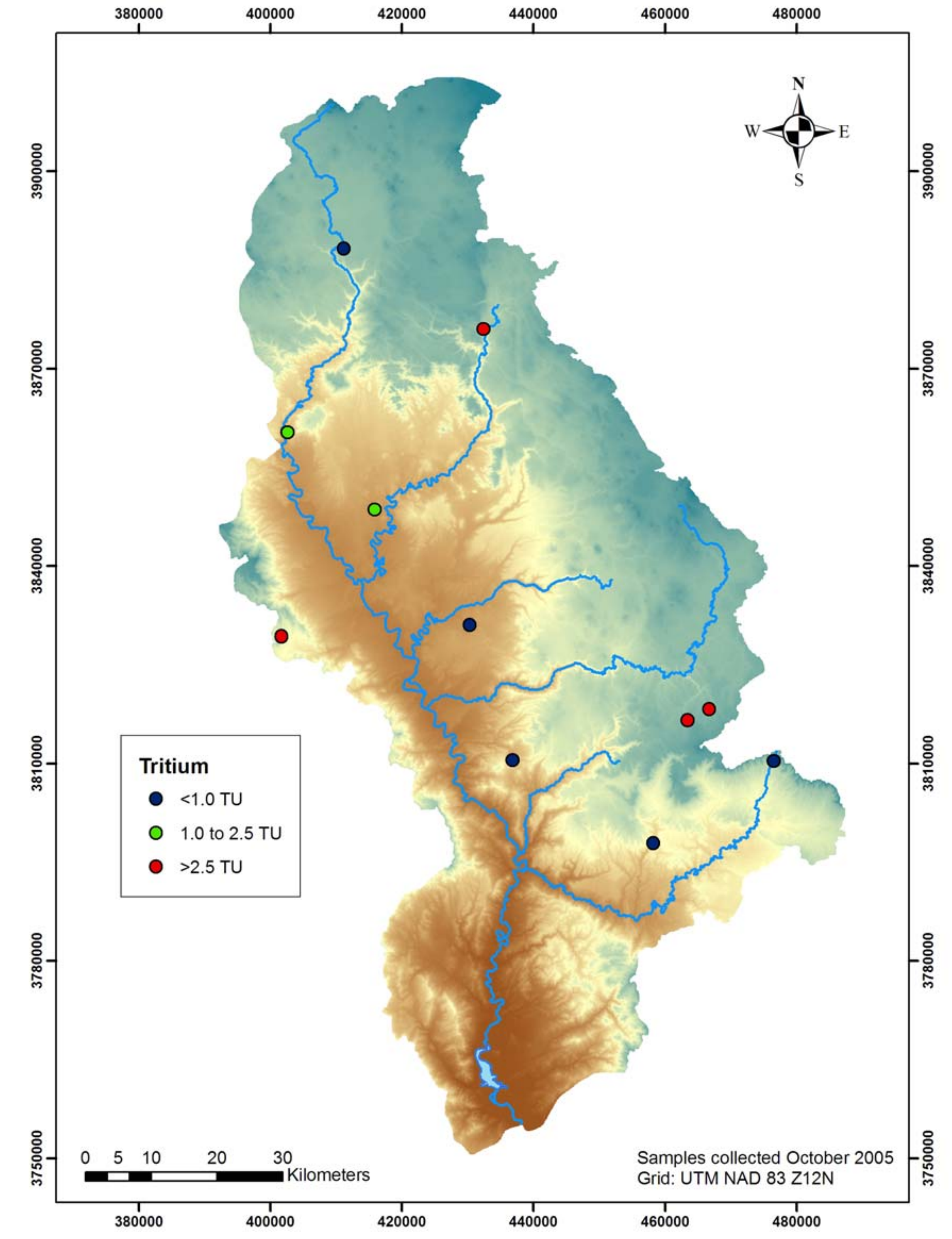


Figure 26. Distribution of 3H values throughout the study area. High values are generally located in shallow aquifer systems. Detectable levels in regional aquifer springs indicates the effect of local recharge.

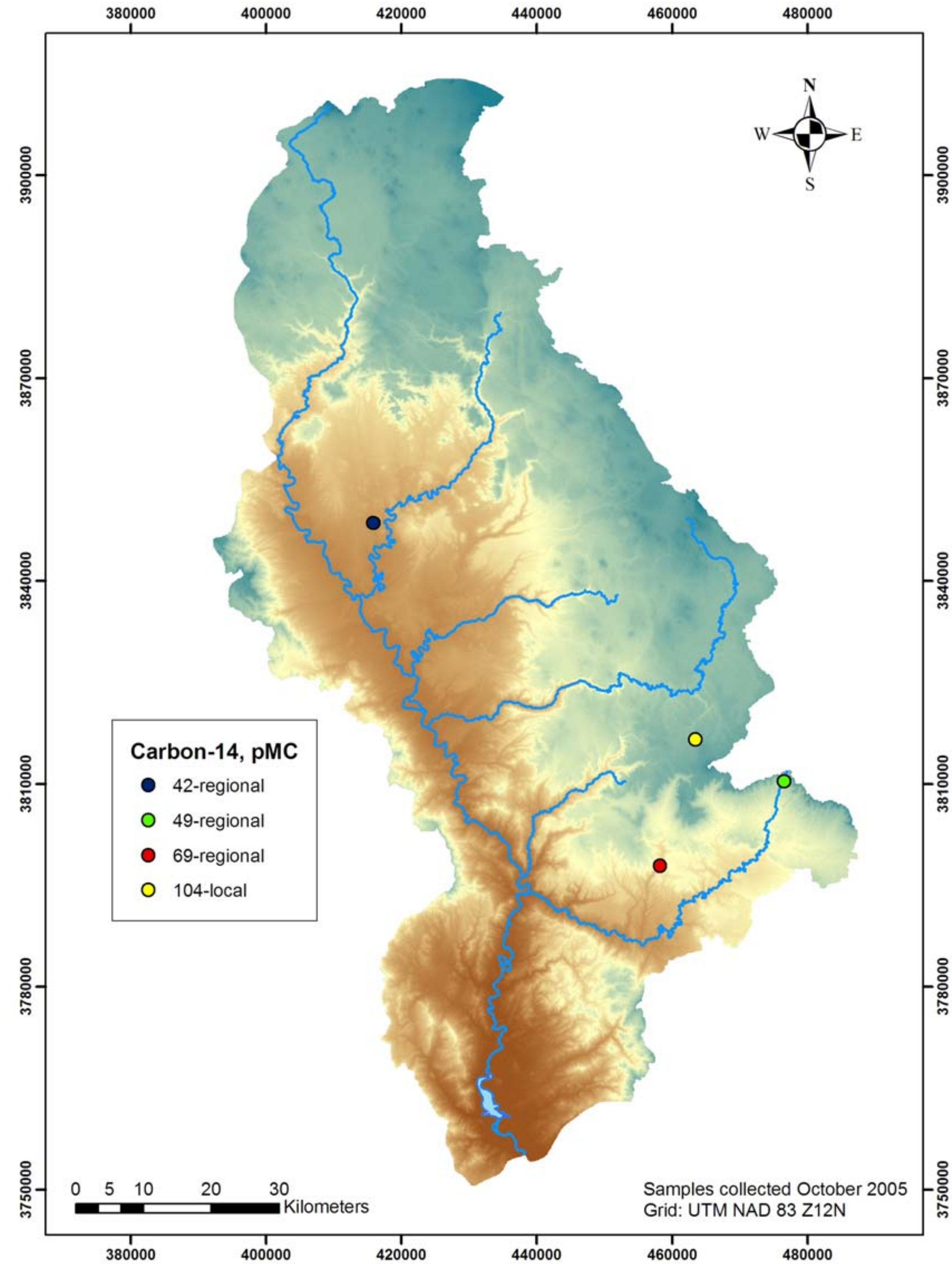


Figure 27. Distribution of 14C throughout the study area. The lowest values come from regional aquifer systems. The one 14C value from a local system indicates the water is modern.

Fritz, 1997) (and therefore representing the upper age limit of the spring water), spring discharge from the five springs analyzed for ^{14}C range from recent to over 11,430 years old (Table 7). There are, however, measurable amounts of ^{3}H in each of these five springs, which indicate some amount of local mixing with younger waters. This input is minimal, as the stable isotope values do not seem to be affected by the influence of local recharge.

3.1.3 Regional and Local Aquifer Distinctions

Two springs in the study area, Spring Creek and Russell, discharged from the local Verde Formation, but geochemical evidence indicates that the regional sandstone aquifer is the source of the spring water. Geochemical data from these two springs were compared against data from two other springs discharging from the regional sandstone aquifer, Sterling Hatchery and Pieper Hatchery springs.

Interpretations of stable and radioactive isotope data indicate that these two springs are being supplied by a regional aquifer system. Stable isotope values for the regional aquifer springs average -11.65 and -80.15 $\delta^{18}O$‰ and $\delta^{2}H$‰, respectively, whereas the two springs discharging from the Verde Formation average -11.68 and -81.35 $\delta^{18}O$‰ and $\delta^{2}H$‰, respectively. Based on these light stable isotope values and the elevation of the discharge point, these springs would not fit on the line of $\delta^{18}O$‰ change with elevation seen in Figure 22. These two springs fall in the range of the regional springs (and are plotted as so in Figure 22). Heavier stable isotope values for Russell Spring in October 2005 compared to February and May 2006 may be the result of mixing

Table 7. Uncorrected groundwater age calculations based on percent modern carbon (pMC) values.

Spring name	Regional/local aquifer	pMC	Uncorrected age (yr), approximate
Pivot Rock	Local	103.8	Recent
Tonto Bridge	Regional	69.2	3,040
Pieper Hatchery	Regional	49.2	5,860
Spring Creek	Regional	42.1	7,150
Fossil	Regional	25.1	11,430

Age calculated using Equation 2 (Clark and Fritz, 1997). Samples collected in October 2005.

of water from the regional aquifer with recharge into the Verde Formation from monsoon precipitation from July-September.

Tritium values for the two Verde Formation springs also indicate a regional aquifer source. Spring Creek Spring had a tritium value of 1.5 TU, and Russell Spring was 0.5 TU. These ^{3}H values represent relatively long residence times, not generally associated with a local aquifer system with a relatively high hydraulic conductivity. These springs were not analyzed for ^{14}C as they were originally thought to be locally sourced and therefore rather young. The location of these two springs also supports the hypothesis that discharge from the regional sandstone aquifer flows into the Verde Formation which fills much of the Verde Valley. Several normal fault zones in the area (Figure 28), including the nearby Page Springs and Sheepshead fault complexes (Blasch, et al., 2006) are seen to drop Paleozoic units, including portions of the Permian Coconino Sandstone to positions adjacent to the Tertiary Verde Formation. Two other large discharge springs, Page Springs and Montezuma Well, are nearby these springs and their locations and discharges are also associated with the faulting in the area (Figure 28). General groundwater flow direction in the area is from the higher elevations of the Coconino Plateau towards the Verde Valley and these springs are all located along this gradient between the plateau and the valley.

3.1.4 Anions and $\delta^{34}S$

Anions and $\delta^{34}S$ were analyzed to look for trends in spring source location, geologic unit of discharge, types of geologic material in contact with the water along its flowpath, and extent of potential groundwater mixing. Some anion data, including nitrite

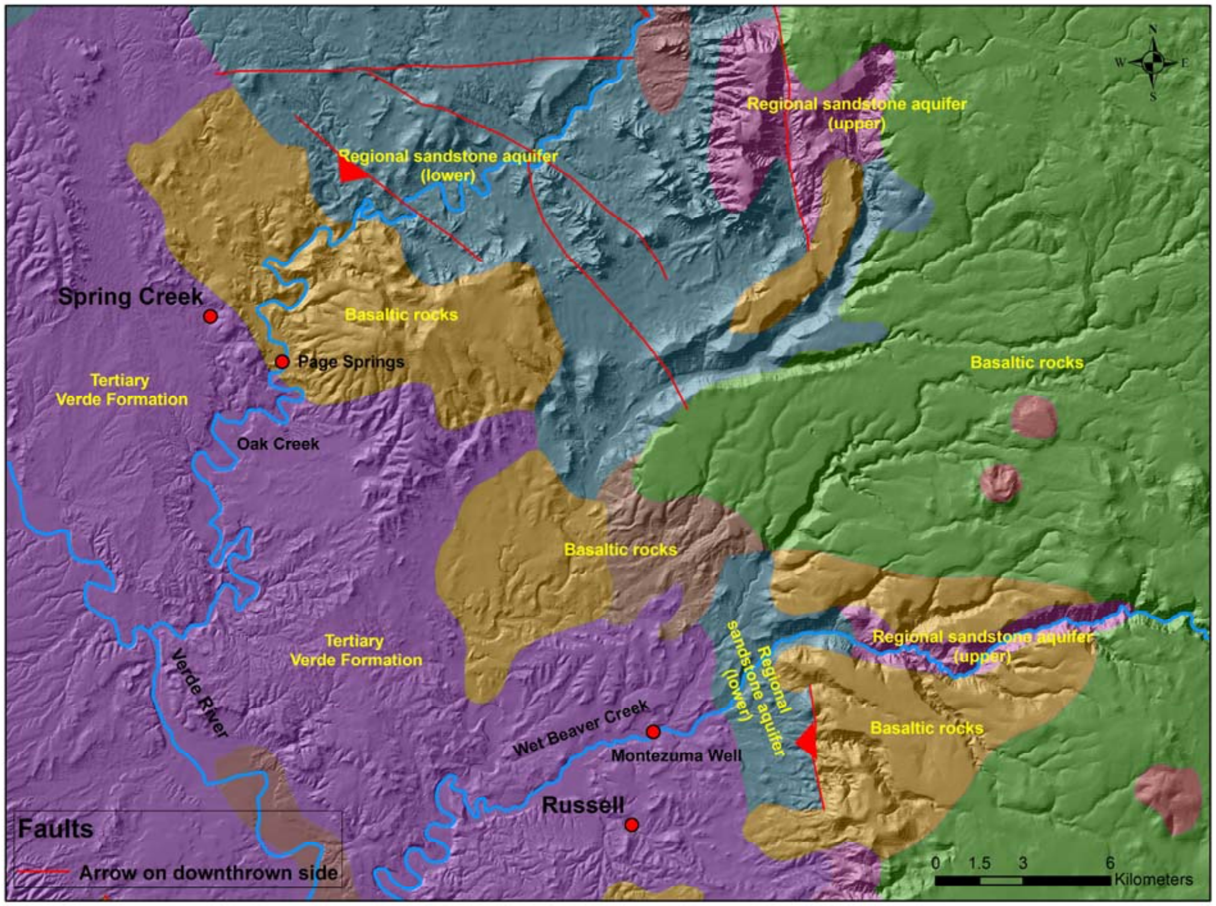


Figure 28. GIS map of geology overlying an elevation hillshade of a portion of the study area. The proximity of Spring Creek and Russell Springs to the regional sandstone aquifer supports the evidence that indicates these springs are sourced from this regional aquifer although they discharge from the Tertiary Verde Formation

(NO_2) and phosphate (PO_4) provided very little information to the study, as the majority of the concentrations were below laboratory detection limits. Maps showing the spatial distribution and concentration of several anions and anion ratios are provided in Appendix B. Generally, most anion concentrations are lower at higher elevation springs and higher at lower elevation springs. Anions associated with salinity and evaporite deposits such as Cl and Br show this trend rather distinctly, and elevated results are likely a result of anion concentration due to increased evapotranspiration at lower elevations.

Nitrate (NO_3) concentrations had a relatively uniform distribution across the study area (Appendix L). The highest concentration (4.08±0.27 average mg/L) was found at Poison Spring, a high elevation spring discharging from a local basalt aquifer. This concentration was much higher than the average of 0.73±0.97 mg/L for the remainder of the springs. The spring is located in close proximity to a Boy Scout summer camp, several moderate-sized ranches and a Christmas tree farm. It is possible that anthropogenic influences (fertilizer use, livestock waste, septic systems etc.) associated with these locations may be infiltrating the shallow local aquifer and affecting the composition of the spring water. No notable variation in nitrate concentration was observed on a seasonal basis.

