Springs Distribution, Flow, and Associated Species in the Verde River Basin, Arizona

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Springs Distribution, Flow, and Springs-dependent Species in the Verde River Basin, Arizona

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Executive Summary:

The Verde River Basin (VRB) is a large watershed in central-northern Arizona. As an aridland river, it is subject to highly variable surface flow inputs, but its baseflow is sourced from a number of springs. The purpose of this report is to provide a summary of springs ecosystem data for the Verde River Basin to help guide water and associated riparian habitat management and policy. The Springs Stewardship Institute's (SSI) Springs Online database (SpringsData.org) includes information on at least 820 VRB springs, with some level of inventory information (primarily flow and water quality) from 717 springs. Of the 717 surveyed springs there are only 133 