Sulfate concentrations were highest in springs discharging from Precambrian granitic rocks (Grimes, Grapevine, and Log Springs) and the one spring discharging from Quaternary alluvium (Hackberry Spring) (Appendix L). Concentrations of sulfate at these locations were higher (average 25.8±7.4 mg/L) than the remainder of the springs sampled (4.99±5.1 mg/L). All of these locations are located at low elevation (<1,400m) except Log Spring, which is located in the Black Hills at an elevation of 1,664 meters. A spring in the Black Hills discharging from a Tertiary sedimentary aquifer was sampled by Blasch, et al. (2006) and also showed elevated sulfate concentrations compared to springs sampled at other locations.

In addition to sulfate, the stable isotope ^{34}S was sampled at 18 locations within the study area during the October 2005 sampling event. Of these 18 samples, nine of them had insufficient amounts of $\delta^{34}S$ for analysis. Of the remaining nine, values for $\delta^{34}S$ ranged from -4.6‰ to 11.5‰, with an average of 7.97±4.97‰ (Appendix E). Sulfate minerals from geologic time periods as well as modern sources such as seawater and the atmosphere have general $\delta^{34}S$ ranges which were compared against the results from the study area (Clark and Fritz, 1997) (Figure 29). The figure shows that the sample results from regional aquifer springs fall on the line that represents common $\delta^{34}S$ values for Devonian to lower Triassic rocks. The two regional aquifers in the study area, a Mississippian/Devonian carbonate aquifer and a Permian sandstone aquifer fit well with this distinction. The samples collected from local aquifers do not show such a pattern. The lowest value, -4.6‰, came from Hackberry Spring, which discharges from Quaternary alluvium in the Verde Valley. This value is firmly in the range of values seen in terrestrial evaporite deposits. The Verde Formation, which fills a large portion of the Verde Valley, is known to contain evaporite deposits (Weir, et al., 1989), so this value appears reasonable.

A plot of the ratio of chloride to bromide concentration versus chloride concentration (Figure 30) shows that most spring samples (n=45) plot on a relatively horizontal line (slope -1.33) between a Cl/Br ratio of 100 and 200, which is a common range for atmospheric deposition (Davis, et al., 1998). Along this line, springs with an

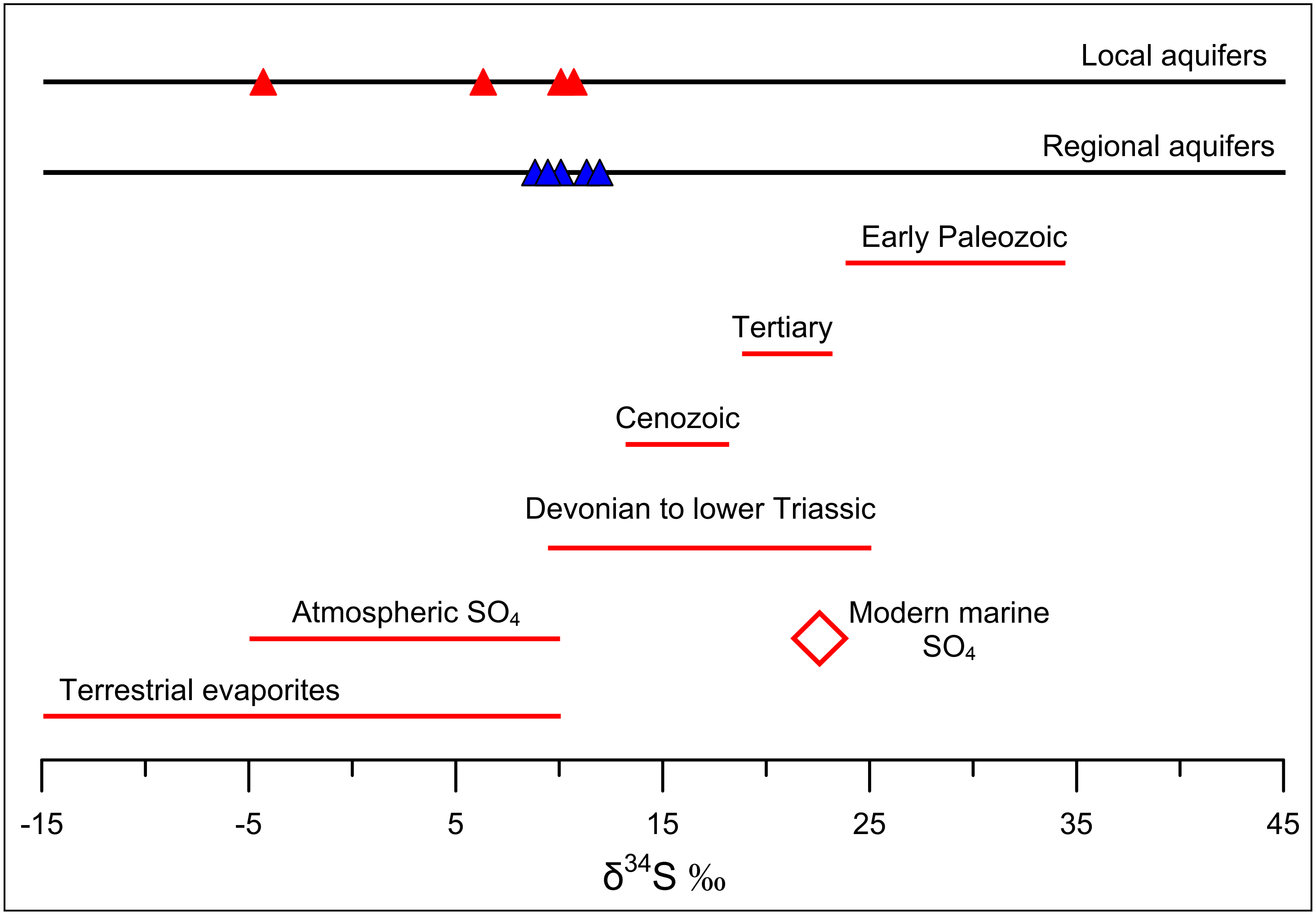


Figure 29. A summary of $\delta^{34}S$ composition in terrestrial sulphates compared to marine and atmospheric sulfates, with spring sample values for regional and local aquifer springs plotted (Samples collected October 2005). Modified from Clark and Fritz, 1997.

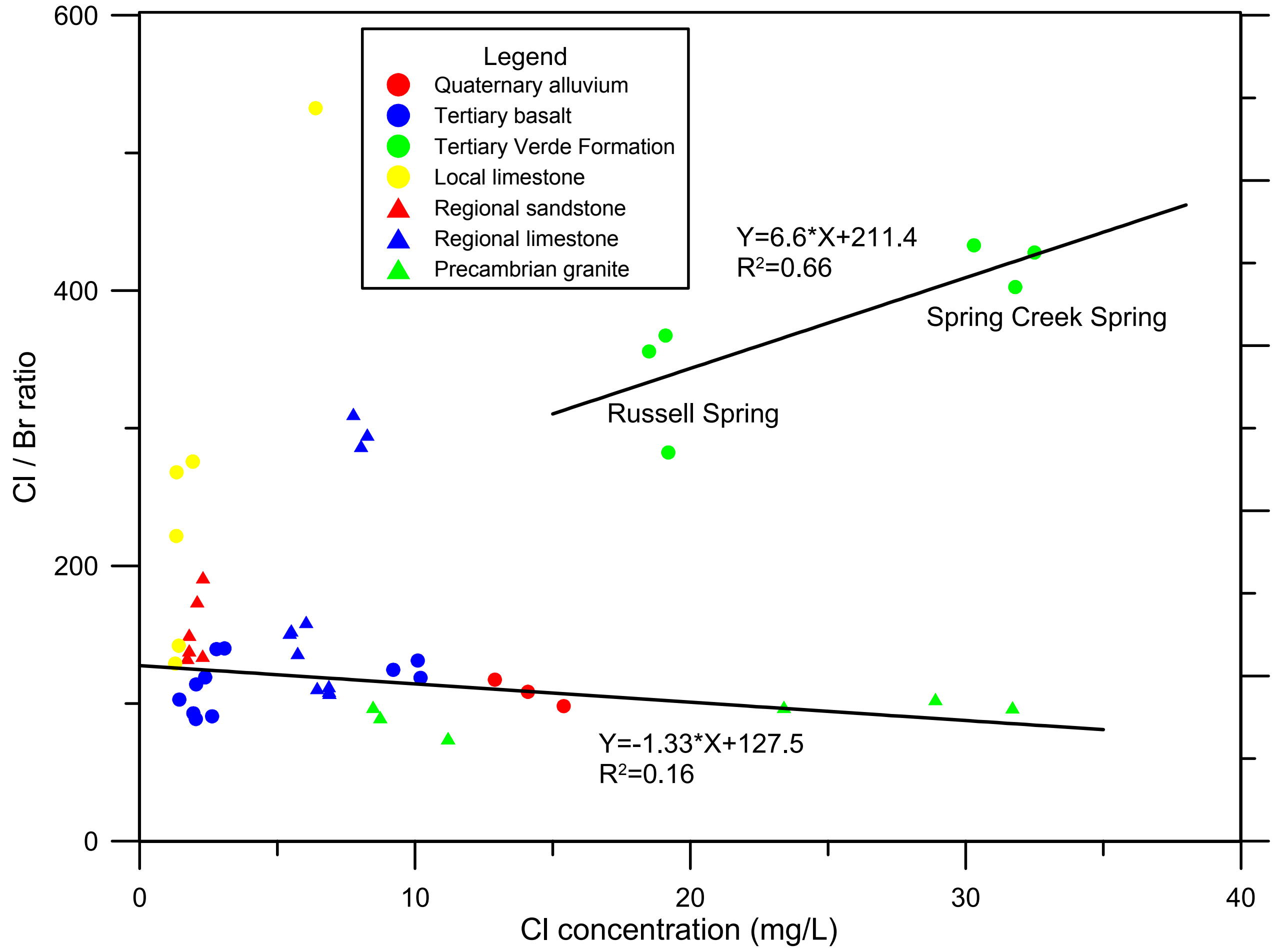


Figure 30. Plot of the ratio of chloride to bromide concentration versus chloride concentration. Cl/Br ratios between 100 and 200 are common for atmospheric deposition (Davis, et al., 1998). The samples from the Verde Formation springs plot on a different trend line with a notably higher Cl/Br ratio. This trend indicates that solute addition from the dissolution of evaporite deposits within the Verde Formation is occurring. Samples collected October 2005, February 2006, and May 2006.

elevated Cl concentration with little to no change in the Cl/Br ratio show the effects of evaporative concentration of Cl. The springs that show this effect are not surprisingly those located at low elevations and are shallow, low discharge springs (Grimes, Grapevine, and Hackberry). Grimes and Grapevine Springs discharge from Precambrian granitic rocks, as does Log Spring, but Log is located at high elevation and is therefore less influenced by the effects of ET and has a lower Cl concentration. The springs showing the least amount of ET influence are the high-elevation Tertiary basalt springs and the regional sandstone aquifer.

The trends of the local and regional limestone aquifer springs, and to a lesser extent the regional sandstone aquifer springs, plot almost vertically on Figure 30. The large range in Cl/Br ratios with little change in Cl concentration indicates that these aquifers had an original Cl source with a very high Cl/Br ratio during the times that the materials were being deposited. Similar trends are seen in surface water samples collected from Oak Creek (J. Hogan, personal communication, Feb. 27, 2007), which receives recharge water from both the regional sandstone and regional limestone aquifer systems.

The samples from the Verde Formation springs (n=6) plot on a different trend line with a notably higher Cl/Br ratio (Figure 30). This trend indicates that solute addition from the dissolution of evaporite deposits within the Verde Formation is occurring. Bromide is excluded during the precipitation of halite, so later dissolution of these evaporite deposits increases the Cl/Br ratio of the groundwater (Davis, et al., 1998). Evaporite deposits are known from the Verde Formation (Weir, et al., 1989), in some places in concentrations large enough to merit economic mining of salts (halite and gypsum) near Camp Verde (Owen-Joyce and Bell, 1983). Cl/Br ratios for Spring Creek Spring are higher than Russell Spring, which may indicate the groundwater feeding the spring may be in contact with a larger amount or higher concentration of halitic evaporite deposits within the Verde Formation than Russell Spring.

A plot of the Cl/ SO_4 ratio versus Cl concentration was also created (Figure 31) to compare to the results of the Cl/Br vs. Cl plot, and the observed trends are similar. As in Figure 30, most springs plot near a horizontal line (slope -0.016) between Cl/ SO_4 ratios of 1.5 and 2.5 (n=45). For the samples from Verde Formation springs, however, the plot shows an increase in Cl/ SO_4 ratio with increased Cl concentration (n=6). Similar to the Cl/Br plot, the Cl/ SO_4 ratios for Spring Creek Spring are much higher than from Russell Spring. If groundwater was dissolving gypsum deposits while passing through the Verde Formation, the Cl/ SO_4 ratio would decrease as sulfate concentration increased. Based on this relationship, groundwater discharging from Russell Spring may have been in contact with more gypsiferous portions of the Verde Formation, leading to a low Cl/ SO_4 ratio. The groundwater near Spring Creek Spring may be passing through a more halitic portion of the Verde Formation leading to a high Cl/ SO_4 ratio, which is supported by the higher Cl/Br ratio shown on Figure 30.

3.2 PHYSICAL RESULTS

Physical data including discharge and water-quality parameters collected during the monthly monitoring of 16 springs in the study area were combined with data (discharge only) for these springs from a previous monitoring cycle (2002-2003) (Flora, 2004) to better understand the behavior and response of springs discharging from a number of

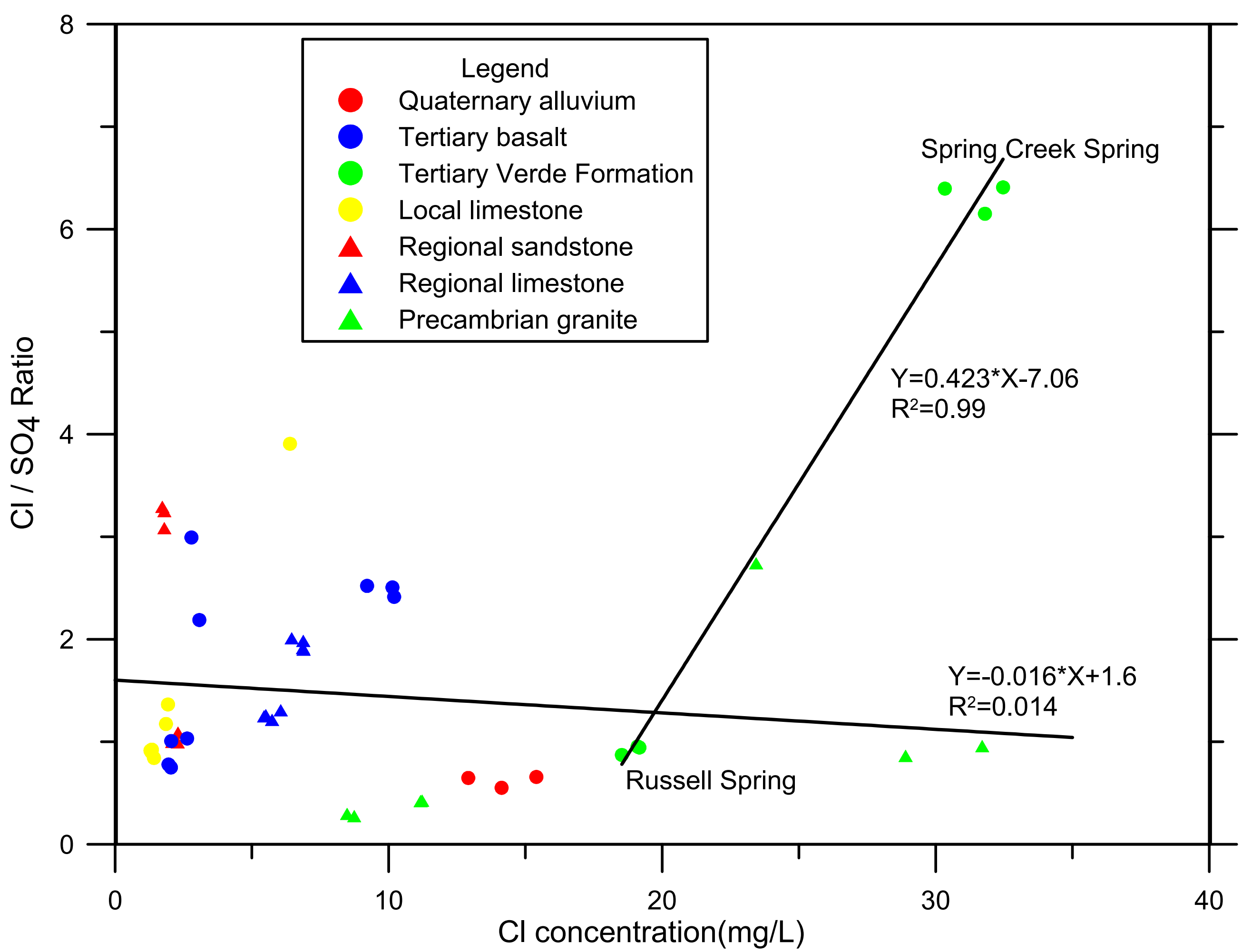


Figure 31. Plot of the ratio of chloride and sulfate concentration versus chloride concentration. The overall trends seen are similar to those seen in Figure 30. Samples from the Verde Formation show an increase in Cl/SO_4 ratio with increased Cl concentration. Groundwater may be dissolving more gypsiferous portions of the Verde Formation near Russell Spring, while dissolving a more halitic portion of the Verde Formation near Spring Creek Spring. Samples collected October 2005, February 2006, and May 2006.

different geologic units to recent climate variability. Additional recent data were collected for two other springs, Clover (Anderson et al., 2004) and Summer (USFS, 2001). Of the 16 monitored springs during the 2005-2006 field season, eleven were perennial, with the remaining five intermittent or ephemeral springs exhibiting no flow over a period ranging from one (Clover and Hackberry Springs) to eight months (Grimes Spring) of the twelve-month monitoring period. Summaries of all spring discharge measurements for the 2002-2003 and 2005-2006 field seasons and spring water-quality parameters from 2005-2006 are provided in Appendices C and D, respectively. Discharge hydrographs for the 16 monthly monitored springs are in Appendix E.

3.2.1 Hydrograph and Chemograph Results

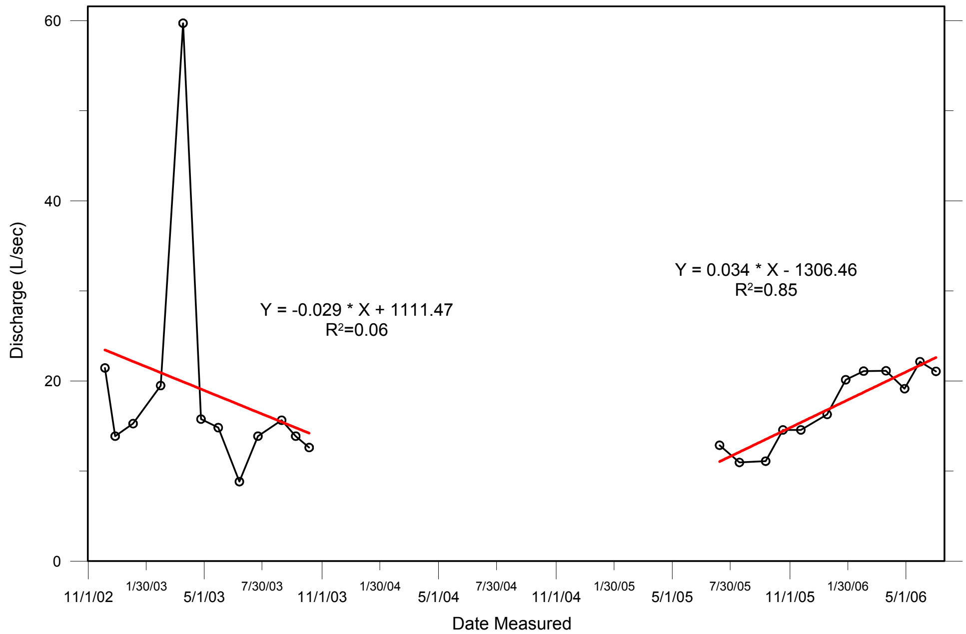
Coefficients of determination (R^2) for all of the hydrographs ranged from 0.0005 at Campbell Spring in 2002-2003 to 0.85 at Pieper Hatchery Spring in 2005-2006. Hydrographs of springs discharging from regional aquifer systems show a distinct lagged response to climate changes. The 2002-2003 monitoring period was not especially dry, but at the end of one of the driest years on record in Arizona (2002). The monitoring period of 2005-2006 was quite dry as well, but followed the historically wet winter of 2004-2005. The regional springs in the study area show the influences of the climate extremes that preceded the monitoring periods.

Four of the six regional springs in the study area had a decreasing discharge trend in the 2002-2003 field season as a lagged response to the dry year of 2002. These same four springs had an increasing trend during the relatively dry 2005-2006 monitoring period in a lagged response to the wet winter of 2004-2005. Examples of these regression curves fitted to discharge hydrographs for a regional spring and a local spring are in Figures 32A and B, respectively. Appendix F contains the hydrographs with linear regression lines and equations, and the R^2 values for those lines for each of the 16 monthly monitored springs.

Only one of the locally-sourced springs exhibited this discharge trend (Grimes), but the increase in 2005-2006 is attributed to the fact that the spring was dry for the first seven months it was monitored. The two regional springs that did not exhibit a trend similar to the rest (Sterling Hatchery and Spring Creek Springs) can be potentially explained. Although Sterling Hatchery Spring discharges from the regional sandstone aquifer, it is close to the top of the geologic section and near the primary recharge area (Coconino Plateau) and therefore has a quicker response time compared to springs that discharge from a deeper part of the section and/or from springs a longer distance from the primary recharge area. Spring Creek Spring, while primarily fed from a regional aquifer, travels through a local aquifer system (the Verde Formation) prior to discharge, and may be influenced and acquire some of the characteristics of the local system. Local recharge directly into the Verde Formation may account for the majority of the groundwater mixing seen based on the ^{14}C dates with the presence of measurable ^{3}H and affect the response time of the spring. Discharge lags similar to those seen in the regional springs have been noted by Manga (1999). These relations are also supported by the trend analyses which are described in the statistical results section.

Interpretations of chemographs with spring discharge also provide information on the properties and responses of aquifer systems to climate changes. Although water-quality parameters for pH, electrical conductivity (EC) and dissolved oxygen (DO) were

A



B

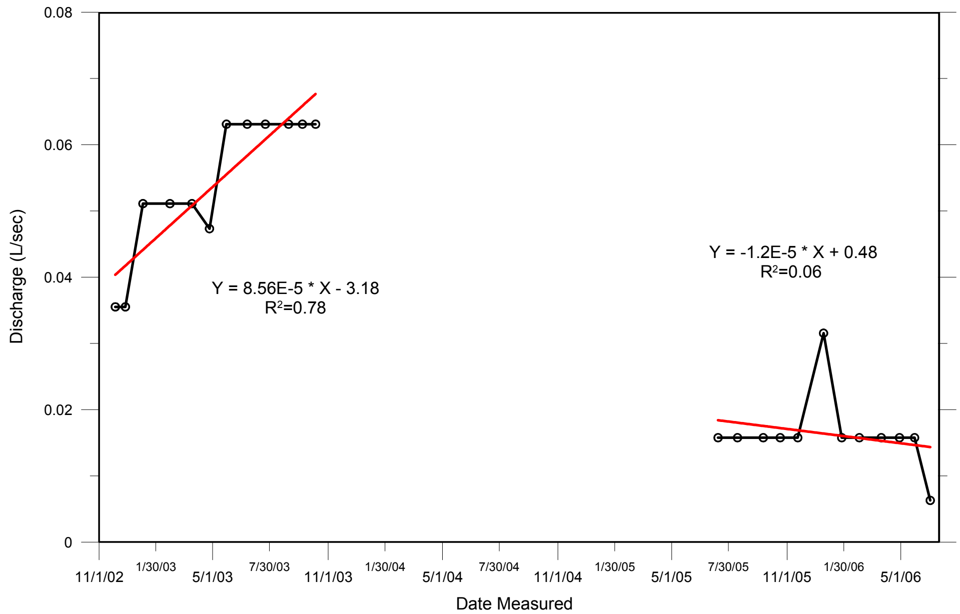


Figure 32. Regression curves fitted to discharge hydrographs of regional (A) (Pieper Hatchery Spring) and local (B) (Gray Spring) springs. The 2002-2003 monitoring season was not especially dry, but was at the end of one of the driest years on record in Arizona. In regional springs (A), discharge is seen to decrease in a lagged response to this dry year. The 2005-2006 monitoring season was quite dry, but after a historically wet winter of 2004-2005. Discharge from regional springs increases as a lagged response to this wet period. Local springs (B) show on average a much closer relation to recent precipitation patterns.

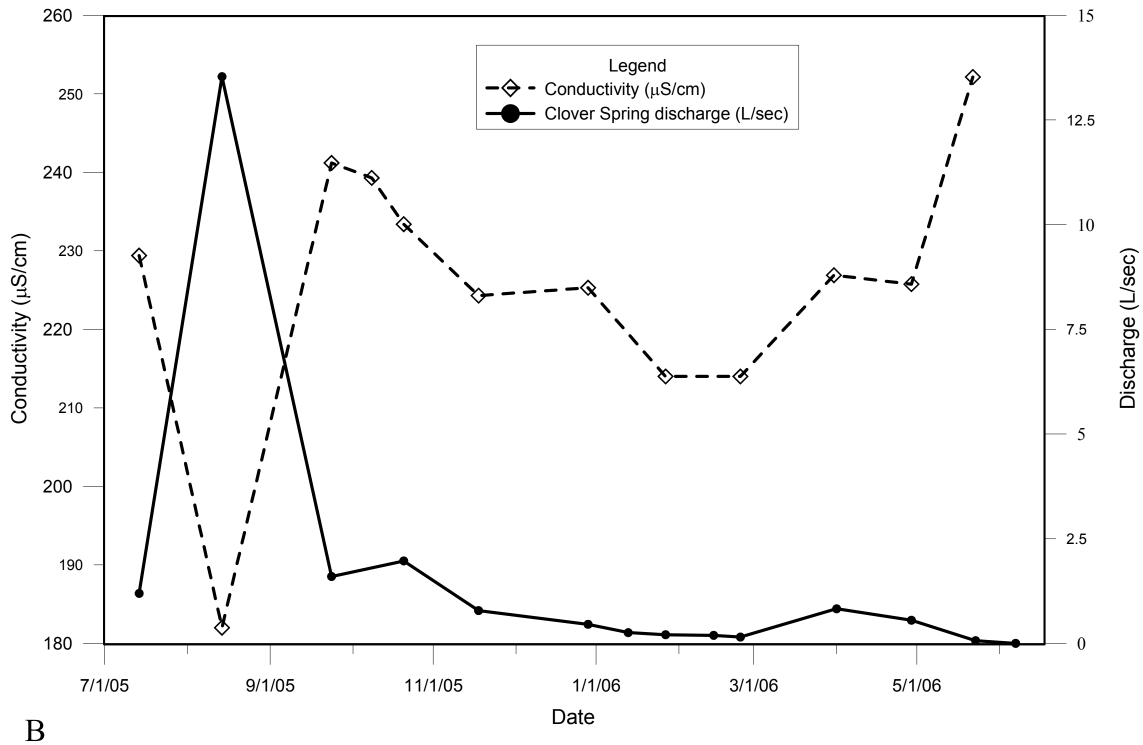
collected during the monthly field visits, only EC data were used in chemograph generation and interpretation. Values for pH and DO contained multiple poor data points and outliers due to malfunction of the sensors attached to the multi-parameter meter.

It has been observed (Desmarais and Rojstaczer, 2002) and modeled (Grasso, et al., 2003) that aquifers with low residence times and or high hydraulic conductivity (K), especially karst systems, “flush out” after significant precipitation events. Two distinct phases of this phenomenon are known as the piston flow phase, followed by a chemically-characterized recession flow (Grasso, et al., 2003). The piston flow phase is controlled by a pressure increase created by recharge water entering the saturated zone and pushing water out the other end of the system. The chemically-characterized recession phase is seen as the aquifer system empties older water as new water infiltrates the aquifer system and is not driven by the initial pressure wave created during the piston flow phase. The difference between the two phases involves recharge water traveling through the high conductivity conduits of the karst system (phase 1) and the lower conductivity aquifer matrix (phase 2) (Grasso, et al., 2003).

Two springs in the study area exhibit this response to precipitation events, Clover and Pivot Rock Springs, and one (Summer Spring) may as well (Figure 33). Both Clover and Pivot Rock discharge from a shallow Permian karst aquifer system, whereas Summer Spring discharges from the regional limestone aquifer. In experiments where karst systems are monitored continuously for responses to precipitation events, EC spikes initially in response to the piston flow phase of aquifer recharge as old water is forced out of the system. EC is then seen to decrease as fresh recharge water enters the system as part of the chemically-based recession phase. After this phase, EC is seen to slowly increase as dissolution of the karst system and the increased residence time in the aquifer matrix allows for dissolution of the surrounding carbonate material (Desmarais and Rojstaczer, 2002). The hydrographs from Clover and Pivot Rock Springs show the drop in EC as part of the chemically-based recession phase, but not the initial spike in response to piston flow (Figures 33A and B). This is because of the discharge and water-quality measurements being conducted on a monthly basis miss the small window of time when piston flow occurs after a storm event. Desmarais and Rojstaczer (2002) indicate that the piston flow phase begins between 1 and 2 hours after a storm event in a similar shallow karst aquifer system. This phase lasts approximately 0.5 to 2.9 days, depending on the intensity of the storm event (less time for more intense storms). Given the intense nature of Arizona summer monsoon storms, this phase would probably be on the shorter end of that range.

The chemograph for Summer Spring shows a similar response to that of the two shallow karst systems described above, but this spring discharges from a deep regional aquifer system. This response is likely the result of local recharge to a regional system. A storm event near the discharge point of Summer spring may locally recharge the limestone aquifer which is either exposed or near land surface in the area where the spring discharges. Chemograph responses as are described here are not seen in any of the other springs investigated. All chemographs are included in Appendix G.

A



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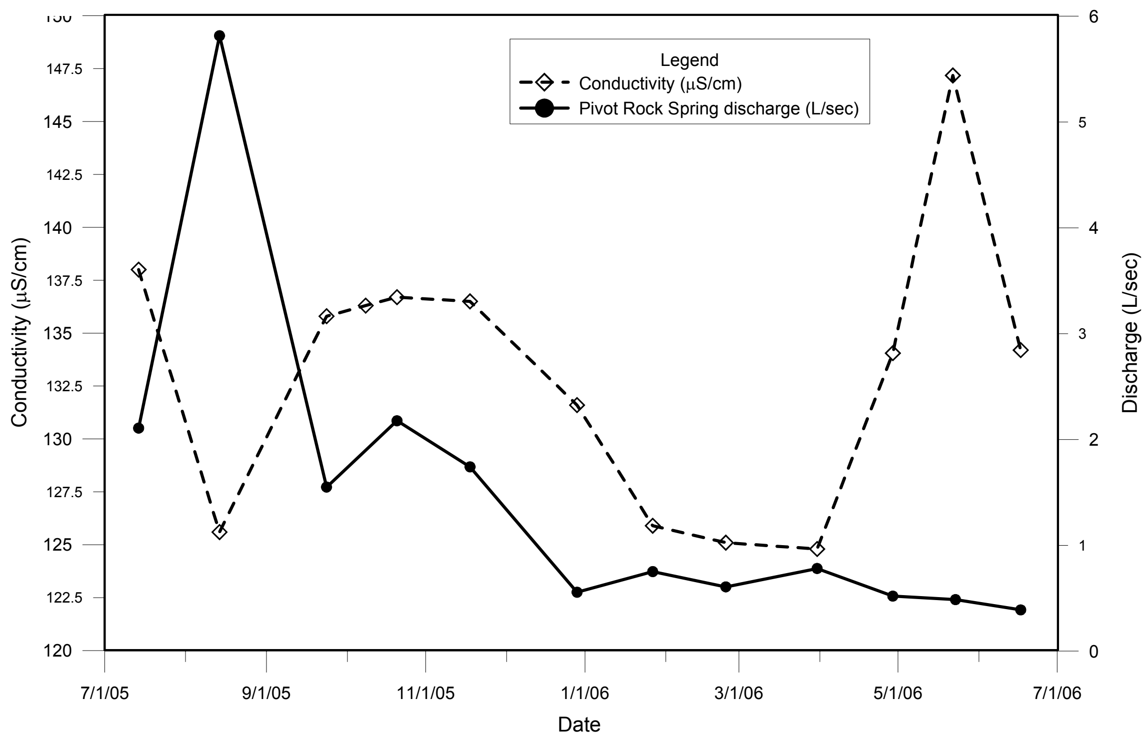

Figure 33. Discharge and electrical conductivity (EC) plots for (A) Clover Springs and (B) Pivot Rock Spring discharging from a shallow karst system. The spikes in discharge correspond to a monsoon storm event. EC is seen to drop as fresh water enters the system during the "chemically-based recession phase" (Desmarais and Rojstaczer, 2002).

3.2.2 Springs Response to Climate Changes

Data gathered at springs locations can also be compared to climate data from the study area, including precipitation amounts and season and air temperature changes. Discharge from the monthly monitored springs was compared to precipitation totals from three climate stations in the study area, and mean monthly air temperatures were evaluated in comparison to changes in spring water temperature. Springs discharging from the shallow karst aquifer (Clover and Pivot Rock Springs) show discharge responses to both monsoon rainfall and snowmelt (R^2 values of 0.66 and 0.74, respectively) (Figure 34). Springs discharging from regional aquifer systems have more muted and delayed responses to precipitation events. Monsoon storm events appear to have a much smaller impact on discharge rate change than spring snowmelt events, demonstrating that winter precipitation is the dominant recharge source for the study area. This response is similar to the results of the stable isotope analyses discussed earlier. Regional aquifer springs have a significantly lower correlation coefficient with precipitation, which is actually negative ($r=-0.22\pm0.42$) with a subsequent R^2 value of 0.05 (Figure 34). Springs not discharging from the shallow karst aquifer or the regional aquifers show little discernable trends with precipitation on a monthly basis.

Spring water temperature from local and shallow aquifers mimics the trends seen in air temperature variations throughout the year (average $R^2=0.67\pm0.23$) (Figure 35). Water temperatures have been seen to respond to air temperature changes in karst systems within 45-60 days (Desmarais and Rojstaczer, 2002). Regional aquifers on the other hand do not show much water temperature variation throughout the year compared to air temperature fluctuations (average $R^2=0.2\pm0.19$) (Figure 35). Manga (1999) noted

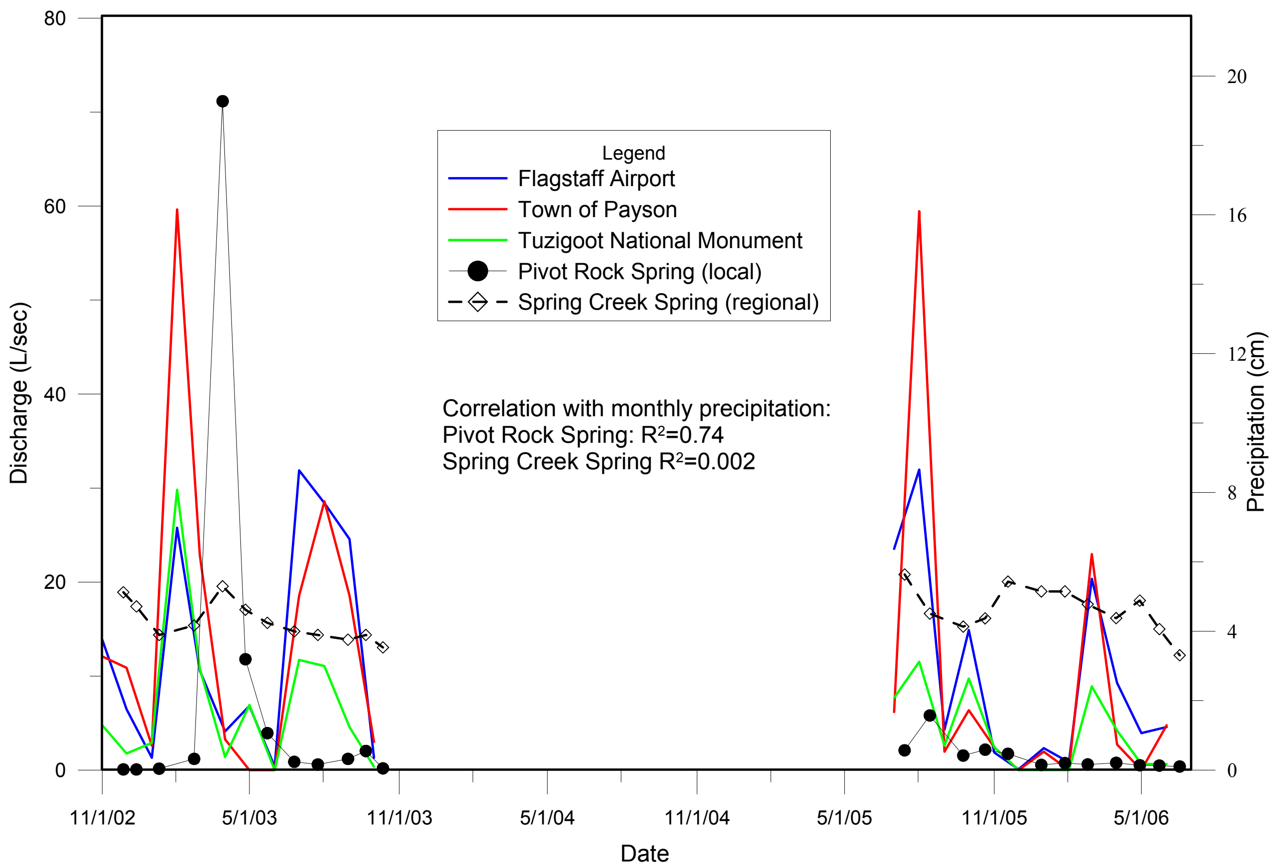

Figure 34. Hydrographs of spring discharge of Pivot Rock Spring and Spring Creek Spring and monthly precipitation totals for three climate stations in the study area. The response of the local aquifer system spring has strong responses to both monsoon precipitation and snowmelt events. The regional aquifer spring has little to no response to monsoon precipitation events and a lagged response to snowmelt events.

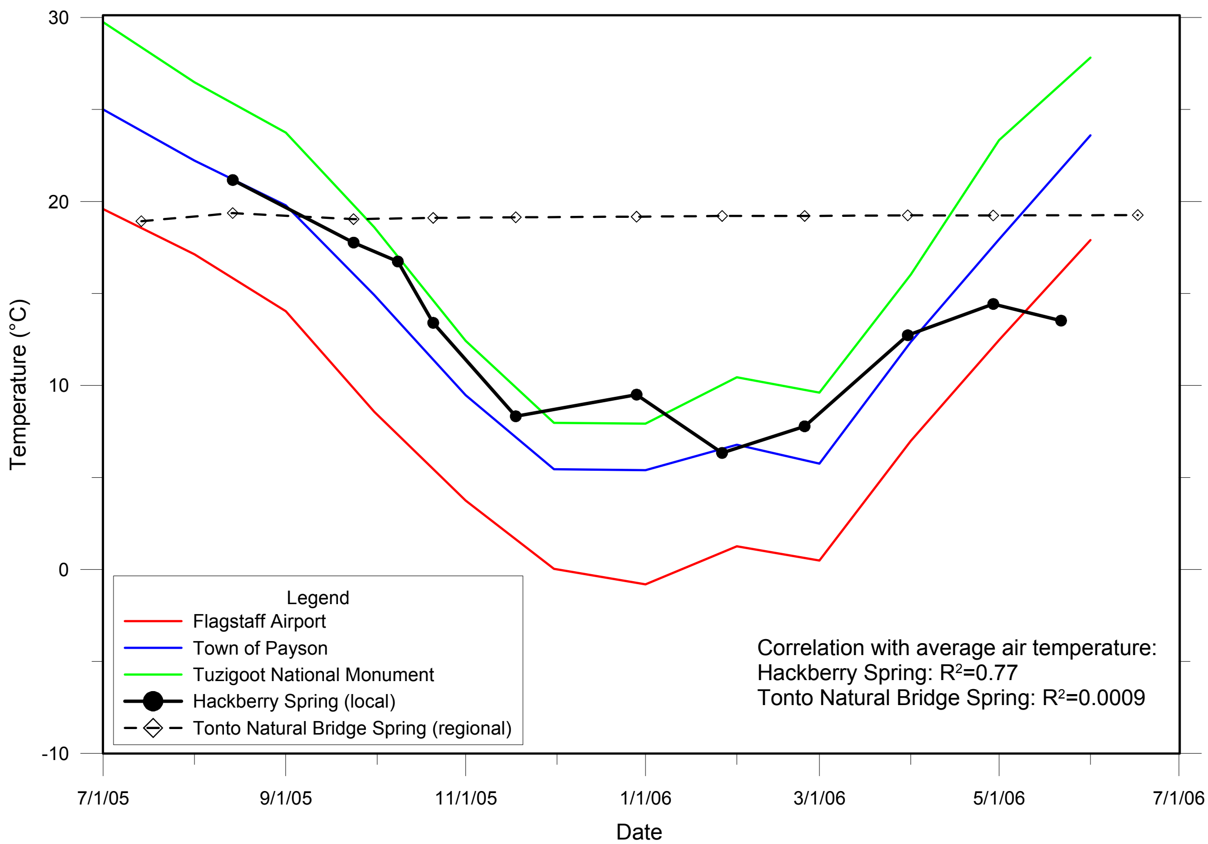

Figure 35. Plots of spring water temperature for a local (Hackberry Spring) and regional (Tonto Natural Bridge Spring) aquifer spring and monthly average air temperature from three climate stations in the study area. Local aquifer springs respond to fluctuations in air temperature, while regional aquifer springs do not respond, indicating a large and stable volume of water supplying the spring.

that the lack of water temperature fluctuation throughout the year represents a large and stable body of water supplying the spring. This interpretation is similar for the regional aquifer systems in the study area and indicates that these aquifers are less sensitive to short-term changes in climate. Another factor which may explain the lack of temperature variation in the regional springs is the depth of the water table, where the overlying geologic material prevents convective heat transfer from the surface to the saturated zone (Bundschuh, 1993). The discharge versus precipitation plots are included in Appendix H and the air temperature versus spring water temperature plots are included in Appendix I.

3.2.3 Reactivation and Deactivation of Springs in Response to Seasonal Climate Change

During the initial survey of 160 springs in the study area in 2002, 50% (80 of 160) were found to be dry. After an anomalously wet winter of 2004-2005, 57 of the 80 dry springs in 2002 were revisited in June and July 2005. It was found that 41 of them (72%) had reactivated. Discharge rates from the reactivated springs averaged 2.8±5.2 L/sec. Then, in the summer of 2006 after an extremely dry winter, the springs that had reactivated in 2005 were revisited. Of the 41 reactivated springs 40 were visited and it was observed that 31 of them (77.5%) had once again deactivated. Discharge of the remaining flowing springs had decreased substantially, with an average discharge rate of 0.042±0.06 L/sec, which is 81.5% lower than the previous year. A series of maps was generated showing the distribution of wet and dry springs for the three investigation seasons (Figure 36). The springs were later examined by elevation of discharge point and geologic unit from which the springs discharged. In the 2005 investigation, it was found

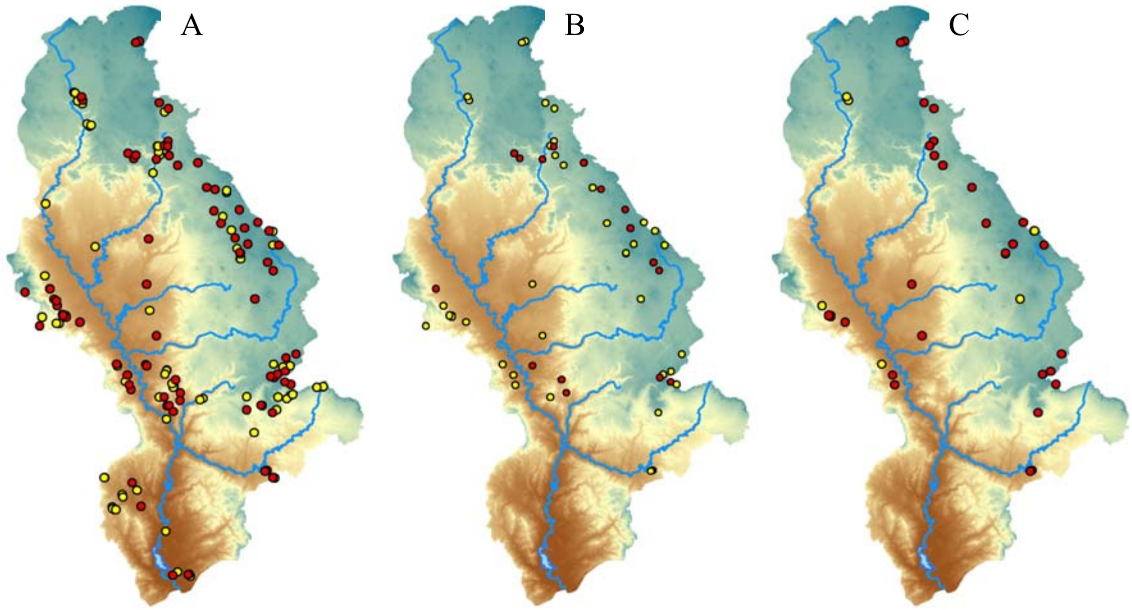

Figure 36. Distribution of wet and dry springs during three field seasons A) 2002, B) 2005, and C) 2006. Dry springs are represented as red dots, while flowing springs are represented as yellow dots. 2002 was the first season of inventory, and was one of the driest years on record in Arizona. The 2005 inventory was conducted after an anomalously wet winter, and the 2006 inventory was conducted after another dry winter season.

that 95% of the reactivated springs discharged from local aquifer systems, but it must be noted that 96.5% of the springs inventoried that summer in total discharged from local aquifer systems. This high percentage indicates that springs sourced from regional aquifers are less sensitive to seasonal climate fluctuations and have a low probability of going dry.

Reactivations and deactivations of the springs appear to be related to the elevation of discharge point, but this relation is rather weak. In 2005, springs at an elevation below 1,500 meters had a reactivation occurrence of 78%, whereas springs at an elevation over 2,000 meters were seen to have reactivated 69% of the time. In 2006, 78.5% of the springs visited below 1,500 meters had deactivated whereas 75% above 2,000 meters had as well. This tenuous relation between elevation and spring reactivation and deactivation may be a result of the higher elevation springs' proximity to the primary recharge areas, which would make them slightly less sensitive to variations in winter precipitation totals. No trend in the reactivation or deactivation rate based on source geology was seen in 2005 (Table 8a) or 2006 (Table 8b). A complete summary of the reactivation/deactivation investigation results is in Appendix J.

3.2.4 Biological Results

The results of the biological inventories of the 16 monthly monitored springs indicate that larger discharge springs generally supported more plant diversity than smaller discharge springs, which agrees with insular biogeographic theory (Stevens and Omana, 2007). However, high elevation springs including Gray (33 species) and Poison Springs (29 springs) had the highest number of species of all the springs inventoried. No

Tables 8A and 8B. Summaries of reactivation and deactivation of springs inventoried in 2005 (A) and 2006 (B).

A

Geologic Unit		% reactivated	Average discharge
% Basalt	56 (32 of 57)	71 (23 of 32)	0.31 L/sec
% Precambrian	16 (9 of 57)	100 (9 of 9)	0.06 L/sec
% Tertiary	7 (4 of 57)	50 (2 of 4)	0.01 L/sec
%Kaibab Fm	7 (4 of 57)	50 (2 of 4)	15.58 L/sec
%Verde Fm	5 (3 of 57)	66 (2 of 3)	0.08 L/sec
%Supai Fm	3.5 (2 of 57)	50 (1 of 2)	0.03 L/sec
% Alluvium	3.5 (2 of 57)	50 (1 of 2)	0.07 L/sec
% Coconino SS	2 (1 of 57)	100 (1 of 1)	6.37 L/sec
Elevation			
% >2000m reactivated - 69% (18 of 24)			
% 1500-2000m reactivated - 75% (2 of 2)			
% <1500m reactivated - 78% (11 of 14)			
All: 57 visited, 41 reactivated (72%)			

B

Geologic Unit		% deactivated	Average discharge
% Basalt	57.5 (23 of 40)	78 (18 of 23)	0.11 L/sec
% Precambrian	20 (8 of 40)	63 (5 of 8)	0.013 L/sec
% Tertiary	5 (2 of 40)	100 (2 of 2)	0
%Kaibab Fm	5 (2 of 40)	50 (1 of 2)	0.003 L/sec
%Verde Fm	5 (2 of 40)	100 (2 of 2)	0
%Supai Fm	2.5 (1 of 40)	100 (1 of 1)	0
% Alluvium	2.5 (1 of 40)	100 (1 of 1)	0
% Coconino SS	2.5 (1 of 40)	100 (1 of 1)	0
Elevation			
% >2000m deactivated - 75% (18 of 24)			
% 1500-2000m deactivated - 100% (2 of 2)			
% <1500m deactivated - 78.5% (11 of 14)			
All: 40 visited, 31 deactivated (77.5%)			

rare or endangered aquatic, wetland, or riparian plants were identified during the inventories, but the timing of the survey (October 2006) may have had an effect on the presence of vernal species. Aquatic and wetland invertebrate diversity ranged from 0-24 species per site, with Gray, Grapevine, and Russell Springs exhibiting the highest species diversity (Stevens and Omana, 2007). Sterling Hatchery and Foster Springs had the lowest invertebrate diversity, attributed to extensive modification of Sterling and the ephemeral nature of Foster in addition to some human modifications. The presence of several species including spring snails, giant waterbugs, elmid and driopid beetles, and stoneflies indicate perennial flow at the springs where they were identified, as they are all fully aquatic and have limited dispersal ability (Stevens and Omana, 2007). These findings were used to relate to the springs variability analyses discussed in the next section.

3.3 STATISTICAL RESULTS

3.3.1 Descriptive Statistics Results

Average spring discharge for the monthly monitored springs ranged from 145.9 L/sec at Summer Spring to 0.01 L/sec at Grimes Spring for the two monitoring seasons (2002-2003 and 2005-2006). Standard deviations averaged ±2.31 L/sec for locally-sourced springs, which is 265% of the average discharge. Regional springs, on the other hand, had an average standard deviation of ±7.21 L/sec, which is only 20% of the average discharge of these springs. The results for the kurtosis and skewness analyses provided data useful to interpreting the distribution of spring discharge data collected. Positive values for both indicate that both local and regional springs exhibit the characteristic of “peakedness” rather than a flat distribution and are skewed towards more positive values (Tabachnick and Fidell, 1996). Values for the two standard errors of kurtosis and skewness (*sek* and *ses*) calculations show significant deviations from normal distribution occurring at a value of 2 for kurtosis and 1 for skewness. Kurtosis values for regional springs averaged 2.06, putting them on the margin of normal distribution, while local springs’ average value (5.93) indicates a distribution that is too tall (leptokurtic) and may violate the assumptions of normal distribution (Tabachnick and Fidell, 1996). The average skewness value for regional springs (0.75) indicate that the discharge data are normally distributed and within the range of fluctuations due to chance. The average value for local springs (1.96) shows that these data are significantly skewed in the positive direction. Pieper Hatchery Spring, a regional aquifer-sourced spring, recorded one exceptionally large discharge reading (59.7 L/sec) in March 2003 which may have been a result of a snowmelt peak and/or a measurement inaccuracy due to the large discharge volume. If this spring is removed from the analysis the regional averages for kurtosis and skewness for the remaining five regional springs change significantly, with kurtosis and skewness values calculated at -0.81 and 0.15, respectively. The negative kurtosis value indicates a flat distribution rather than a peaked one, and being closer to zero indicates a distribution closer to normal. Skewness values still indicate a positive skew, but once again the value is closer to zero indicating a distribution closer to normal.

The normal distribution values for the regional springs discharge indicate that these springs have stable discharge and are not affected by small-scale fluctuations in climate change. The local springs average discharge values are most likely affected by the intermittent or ephemeral nature of some of the springs (Foster, Clover, Hackberry, Grimes and Grapevine Springs) and the flashy discharge nature of the two karst springs (Clover and Pivot Rock) which notably increase the average values for both kurtosis and skewness of discharge. A summary of all of the descriptive statistics results for the 16 monthly monitored springs is in Appendix K.

3.3.2 Springs Variability Analyses

The monthly monitored springs were analyzed for discharge variability using a 90th percentile versus 10th percentile ratio and a coefficient of variation ratio of the standard deviation and the mean (Table 9). Of the 16 monthly monitored springs in 2002-2003, the distribution of variability classes was 3 ephemeral, 3 very unsteady, 3 balanced, 1 well balanced, and 6 steady. The distribution in 2005-2006 was found to be 2 ephemeral, 2 very unsteady, 4 well balanced, and 8 steady. Between the two years of monitoring, the variability classes matched 56% (9 of 16) of the time. When allowing a cushion of one variability class above and below the calculated one, this agreement was increased to 75% (12 of 16). The coefficient of variation analysis had a similar distribution, with results from 2002-2003 agreeing with 2005-2006 69% (11 of 16) of the time, and had a 100% agreement when allowing for one variation class above or below the calculated one.

In 2005-2006, five of the six springs discharging from regional aquifer systems were classified as steady, and one (Russell) was considered well balanced (Table 9). By contrast, six of the ten local aquifer springs were considered ephemeral or very unsteady. The local springs with lower variability were Poison, Gray, and Log Springs. Poison and Gray Springs discharge from Tertiary basalt flows at high elevation.

Table 9. Results of Q_{90}/Q_{10} and Coefficient of Variation calculations on spring discharge from the 2002-2003 and 2005-2006 field seasons.

Spring Name	Regional / Local Aquifer	Q_{90}/Q_{10} Variability 2002-2003	Variability Class	Q_{90}/Q_{10} Variability 2005-2006	Variability Class	Coefficient of Variation 2002-2003	Variation Class	Coefficient of Variation 2005-2006	Variation Class	Overall Variability (2002-2006)	Overall Variation (2002-2006)
Grimes	Local	infinite	ephemeral	infinite	ephemeral	100	high	153	high	ephemeral	high
Grapevine	Local	infinite	ephemeral	43.6	v. unsteady	167	high	72	moderate	ephemeral	high
Log	Local	3.7	well balanced	3.3	well balanced	35	low	49	low	balanced	moderate
Clover[1]	Local	793	very unsteady	26.5	v. unsteady	226	v. high	211	v. high	v. unsteady	very high
Pivot Rock	Local	infinite	ephemeral	4.4	well balanced	243	v. high	104	high	v. unsteady	very high
Campbell	Local	14.4	v. unsteady	4.6	well balanced	120	high	71	moderate	well balanced	high
Foster	Local	12.8	v. unsteady	infinite	ephemeral	70	moderate	76	moderate	ephemeral	high
Poison	Local	1.8	steady	1.8	steady	18	low	26	low	steady	low
Gray	Local	1.8	steady	1	steady	25	low	34	low	steady	moderate
Hackberry	Local	6.9	balanced	2.2	steady	77	moderate	46	low	unbalanced	high
Summer	Regional	1.3	steady	1.6	steady	12	low	17	low	steady	low
Tonto Bridge	Regional	1.6	steady	1.2	steady	17	low	9	low	well balanced	low
Pieper Hatchery	Regional	5.1	balanced	1.9	steady	72	moderate	24	low	steady	moderate
Sterling	Regional	1.3	steady	2	steady	11	low	28	low	steady	low
Russell	Regional	5.6	balanced	4.3	well balanced	55	moderate	50	moderate	well balanced	moderate
Spring Creek	Regional	1.3	steady	1.3	steady	13	low	14	low	steady	low

[1]Period of record 1999-2006 (43 measurements)

Log Spring discharges from Precambrian granitic rocks. Based on ^3H results from the geochemical survey, Poison Spring has a relatively long residence time (0.4 TU) (Appendix A) in comparison to the other local spring sampled. Gray Spring was not sampled for ^3H, but the proximity (1.4 km) and similar behaviors of the two springs indicate they discharge from the same or similar local system. Log Spring discharges from a unit (Precambrian Cherry Springs Granite) which is presumed to have a relatively low hydraulic conductivity, based on the behavior of similar geologic material (Schwartz and Zhang, 2003). These factors most likely affect the lower variability designations of these local springs. The regional springs coefficients of variation, like the variability analysis, show five of the six having low variability, with Russell Spring classified as moderate (Table 9). Again, six of the ten local springs had variation classifications of moderate to very high. The local springs with the lowest variation were again Poison, Gray, and Log springs, with Hackberry Spring (Quaternary alluvium) added to the list as well.

The results from the 2002-2003 variation analysis data agree with the regional springs classifications except Pieper Hatchery Spring, which has lower variation classifications in 2005-2006. This disagreement is interpreted to be a large lagged snowmelt response of Pieper Hatchery in March 2003 that was not as pronounced in other regional springs that year and was not seen at all in 2005-2006 due to a very dry winter. This spike in discharge affected the Q_{90} and standard deviation of that year's data and skewed the variability classifications.

In addition to calculating the variability of spring discharge in the study area, the water temperature of the springs was also seen as a good indicator of spring variability and sensitivity to seasonal (short-term) changes. Variability classifications similar to the ones created for discharge were created for temperature (Table 10). These variability analyses on water temperature were also conducted on monthly average air temperature for the three climate stations used for other climate information in the study area (Table 10). For the regional springs, Sterling Hatchery is not included in the temperature variability analysis as water is piped from the source through a trout hatchery, undoubtedly affecting temperature and water-quality parameters. Of the remaining regional springs, four of five have steady temperature variation classifications and a low coefficient of variation. Russell Spring is the only one that does not, with variability and variation classifications of unbalanced and high, respectively. Russell Spring, although sourced by a regional aquifer, travels through a local system (Verde Formation) prior to discharge. Travel through this shallow aquifer system allows for mixing of local groundwater, which is more susceptible to influence from air temperature variation. Spring Creek Spring, which is also sourced from a regional aquifer and travels through the Verde Formation prior to discharge, does not show this strong influence however. This spring has a much higher discharge rate (17.2 versus 0.39 L/sec) than Russell Spring, which makes the spring more resistant to temperature variation due to the large volume of water, as was discussed in Section 3.2.2, and may indicate a smaller percentage of local recharge to this spring. This is not to say that groundwater mixing does have some effect on the discharge temperature at Spring Creek Spring. Pieper Hatchery Spring and Tonto Natural Bridge Spring have average discharge rates (17.1 and 16.4 L/sec, respectively)

Table 10. Summary of T_{90}/T_{10} and Coefficient of Variation analyses conducted on spring water temperature and air temperature from three climate stations within the study area.

Spring Name	Variability T_{90}/T_{10}	Variability Class	Coefficient of Variation	Variation Class	Regional /Local
Hackberry	2.37	Highly Unsteady	37.3	Very High	Local
Log	1.48	Highly Unsteady	17.1	High	Local
Grimes	1.40	Unbalanced	21	Very High	Local
Gray	1.39	Unbalanced	13.3	High	Local
Grapevine	1.38	Unbalanced	15.2	High	Local
Russell [1]	1.36	Unbalanced	13.3	High	Regional
Campbell	1.15	Well Balanced	7.4	Moderate	Local
Pivot Rock	1.14	Well Balanced	7	Moderate	Local
Clover	1.12	Well Balanced	5.6	Moderate	Local
Poison	1.08	Steady	5.6	Moderate	Local
Summer	1.02	Steady	0.64	Low	Regional
Pieper Hatchery	1.02	Steady	2.3	Low	Regional
Spring Creek	1.01	Steady	0.93	Low	Regional
Tonto Bridge	1.01	Steady	0.62	Low	Regional
Climate Station [2]	**Variability T_{90}/T_{10}**	**Variability Class**	**Coefficient of Variation**	**Variation Class**	**Elev. (m)**
Flagstaff Airport	243.11	Highly Unsteady	89.7	Very High	2,137
Town of Payson	4.28	Highly Unsteady	53.4	Very High	1,527
Tuzigoot Natl. Mon.	3.4	Highly Unsteady	45.7	Very High	1,058

[1] Russell Spring, although sourced from a regional aquifer, travels through a local aquifer (Verde Fm.) prior to discharge. This shallow aquifer is affected more by air temperature variations. Spring Creek Spring also discharges from the Verde Fm., but has a much higher discharge rate and the larger volume of water makes the spring more resistant to air temperature changes.
[2] The period of record for the temperature data used in this analysis was the extent of the period of investigation of the springs when water temperature was being collected on a monthly basis: July 2005-June 2006.

Classification Distribution

Variability		**Coefficient of Variation**	
1 to 1.1	Steady	0 to 5	Low
1.11 to 1.2	Well Balanced	5 to 10	Moderate
1.21 to 1.3	Balanced	10 to 20	High
1.31 to 1.4	Unbalanced	>20	Very High
>1.4	Highly Unsteady		

similar to that of Spring Creek Spring, and discharge directly from regional aquifer systems. Variability and variation classifications (steady and low, respectively) are the same for the three springs, but coefficients of determination of air and water temperature at Pieper Hatchery and Tonto Natural Bridge Springs (R^2=0.24 and 0.0009, respectively) are much lower than that of Spring Creek Spring (R^2=0.49), indicating less of an influence from air temperature on these aquifers.

Based on the discharge record of the two shallow karst aquifer springs, Clover and Pivot Rock, it is curious that these springs are considered "well balanced" and "moderate" when describing water temperature variability and variation classifications, respectively. This may be due to the nature of the monitoring cycle (one monthly measurement) which likely misses the changes in temperature associated with peaks in discharge.

3.3.3 Correlation Results

Correlation coefficients (r) and coefficients of determination (R^2) were generated for each of the 16 monthly monitored springs, quantifying the relations between spring parameters (discharge, water temperature, electrical conductivity) to a number of study area-based hydrologic information sources including precipitation totals, SPI, air temperature, and stream discharge of seven USGS gages (Appendix L1). Local aquifer springs were correlated with these study area hydrologic data from the same month the discharge and water-quality parameters were collected. Regional aquifer springs were correlated with these values, but correlations were also calculated for lags of one through six months due to these springs increased residence times.

Karst aquifer system springs were best correlated to recent precipitation totals. Correlation coefficients for precipitation and spring discharge at Clover and Pivot Rock Springs were 0.81 and 0.86 (R^2=0.66 and 0.74), respectively (Table 11). No other springs in the monthly monitoring network of springs showed correlations with precipitation as high as these. Summer Spring exhibited a significant correlation to precipitation, but was negative (r = -0.84). Correlations between this spring and precipitation increase substantially when the parameters are lagged for several months, which are described later in the section. Correlations of precipitation and discharge were also evaluated on the basis of whether the spring was regionally or locally sourced, if the source geologic unit had a relatively high or low hydraulic conductivity, or had a relatively short or long residence time (Table 11). Besides the high correlations between precipitation and discharge in the karst aquifer system springs and the lagged responses seen in the regional springs discussed later, no strong correlation trends were seen in these correlation analysis groups. The most potentially significant of these trends is the affect of elevation on the coefficients of determination. Springs discharging from higher elevations (above 1,500 meters, and closer to the primary recharge areas) have a higher R^2 value (0.33) than springs discharging from low elevations (0.06). This relationship appears to be rather weak, however.

Correlation coefficients (r) between spring discharge and the Standard Precipitation Index were calculated using the 3, 6, 12, 24, 36, and 48-month SPI indices (Table 12). Overall, it is seen that local springs are best correlated with the short-term (3, 6, and 12-month SPI) while the regional springs are best correlated with the long-term (24, 36, and 48-month SPI). Correlation coefficients are highest with the 3-month SPI

Table 11. Comparison of correlations between spring discharge and precipitation, with distinctions made between regional and local aquifer systems, elevation of spring discharge, and residence times.

Spring	Discharge correlation coefficient with precipitation - r	Coefficient of determination - R^2	Regional/Local aquifer	High/Low elevation [1]	Short/Long residence time
Clover [2]	0.81	0.66	Local	High	Short
Grapevine	0.1	0.01	Local	Low	Long
Grimes	-0.17	0.03	Local	Low	Long
Gray	-0.14	0.02	Local	High	Short
Poison	-0.66	0.44	Local	High	Short
Foster	0.07	0.005	Local	High	Short
Campbell	0.36	0.13	Local	High	Short
Log	0.46	0.21	Local	High	Long
Pivot Rock	0.86	0.74	Local	High	Short
Hackberry	-0.16	0.03	Local	Low	Short
Sterling	0.13	0.02	Regional	Low	Long
Pieper Hatchery	-0.53	0.28	Regional	Low	Long
Spring Creek	0.04	0.002	Regional	High	Long
Tonto Bridge	0.29	0.08	Regional	High	Long
Summer	-0.84	0.71	Regional	High	Long
Russell	-0.09	0.01	Regional	Low	Long
		Average R^2	Local - 0.23	High - 0.30	Short - 0.29
			Regional - 0.18	Low - 0.06	Long - 0.15

[1] Low elevation is assumed <1500m
[2] Period of record is 1999-2006 (43 measurements). Remainder of springs period of record July 2005-June 2006 (12 measurements)

Table 12. Comparison of correlations coefficients (r-value) between spring discharge and the Standard Precipitation Index (SPI) at different time increments for the study area (NOAA AZ Climate Division 3).

Spring	Regional/Local	SPI 3-month	SPI 6-month	SPI 12-month	SPI 24-month	SPI 36-month	SPI 48-month
Clover	Local	0.44	0.31	0.11	-0.14	-0.10	-0.07
Grimes	Local	0.40	0.01	-0.56	-0.49	-0.52	-0.43
Pivot Rock	Local	0.35	0.24	-0.002	-0.21	-0.19	-0.12
Campbell	Local	0.35	0.37	0.19	-0.22	-0.18	-0.16
Foster	Local	0.34	0.36	-0.10	-0.70	-0.67	-0.67
Hackberry	Local	0.33	0.09	-0.38	-0.60	-0.58	-0.64
Grapevine	Local	0.31	0.06	0.04	0.10	0.11	0.18
Gray	Local	0.22	0.38	-0.25	-0.91	-0.87	-0.92
Log	Local	-0.21	0.23	0.79	0.62	0.71	0.51
Poison	Local	-0.52	-0.60	-0.01	0.59	0.52	0.62
Pieper Hatchery	Regional	0.27	-0.06	-0.27	-0.11	-0.15	0.02
Sterling	Regional	0.25	0.30	0.33	0.21	0.26	0.21
Russell	Regional	-0.10	-0.44	-0.08	0.39	0.37	0.37
Spring Creek	Regional	-0.12	0.04	0.28	0.34	0.37	0.27
Summer	Regional	-0.20	-0.68	-0.31	0.36	0.25	0.44
Tonto Bridge	Regional	-0.29	-0.32	0.37	**0.95**	0.92	**0.98**
	Average - Local	0.20	0.15	-0.02	-0.20	-0.18	-0.17
	Average - Regional	-0.03	-0.19	0.05	0.36	0.34	0.38

Note: Period of record for all springs is November 2002-October 2003 and July 2005-June 2006 (24 measurements) for local springs and with the 48-month SPI for regional springs. Within the local springs, Clover Spring in the shallow karst aquifer had the highest correlation coefficient (0.44), while Poison Spring (Tertiary basalt) had the lowest (-0.52) (Table 12). The value for Poison Spring is much more similar to that of a regional aquifer spring, but as was noted before, this spring has a relatively long residence time and a low correlation with monthly precipitation totals.

For the regional springs, the two springs fed directly from the upper regional sandstone aquifer (Sterling Hatchery and Pieper Hatchery) had higher correlations with the short-term SPI values than with the long-term. The two springs fed by the regional sandstone aquifer but traveling through the Verde Formation (Russell and Spring Creek Springs) are more closely correlated with the long-term SPI values. The two regional springs discharging from the deep limestone aquifer were notably well correlated with the long-term 48-month SPI. Summer Spring and Tonto Natural Bridge Spring had correlation coefficients of 0.44 and 0.98 with the 48-month SPI, respectively (Table 12). The regional springs appear to be better correlated with longer-term SPI indices based on the distance from the primary recharge area (Coconino Plateau) and/or the depth of the aquifer system supplying the spring.

Evaluations of the correlation significance between spring water temperature and air temperature were conducted based on regional or local aquifer system designation, elevation of spring discharge, and length of aquifer residence time (Table 13). Springs discharging from local aquifer systems have a higher coefficient of determination than regional springs (R^2 = 0.67 versus 0.2, respectively). Additionally, analysis showed that springs discharging from low elevations (below 1,500 meters) have a higher correlation

Table 13. Comparison of correlations between air temperature and spring water temperature, with distinctions made between regional and local aquifer systems, elevation of spring discharge, and residence times.

Spring	Spring water temperature correlation coefficient with air temperature - r	Coefficient of determination - R^2	Regional/Local aquifer	High/Low elevation [1]	Short/Long residence time
Clover	0.51	0.26	Local	High	Short
Grapevine	0.97	0.94	Local	Low	Long
Grimes	0.99	0.98	Local	Low	Long
Gray	0.68	0.46	Local	High	Short
Poison	0.68	0.46	Local	High	Short
Campbell	0.84	0.71	Local	High	Short
Log	0.90	0.81	Local	High	Long
Pivot Rock	0.74	0.55	Local	High	Short
Hackberry	0.88	0.77	Local	Low	Short
Russell [2]	0.94	0.88	Local	Low	Long
Spring Creek [2]	0.70	0.49	Local	Low	Long
Sterling	NM	NM	Regional	High	Long
Pieper Hatchery	0.49	0.24	Regional	High	Long
Tonto Bridge	-0.03	0.00	Regional	High	Long
Summer	0.61	0.37	Regional	Low	Long
		Average R^2	Local - 0.67	High - 0.44	Short - 0.54
			Regional - 0.20	Low - 0.74	Long - 0.59

[1] Low elevation is assumed <1500m

[2] Although sourced from a regional aquifer, these springs travel through a shallow local aquifer (Verde Fm.) prior to discharge which allows for heat flux from air temperature variations.

value with air temperature and water temperature than higher elevations (R^2 = 0.74 versus 0.44, respectively). Interestingly, air and spring water temperature correlations based on residence time showed no discernable trend. R^2 values for short and long residence time were calculated to be 0.54 and 0.59, respectively.

Other trends include the correlation calculations between discharge and air temperature. Values indicate that springs discharging at low elevation, and therefore higher average annual temperatures, have large negative correlation coefficients with air temperature. As air temperature rises, potential evapotranspiration (ET) increases, which lowers the discharge at these springs. Correlation coefficients for the local low elevation springs of Grimes, Grapevine, and Hackberry were -0.65, -0.51, and -0.78, respectively (Appendix L1). A few other springs showed a similar negative correlation with air temperature, but were interpreted differently. Summer and Russell Springs, for example, have correlation coefficients of -0.65 and -0.72, respectively, with air temperature (Appendix L1). These springs discharge from regional aquifers and do not respond on a month-to-month basis as most of the local aquifer springs. The lagged responses of these springs are discussed in the next section. Poison (-0.59) and Gray (-0.51) Springs also have substantial negative correlation coefficients with air temperature, and are located at high elevation (above 2,000 meters) (Appendix L1). These springs have a somewhat lagged response to air temperature fluctuation as well, due to the fact that these springs have relatively long residence times for a local aquifer system.

Correlation values for regional springs were calculated for the same set of variables as above, but on time lags of one through six months (Table 14), (Appendix L2). These calculations resulted in a number of correlations not seen for a non-lagged

Table 14. Summary of highest correlation coefficient values between various parameters and lagged spring discharge of regional aquifer springs. Bold values indicate the spring with the highest correlation coefficient for the variable listed.

Correlation Parameter	**Highest correlation coefficient (r) and lagged month (in parentheses)**					
	Summer	Sterling	Russell	Pieper Hatchery	Spring Creek	Tonto Bridge
Electrical Conductivity (EC)	0.46 (1)	NC[1]	0.57 (5)	0.59 (6)	**0.80** (5)	0.45 (4)
Spring Water Temperature	**0.89** (2)	NC	0.62 (5)	0.73 (6)	0.68 (5)	0.31 (1)
Air Temperature	0.74 (6)	-0.04 (0)	0.69 (5)	**0.95** (4)	0.36 (5)	0.57 (2)
Palmer Drought Severity Index	-0.68 (0)	0.10 (1)	-0.07 (0)	-0.76 (6)	0.51 (0)	**0.67** (5)
Precipitation	0.49 (6)	**0.64** (6)	0.55 (2)	0.26 (5)	0.61 (3,4)	0.52 (5)
Flow - Clarkdale	-0.06 (0)	0.22 (3,4)	**0.74** (0)	-0.27 (0)	0.66 (1)	0.51 (5)
Flow - Oak Creek-Sedona	0.06 (0)	0.55 (6)	0.63 (0)	-0.26 (0)	0.55 (0)	**0.78** (5)
Flow - Beaver Creek	0.22 (2)	0.28 (0)	0.53 (0)	-0.14 (2)	**0.69** (1)	0.55 (5)
Flow - West Clear Creek	0.20 (2)	0.32 (5,6)	0.51 (0)	-0.11 (2)	**0.67** (1)	**0.67** (5)
Flow - Verde River @Camp Verde	-0.03 (2)	0.19 (0)	**0.85** (0)	-0.18 (0)	0.76 (1)	0.59 (5)
Flow - East Verde @ Childs	-0.14 (2)	0.54 (5)	0.29 (0,2)	-0.29 (2)	0.60 (1)	**0.68** (5)
Flow - Verde River below Tangle Ck.	0.81 (2,4,5)	0.70 (6)	0.66 (2)	**0.90** (2)	0.51 (1)	0.20 (1)

[1] NC-Not Collected

Note: period of record is July 2005 to July 2006, as some parameters during the investigation in 2002-2003 were not collected.

evaluation. For example, discharge at Pieper Hatchery Spring has an R^2 value of 0.02 with flow of the Verde River below Tangle Creek, which is the most downstream gage in the study area, representing the response of the entire study area. When discharge is lagged two months, however, this value increases to 0.81. Similar dramatic increases in correlation significance are seen at varying lag times for the other regional springs. Based on a number of the parameters used in the correlation calculations, it appears that springs such as Russell and Spring Creek are best related to lag times of 0 to 1 month, whereas Tonto Bridge is best related to a lag of 5 months, and Sterling Hatchery Spring 6 months (Table 14). Other regional springs have higher correlation values for different parameters located at different lag times. Knowing the extent and timing of correlations on these springs is imperative in the generation of drought trigger levels discussed in Section 3.4.

Correlations between biological metrics of perenniality and spring discharge variability and coefficient of variations were conducted by Stevens and Omana (2007). Discharge variability showed strong, positive relations with biological indices, and one value was considered statistically significant. The correlation between spring discharge variability for the 2005-2006 monitoring season and a composite bio-indicator score for each inventoried spring had a correlation coefficient of 0.76. Therefore, certain groups of aquatic organisms such as hydrobiid snails, amphipods, stoneflies, elmid and dryopid beetles, and northern leopard frogs appear to be good indicators of spring perenniality (Stevens and Omana, 2007). In contrast, aquatic and wetland plant diversity appear to be poor indicators of spring perenniality and discharge variation, as no significant relations were identified (Stevens and Omana, 2007).

3.3.4 Covariance Resluts

Average covariance values for local aquifer springs are positive, with covariances of 0.72 and 0.15 for the raw data and the centered and scaled data, respectively, which indicate a trend that spring discharge decreases as drought-level increases (Table 15). The two Permian karst aquifer springs, Clover and Pivot Rock, exhibited the highest positive covariance values at 3.07 and 3.91, respectively. These indicate a strong relationship between the discharge of these springs and short-term drought severity. Conversely, these two springs also exhibit the two most negative values of local aquifer springs for long-term drought, at -1.78 and -4.41, respectively. The average covariance values for all the local springs to long-term drought was negative, with values of -0.63 and -0.22 for the raw and centered and scaled data, respectively.

Regional aquifer springs have a negative average covariance value for short-term drought conditions (-2.72 and -0.19 for raw and centered and scaled data, respectively) (Table 15). Summer Spring, which has the largest discharge of the monitored springs, exhibited the most negative covariance to short-term drought levels, at -14.49. The regional springs have a positive covariance average to long-term drought levels, however. Covariance values for the raw as well as the centered and scaled data versus long-term drought levels averaged 1.05 and 0.19, respectively. The highest positive values, 4.08 and 4.45, reflecting the closest relations to long-term drought conditions both came from the deep regional limestone aquifer springs (Summer and Tonto Bridge, respectively).

The covariance results for the local aquifer springs follow the overall pattern of short-term drought-level designations, with the springs discharging from the shallow karst aquifers most closely related.

Table 15. Covariance of spring discharge and State of Arizona Drought Monitoring Technical Committee (MTC) short and long-term drought designations.

Spring	Discharge and short-term drought covariance	Discharge and long-term drought covariance	Centered and scaled covariance, short-term drought	Centered and scaled covariance, long-term drought	Regional/Local Source
Foster	0.06	-0.09	0.43	-0.60	Local
Campbell	0.10	-0.06	0.43	-0.24	Local
Poison	-0.02	0.03	-0.51	0.54	Local
Gray	0.01	-0.02	0.36	-0.73	Local
Clover	3.07	-1.78	0.36	-0.19	Local
Pivot Rock	3.91	-4.41	0.26	-0.26	Local
Hackberry	0.00	-0.08	0.02	-0.62	Local
Log	0.07	0.14	0.30	0.56	Local
Grimes	0.00	-0.01	-0.21	-0.57	Local
Grapevine	0.00	0.00	0.06	-0.04	Local
Sterling	0.53	-0.27	0.12	-0.06	Regional
Summer	-14.49	4.08	-0.60	0.15	Regional
Spring Creek	0.05	0.58	0.02	0.21	Regional
Russell	-0.06	0.06	-0.34	0.29	Regional
Pieper Hatchery	-1.00	-2.61	-0.10	-0.23	Regional
Tonto Bridge	-1.38	4.45	-0.27	0.80	Regional
Average-Local	0.72	-0.63	0.15	-0.22	
Average-Regional	-2.72	1.05	-0.19	0.19	

Note: period of record for analysis is November 2002-October 2003 and July 2005-June 2006 (24 measurements)

The regional aquifer springs were not well related to short-term drought levels, and are more closely related to long-term drought-level designations, with the springs discharging from the deep regional limestone aquifer being the most closely related.

3.3.5 Trend Analysis Results

The results of the Kendall-Theil trend analysis detected several statistically significant trends in spring discharge, and they compare favorably to the slopes of the regression lines fitted to the discharge data as well. By running the trend analysis on the data sets from 2002-2003 and 2005-2006, there were 32 different trends developed based on two sets of data from 16 springs (Table 16). Based on the p-value cutoff of 0.05, there were 14 trends detected that were considered statistically significant, and one considered marginal. This represented 44% (14) of the 32 trends generated (47% counting the marginal result). Based on the relatively small data sets on which to conduct these analyses, the results are seen as quite favorable. It is difficult to conduct trend analyses on data sets of this size, and as observed by Loftis, et al., (1989), it is "generally not possible for statistics to detect trends that are not apparent by inspection, especially for data records of short to moderate length-say 20 years or less. It is preferable to think of trend tests as a quantitative basis for deciding whether apparent trends are real". Essentially, trend analyses on data sets of this size should merely be used to corroborate and quantify the significance of trends seen by plotting the data and fitting a regression line.

Table 16. Results of Kendall-Theil trend analysis on spring discharge in 2002-2003 and 2005-2006. A cutoff p-value for statistical significance was 0.05 (5% chance of random trend occurrence).

Spring	Season	Trend (+/0/−)	S-value	P-value (%)	Statistically Significant
Grimes	2002-2003	−	-35	1.0	Yes
	2005-2006	0	15	19.0	No
Grapevine	2002-2003	0	0	52.7	No
	2005-2006	0	1	52.7	No
Log	2002-2003	−	-13	23.0	No
	2005-2006	−	-50	0.01	Yes
Summer	2002-2003	−	-18	12.5	No
	2005-2006	+	38	0.44	Yes
Tonto Bridge	2002-2003	−	-18	12.5	No
	2005-2006	+	10	27.3	No
Pieper Hatchery	2002-2003	−	-27	4.3	Yes
	2005-2006	+	49	0.02	Yes
Sterling	2002-2003	−	-19	12.5	No
	2005-2006	−	-9	27.1	No
Clover	2002-2003	+	9	31.9	No
	2005-2006	−	-44	0.09	Yes
Pivot Rock	2002-2003	+	11	27.3	No
	2005-2006	−	-48	0.02	Yes
Campbell	2002-2003	+	15	19.0	No
	2005-2006	−	-39	0.44	Yes
Foster	2002-2003	+	26	4.3	Yes
	2005-2006	0	-7	36.9	No
Poison	2002-2003	+	23	7.6	No
	2005-2006	+	35	1.0	Yes
Gray	2002-2003	+	41	0.27	Yes
	2005-2006	0	-11	27.3	No
Russell	2002-2003	−	-39	0.44	Yes
	2005-2006	+	7	36.9	No
Spring Creek	2002-2003	−	-41	0.27	Yes
	2005-2006	−	-25	5.8	Marginally
Hackberry	2002-2003	−	-27	4.3	Yes
	2005-2006	0	0	52.7	No

The results of the trend analyses agreed with the slopes of the regression lines fitted to the discharge hydrographs in 23 of 32 instances (72%). This was relatively equally spread across the two monitoring periods, with the data from 2002-2003 agreeing 12 of 16 possible times, and the data from 2005-2006 agreeing 11 of 16 times (Table 16). Only one spring in the study both agreed with the slopes of the fitted regression lines and also had statistically significant p-values for both 2002-2003 and 2005-2006, Pieper Hatchery Spring.

3.3.6 Centered and Scaled Discharge and Drought Level Results

The correlation coefficients generated between the centered and scaled values for spring discharge and both short and long-term drought-level designations (Table 17) agree very closely with the results of the covariance analyses (Table 15). Local aquifer springs have correlation coefficients of 0.16 and -0.23 with short-term and long-term drought levels, respectively. Regional aquifer springs have correlation coefficients with the short- and long-term drought levels of -0.21 and 0.20, respectively. As was observed with the covariance analyses, local springs have a positive correlation with short-term drought and a negative correlation with long-term drought, and the regional springs exhibit the opposite relation to drought level.

The average correlation values are almost identical to the covariance values even though the correlation calculation is scaled to values between -1 and +1 whereas covariances are not scaled. This is not surprising, however, as the calculations for both correlation and covariance are measures of how variables vary together.

Table 17. Correlations with short and long-term drought designations with centered and scaled discharge data.

Spring	Centered and scaled correlation (r), short-term drought	Centered and scaled correlation (r), long-term drought	Regional/Local Source
Foster	0.45	-0.62	Local
Campbell	0.45	-0.26	Local
Poison	-0.54	0.56	Local
Gray	0.37	-0.76	Local
Clover	0.38	-0.20	Local
Pivot Rock	0.27	-0.27	Local
Hackberry	0.03	-0.66	Local
Log	0.31	0.58	Local
Grimes	-0.22	-0.60	Local
Grapevine	0.06	-0.04	Local
Sterling	0.09	-0.04	Regional
Summer	-0.62	0.16	Regional
Spring Creek	0.02	0.22	Regional
Russell	-0.35	0.30	Regional
Pieper Hatchery	-0.10	-0.24	Regional
Tonto Bridge	-0.29	0.83	Regional
Average - Local	0.16	-0.23	
Average - Regional	-0.21	0.20	

Note: period of record for analysis is November 2002-October 2003 and July 2005-June 2006 (24 measurements)

Normally, the correlation coefficient is independent of the units of the variables examined, such as discharge (L/sec), precipitation (cm), and temperature (°C). When the data were centered and scaled, they were essentially transformed to a common unit of measurement, and this would result in very similar results to the covariance calculation. The values of the centered and scaled values of discharge and drought are in Table 17, and plots showing the trends of centered and scaled spring discharge, short-term drought levels, and long-term drought levels are in Appendix M.

3.4 GENERATION OF DROUGHT TRIGGER LEVELS

3.4.1 Discharge Percentiles

Percentiles of average discharge rates were generated for all 16 monitored springs for data from 2002-2003 and 2005-2006 (Appendix N). Percentiles of average discharge for regional springs varied much less than local springs, with percentile ranges from 28% to 333% of average. The standard deviation of the percentiles for regional springs (1-sigma) was ±18.4%, indicating a relatively low range of variability. Local springs, on the other hand, exhibited a wide range of discharge rates in response to climate changes and this was reflected in the percentile of average calculations. Percentiles ranged from 0% to 1,542%, with a standard deviation of ±128.7%. These values attest to the general high sensitivity of local aquifer systems to recent climate variability.

3.4.2 Comparison to State Drought Levels

Once the percentiles of average discharge were calculated, these values were converted to drought level designations between 0 and 4 as described in Section 2.5.4.

Based on the data representing two individual one-year monitoring periods, once the values were converted to the State's drought level system, regional springs did not register on the short- or long-term drought levels due to the short period of record for these springs and the longer-term climate changes necessary to influence them (Table 18). The short-term drought levels represent 3, 6, and 12-month percentiles and long-term drought levels represent 24, 36, and 48-month percentiles. Calculated drought levels based on the two-year historical discharge averages for the regional springs are 0 (no drought) for each of the 24 months of discharge on hand, except for three months of Level 1 for Russell Spring (Table 18). It is obvious that these springs would require a much longer period of record (10s of years) to properly calculate a historical average discharge from which to compare recent responses, or conversely the responses to a multi-year drought.

Most of the local springs' generated drought levels also did not compare well with the State's drought levels. The springs with the best comparisons to the State's drought designations were Clover and Pivot Rock Springs, which discharge from the Permian shallow karst aquifer. On the State's short-term drought designations these two springs agreed only 21% and 29% of the time, respectively (Table 18). On the long-term drought levels, the springs were marginally better, at 33% and 25%, respectively. The remainder of the local aquifer springs only agreed with the State's short-term and long-term drought levels an average of 5.7% and 8.3% of the time, respectively.

The response behavior of the springs may be somewhat different than the parameters the State currently uses to calculate their drought levels, such as precipitation and streamflow.

Table 18. Comparison of Sate of Arizona drought-level designations against calculated drought levels based on spring discharge.

Date Measured	ADWR drought level-short term	ADWR drought level-long term	Foster level	Campbell level	Poison level	Gray level	Clover level	Pivot Rock level	Sterling level	Summer level
11/27/2002	2	4	1	1	0	0	4	4	0	0
12/13/2002	2	4	1	0	0	0	4	4	0	0
1/10/2003	3	4	0	0	0	0	4	4	0	0
2/22/2003	2	4	0	0	0	0	0	1	0	0
3/29/2003	1	4	0	0	0	0	0	0	0	0
4/26/2003	1	4	0	0	0	0	0	0	0	0
5/23/2003	1	3	0	0	0	0	0	0	0	0
6/25/2003	2	3	0	0	0	0	4	2	0	0
7/24/2003	1	3	0	0	0	0	4	3	0	0
8/30/2003	1	4	0	0	0	0	2	1	0	0
9/21/2003	1	3	0	0	0	0	0	0	0	0
10/12/2003	2	3	0	1	0	0	4	4	0	0
7/14/2005	1	1	4	0	0	0	1	0	0	0
8/14/2005	0	1	1	0	0	0	0	0	0	0
9/24/2005	1	1	1	0	0	0	0	1	0	0
10/21/2005	1	1	1	0	0	0	0	0	0	0
11/18/2005	2	2	1	0	0	0	2	1	0	0
12/29/2005	2	2	1	0	0	0	3	3	NA	0
1/27/2006	3	1	1	1	0	0	3	2	0	0
2/24/2006	4	1	1	1	0	0	4	3	0	0
3/31/2006	4	2	1	1	0	0	1	2	0	0
4/29/2006	3	2	4	0	0	0	2	3	0	0
5/23/2006	3	2	4	2	0	0	4	3	0	0
6/17/2006	3	2	4	1	0	2	4	3	0	0
% agreement with ADWR short term			8.3	0.0	4.2	4.2	20.8	29.2	4.2	4.2
% agreement with ADWR long term			20.8	12.5	0.0	4.2	33.3	25.0	0.0	0.0
% agreement +/- 1 drought level, short term			54.2	50	41.7	45.8	62.5	75	41.7	41.7
% agreement +/- 1 drought level, long term			33.3	37.5	25	29.2	58.3	70.8	25	25

NA Anomalous data point not used in analysis

Table 18, cont.

Date Measured	ADWR drought level-short term	ADWR drought level-long term	Spring Creek level	Russell level	Hackberry level	Log level	Pieper level	Tonto Bridge level	Grimes level	Grapevine level
11/27/2002	2	4	0	0	0	0	0	0	0	4
12/13/2002	2	4	0	0	0	1	0	0	0	4
1/10/2003	3	4	0	0	0	0	0	0	0	4
2/22/2003	2	4	0	0	0	0	0	0	0	0
3/29/2003	1	4	0	0	0	0	0	0	0	0
4/26/2003	1	4	0	0	0	0	0	0	0	0
5/23/2003	1	3	0	0	0	0	0	0	0	1
6/25/2003	2	3	0	0	0	0	0	0	4	4
7/24/2003	1	3	0	1	0	0	0	0	4	4
8/30/2003	1	4	0	1	0	0	0	0	0	1
9/21/2003	1	3	0	0	0	1	0	0	0	1
10/12/2003	2	3	0	0	0	2	0	0	0	4
7/14/2005	1	1	0	1	NM	0	0	0	4	4
8/14/2005	0	1	0	0	1	0	0	0	4	0
9/24/2005	1	1	0	0	1	0	0	0	4	0
10/21/2005	1	1	0	0	2	0	0	0	4	0
11/18/2005	2	2	0	0	0	0	0	0	4	0
12/29/2005	2	2	0	0	0	0	0	0	4	0
1/27/2006	3	1	0	0	0	0	0	0	0	0
2/24/2006	4	1	0	0	1	0	0	0	0	0
3/31/2006	4	2	0	0	1	0	0	0	0	0
4/29/2006	3	2	0	0	1	0	0	0	0	0
5/23/2006	3	2	0	0	1	0	0	0	4	0
6/17/2006	3	2	0	0	4	2	0	0	4	4
% agreement with ADWR short term			4.2	16.7	4.2	8.3	4.2	4.2	0.0	16.7
% agreement with ADWR long term			0.0	4.2	12.5	4.2	0.0	0.0	0.0	12.5
% agreement +/- 1 drought level, short term			41.7	41.7	41.7	54.2	41.7	41.7	29.2	37.5
% agreement +/- 1 drought level, long term			25	16.7	33.3	33.3	25	25	16.7	45.8

Understanding this, it may be that the percentile ranking system is appropriate for spring data, but the percent of average cut-off values for the drought levels may be different. To investigate this, the drought levels calculated by the State were compared against the springs' drought levels plus or minus one drought designation level. As was predicted, this change increased the number of times the springs drought levels agreed with the State's levels, but the trends were still the same. Clover and Pivot Rock Springs were still the closest to the State's drought levels, with Clover Spring agreeing with the short-term and long-term levels 62.5% and 58.3% of the time, respectively, and Pivot Rock agreeing with the short and long-term drought levels 75% and 71% of the time, respectively (Table 18). The remainder of the local aquifer springs still agreed with the State's designations less than 50% of the time, even with a buffer of one drought level. Regional springs fared much better than on a level-to-level comparison, but they too agreed with the State's designations less than 50% of the time.

CHAPTER 4 – CONCLUSIONS

4.1 DISCUSSION

The results of this study of springs in the Middle Verde River watershed, including the geochemical, physical, and biological investigations, all provide information on how the hydrologic system responds to changes in climate. The relations between the springs data and other hydrologic information from the study area give a more complete view of how the reaction of springs to climate changes relates to the responses of the watershed as a whole.

4.1.1 Geochemical Findings

Isotopes were used to determine the season of precipitation for recharge. The stable isotope (δ^2H and $\delta^{18}O$) data indicate that winter precipitation is the dominant source of recharge in the study area for all springs studied (Figures 21 and 22). This indicates that short-term drought conditions occurring during the summer months may affect the SPI and stream gage readings (the primary State drought indicators for the study area (ADPP, 2004)), but may not have a large effect on springs, especially regional aquifer springs, which would not be expected to receive significant recharge during this period anyway. It appears that perturbations in winter precipitation totals in the primary recharge areas will have the greatest effect on spring discharge in general.

Radioactive isotopes give an excellent indication of qualitative aquifer residence times (Figure 25, Table 7), but it must be understood that this residence time may differ from the physical *response* time of the springs in question. Drought conditions may not register for some time at spring discharge locations, especially if the discharge point is located at a large distance from the primary recharge area or if the spring discharges from a deep aquifer. Wet periods, however, may cause increased discharge sooner due to recharge pressure on the aquifer from head changes, and propagate through the aquifer system as a “pressure wave” moving much faster than the groundwater itself. Physical responses to wet periods may therefore be much quicker than the residence times given by the radioisotopes. These responses will vary based on the hydraulic conductivity of aquifer materials in both the horizontal and vertical direction.

Local and regional aquifer spring distinctions for this study were initially made based on the geologic unit of discharge. During this study, however, it was determined that using such a singular designation criterion did not fully explain the variations found within the springs studied, and therefore affected the expected reactions of the springs to drought conditions. Using geochemical evidence it was determined, in the cases of Russell and Spring Creek Spring, that unit of discharge did not always reflect the geologic unit supplying the groundwater (Appendix A, Figure 28, Table 7). Based on the geochemical signatures, as well as the physical evidence including hydrographs (Figure 32, Appendix E), spring response to climate changes including precipitation (Figure 34, Appendix H) and temperature (Figure 35, Appendix I), and the results of the seasonal wet/dry springs investigation (Figure 36, Tables 8A and 8B, Appendix J), it is best to think of springs as arranged on a continuum between regional and local end members.

The statistical analyses support this distinction, because some springs considered “regional” have behaviors more closely related to local springs, and that some “local” springs exhibit traits of regional springs. The behaviors of the springs, coupled with the variation and variability analyses (Tables 9 and 10) as well as correlation analyses between spring discharge and precipitation totals, SPI, and air temperature versus spring water temperature (Tables 11, 12, and 13, respectively) all support a broader definition of what constitutes a regional or local spring. Using a continuum between true regional and true local end members, a true regional end member spring would have essentially no response to climate changes and would therefore be useless as a drought indicator, whereas a true local end member may only be useful as an indicator for a relatively small geographic location. The results from the ^{3}H and ^{14}C analyses indicate that no spring studied would be considered a true regional spring, as they all have some component of local recharge that would show the influence of climate change.

It has been determined that geochemical evidence, primarily stable isotope values, coupled with analyses of trends and variability of discharge data, are ideal for determination of where springs fall on the continuum line between regional and local aquifer sources. When designing a regional spring monitoring program, the continuum should be considered to best quantify the response of the watershed as a whole to climate changes.

Anion data (Appendices A and B), especially chloride, bromide, and sulfate, show the effects of evapotranspiration and anion concentration and ratio changes along the groundwater flowpath due to interactions with geologic materials at several springs (Figures 29, 30, and 31). Early and late Paleozoic limestones (Redwall/Martin/Naco Formations, and Kaibab Formation, respectively) had initial chloride sources with a high Cl/Br ratio which results in a distinct character when plotted on a Cl/Br ratio vs. Cl concentration graph (Figure 30). The Cl/Br ratio varied over a large range while the Cl concentrations remained fairly stable. Springs discharging from the Verde Fm. (Russell and Spring Creek) have a notably higher Cl/Br ratio, a trend which indicates that solute addition from dissolution of evaporite deposits within the Verde Fm. is occurring. Springs discharging from basalt, alluvium, and granites do not contain any input of additional chloride, either from initial aquifer source material or from dissolution of evaporite deposits. These springs could therefore act as proxies for drought conditions by monitoring chloride concentrations, as extended periods of drought would increase chloride by evaporative concentration, and could be relatively easily tracked over time.

4.1.2 Physical Findings

The spring discharge hydrographs from regional-type springs show a lagged response to climate changes. These springs would require a long period of record (>10 years) to have statistical significant analyses for drought monitoring conducted. As an example, the spring complexes that supply the baseflow to the Verde River headwaters (sourced from the Big Chino Valley and the regional limestone aquifers) are known to have lags much longer than the period of monitoring conducted during this study. The Verde River at Paulden and Clarkdale, fed by these headwaters springs, generally lags 1-2 years behind precipitation patterns (Bills, et al., 2007).

An understanding of the response and residence times of the aquifers supplying the springs is necessary to predict when the effects of climate change will be reflected at the spring. These time-periods are controlled by the distance of the spring from the primary recharge area, the depth of the aquifer, and physical properties of the aquifer including karst topography, hydraulic conductivity, and faulting, and in the case of more regional springs, the percent contribution of local recharge. Investigations of spring discharge versus precipitation totals (Figure 34), and air versus water temperature (Figure 35) were used to interpret the response times of the monthly monitored springs and place the springs on the continuum between regional and local.

Interpretations of the precipitation versus discharge results indicate that regional-tending springs do not respond much to monsoon storm events, so summer-season droughts will have a muted response when other drought indicators including the SPI and USGS stream gage measurements may register increased drought conditions. As a result, the discharges of these springs during a period such as this would not match well with the State drought-level designations. The responses of these springs based on the physical data are supported by several of the statistical analyses conducted and discussed in the next section. The reactivation/deactivation investigation of springs during the summer of 2005 and 2006 found that local springs are better suited to quantify short-term (months to years) drought conditions, while the trend along the continuum towards more regional spring systems are better for longer (years to decades) droughts. An obvious requirement for assessing these long-term drought-responding springs is a long period of record, which supports the need for instrumentation at these regional spring locations.

4.1.2 Statistical Findings

Interpretations of the results of the spring discharge variability and coefficient of variation investigation show that local springs are best-suited for short-term analysis of drought. Variability classifications of local springs were generally from ephemeral (infinite variability) to unsteady; however, some springs with local designations were found to be well balanced to steady, consistent with an expanded definition of a local versus regional spring. Similar trends were seen in the coefficient of variation results. Regional springs were generally steady with a low variation, but Russell Spring exhibited traits similar to more local springs. The variability and variation analysis using water temperature had very similar results to the discharge-based analysis. The variability and variation analyses are also effective in helping plot springs on the continuum between regional and local. Based on these analyses, springs such as Poison Spring behave more as regional springs with respect to discharge and water temperature variability and variation, while Russell Spring, discharging from the regional sandstone aquifer and traveling through the local Verde Fm., exhibits behavior similar to a regional spring, but towards the local end of the continuum. These behaviors are imperative to compare the responses of these springs to climate variations.

For monitoring purposes, springs determined to be ephemeral or intermittent could be fitted with resistance sensors that could measure presence or absence of flow (Adams, 2005). This would be a cost-effective way of quantifying the responses of several springs to climate variability. Selected perennial springs could be fitted with pressure transducers which can measure variability of discharge as well as water temperature and or conductivity on a continuous basis. These instrumentation techniques require more resources, and in some cases, modification of the discharge point or channel, but are still orders of magnitude more cost-effective and less invasive than the installation of a stream gage, for example.

The results of these analyses are consistent with the results of the descriptive statistics for spring discharge (Appendix K), which show the standard deviations of discharge averaged 265% of the mean discharge of local springs, but only 20% of the mean discharge of regional springs. Kurtosis and skewness analyses show that more regional springs have a normal discharge distribution, while local springs often exhibited values that suggest the discharge patterns violate the assumptions of normal distribution. These results illustrate the assumption that local-type springs are more susceptible to discharge fluctuation due to short-term climate variability.

Correlation analyses illustrate that some local springs are well correlated with the primary State drought indices for the study area, primarily those with short residence and response times, such as the karst springs Clover and Pivot Rock (Appendix L1). The high R^2 values with many of the USGS stream gages in the study area indicate an almost runoff-like response of these springs. Correlations of spring discharge from regional springs with hydrologic information such as precipitation, SPI, and stream gage data were quite weak on a month-to-month basis, but when discharge was lagged a number of months in comparison to these other variables, it was found that correlation significance increased for all springs (Appendix L2). However, the range in the number of months lagged for the highest correlation values varied, illustrating the continuum within the regional spring designation. These lagged responses also show the need for a much longer period of record for these springs. Due to the extent of the data set for this study, lagged data could only extend six months. Knowing the response of some of the regional springs in the Verde River watershed (1-2 year lag on precipitation trends (Bills, et al., 2007)), correlations with other hydrologic information sources used in the generation of drought indicators with these regional springs may become even closer with an extended lag time.

When the percentile ranking system of spring discharge was developed (Table 17) for the monthly monitored springs, it was found that regional springs did not register at all on a scale similar to that used by the State (Table 18) for either short-term or long-term drought-level designations. It is presumed that this is due to both the relatively short period of record at these locations and the fact that it takes a more significant climate perturbation to influence them. Based on other sources of insight into their behaviors from the geochemical, physical, and statistical analyses, it would seem that local springs would agree better with the State's short-term drought designations, but it was found that they on average did not. This rather surprising result leads to the inference that perhaps the springs are providing a different type of hydrologic indication of the status of the watershed that is not reflected by the indicators currently used by the State. While the indices and drought trigger levels used by the State in the study area may reflect an availability of water, the trigger levels designated by spring discharge may be more of a reflection of the status of groundwater storage in the watershed. If this is the case, drought trigger levels based on spring discharge may best be related to a system based on groundwater well levels rather than precipitation and stream gage records; but to reintroduce a problem highlighted in the introduction, well levels are susceptible to fluctuations based on groundwater pumping rates. This makes the data gathered from springs more reliable due to their generally rural and uninfluenced nature.

When comparing the drought-level designations based on spring discharge to those generated by the State for the study area, it was found that discharge-based drought levels changed less often than the State's levels, both on a short-term and long-term basis (Table 19). Only the shallow karst aquifer springs had drought-level fluctuations similar

Table 19. Relation of drought trigger level changes between indices currently used by the State and those calculated from spring discharge.

Spring	Regional/ Local	Number of changes in spring-based drought level, 2002-2003	Number of changes in spring-based drought level, 2005-2006
Foster	Local	1	2
Campbell	Local	2	4
Poison	Local	0	0
Gray	Local	0	1
Clover	Local	5	7
Pivot Rock	Local	7	8
Hackberry	Local	0	4
Log	Local	4	1
Grimes	Local	2	2
Grapevine	Local	5	2
Russell	Regional	2	1
Sterling Hatchery	Regional	0	0
Summer	Regional	0	0
Spring Creek	Regional	0	0
Pieper Hatchery	Regional	0	0
Tonto Bridge	Regional	0	0
		Number of changes in State drought level, 2002-2003	**Number of changes in State drought level, 2005-2006**
	Short-term	6	6
	Long-term	3	3

to those of the State, and only compared to the short-term drought designation. This overall pattern appears to reflect that springs in general are less sensitive to the types of climate changes that drive the current drought level designations. Climatic perturbations that trigger a State drought level change may not actually be reflecting a change in true "drought conditions", at least from a water management perspective.

4.2 RECOMMENDATIONS FOR FUTURE AUTHORS

To maximize the amount and quality of data collected, continuous or at least seasonal monitoring of a set of springs spanning the regional/local continuum would best show how climate change affects the springs and the watershed as a whole. The importance of springs as a data source for information on the status of a hydrologic system has been noted by others, and a similar recommendation has been made by the USGS for the areas of the Coconino Plateau and Grand Canyon (Bills, et al., 2007). Many springs in study area have only been measured once or twice since the 1950s, and some have still not been inventoried (Bills, et al., 2007). Data on other springs in the region are more robust, but most do not have enough data to accurately determine discharge trends.

Based on the findings of this study, although continuous monitoring of any spring would be an optimal situation, due to their more pronounced variations due to short-term climate fluctuations, local springs would benefit from continuous monitoring more than regional springs. Regional springs are more in need of a long period of record (multiple years at a minimum), and monthly or seasonal data points from the springs would be more valuable than a daily measurement over a period of a few months. With larger data sets from these springs, more robust statistical analyses including trend analyses and trigger-generating statistical methods similar to Paulson, et al. (1985), Rao and Voeller (1997), Schreffler (1997), and Hall, et al. (2006) could be implemented.

Instrumentation can range from simple resistance sensors to permanent flumes and pressure transducers installed in the discharge channels of springs. A goal for instrumentation would be to select locations which are relatively easy to access and that would minimize the impact on the spring itself and the surrounding ecosystems that rely on them. Luckily, there are several of the sixteen monthly monitored springs that have various features that make them ideal candidates for instrumentation and/or more regular monitoring. Table 20 summarizes several spring locations along the regional/local continuum that would require minimal effort to instrument and would minimize impact. These locations were selected based on variables such as location, discharge rate and variability, amount of existing modification, and channel/orifice morphology. Instrumented correctly, these locations could provide a wealth of information on how the watershed is responding to future climate variations, and could be monitored and maintained at a cost less than that of a stream gage or one completely-outfitted climate station.

Beyond the acquisition of more physical data at these spring locations, the value of geochemical analyses has proven invaluable in this study, and represents an important contributor to the overall understanding of how the springs react to climate variations. Samples for stable isotopes, for example, are relatively easy to collect, inexpensive to analyze, and provide a tremendous amount of information regarding the source location, elevation, and season of recharge, the amount of evaporation occurring before recharge,

Table 20. List of springs in the study area that would be easiest to instrument and monitor based on location, discharge rate, amount of existing modification, and channel/orifice morphology.

Spring	Justifications
Tonto Bridge	Flume already installed, transducer only required Easy access, could be downloaded with assistance of State Parks
Sterling Hatchery	Piping exists with hatchery, just instrument input from spring or outflow into Oak Creek Water chemistry may (or could easily be) measured already
Pieper Hatchery	Well-defined channel, flume could be installed at confluence with East Verde SRP may be interested in funding to better follow basefow at their diversion site
Clover	Culvert exists already (resistance sensor) Long discharge record exists
Campbell	Spring box exists (transducer)
Gray	Spring box exists (transducer)

as well as the amount of groundwater mixing occurring. All of these data are important in understanding the hydrologic system of a study area.

Other geochemical analyses including anions can provide important information for minimal effort. Like the analysis of stable isotopes, the collection of anion samples is relatively simple and cost-effective. In this study, it is thought that the analysis of chloride concentrations over time from aquifers without additional chloride inputs (the basalt, alluvium, and granite aquifers in this study) (Figure 30) can act as a proxy for drought conditions. As drought conditions increase, chloride in these aquifers would increase by evaporative concentration. By sampling for chloride on as little as a seasonal basis, fluctuations of chloride concentration can be compared to drought severity changes over the same time period; although this would be qualitative until a record of sufficient size existed so a scale could be developed for quantitative comparisons.

4.3 CONCLUSIONS

Drought is a recurring phenomenon that has negatively affected societies throughout recorded history. In the western U.S., the worry of drought conditions affecting current and future water use and supply plans has been coupled with the rapid population growth over the past decade to push water resource management into the spotlight. Management practices must respond to the changing climate and have appropriate reactions in place to deal with conditions such as drought while juggling the demands of population growth and the health of the watershed. Adding to the complexity is the fact that droughts are cumulative, and the effects are felt long after climatic conditions return to “normal”.

Currently in Arizona, drought levels are quantified based on the responses of several hydrologic indices, including precipitation, streamflow, reservoir levels, and groundwater levels. In this study, a group of springs in the Middle Verde River watershed were studied and the viability of their use as an indicator of drought to correlate with and/or refine the existing indices used by the State was assessed. The development of more reliable drought indicators will allow for more effective actions to be set into place prior to the onset of more severe drought, to help mitigate the impacts of the affected areas and help develop tools to reduce drought vulnerabilities.

Spring discharge, water-quality parameters, and geochemical data were collected from sixteen springs in the Middle Verde River watershed between July 2005 and June 2006. These data were compiled with discharge data from the same set of springs from November 2002 to October 2003. Stable isotope data assisted in quantifying the sources of recharge water for the springs in question, as well as the predominant season of recharge. Radioactive isotopes provided estimates of aquifer residence times, and the geochemical data combined with regression fits of spring discharge hydrographs led to a refinement of the designation of springs classified as "regional" or "local". The idea of a continuum between regional and local end members was developed, and this assisted in the evaluation of how these springs responded to climate variability.

Several statistical analyses were conducted on the data, and assessments of the variability of discharge and spring water properties as well as correlations and covariances of the physical properties of the springs with other hydrologic data provided additional insight into the response of springs to changes in climate. Ultimately, drought trigger levels were calculated from spring discharge data in a manner similar to that used by the State in the generation of their drought levels. It was found that drought levels based on the springs did not agree well with the State's levels, but that springs provide a different indication of the status of the watershed. Drought levels based on springs data fluctuated less than the State-generated ones; a pattern that seems to reflect that springs in general are less sensitive to the types of climate perturbations that drive the current drought-level designations. This may be a useful tool to compare with the State's existing indicators, especially when the State is prepared to either rise or lower the drought-level in the watershed based on their trigger levels.

The combination of the physical, geochemical, and statistical approaches to understanding the behaviors of the springs in the study area allow for confirmation and support to the conclusions drawn from them individually. Future estimates of drought conditions in the West indicate that large-scale droughts will occur, and that these may be exacerbated by the effects of human land use and global warming. Understanding the responses of springs to these climatic changes will allow water managers and the population as a whole to better manage water resources in a progressive fashion, rather than a crisis response to a drought-level status change of moderate to severe overnight.

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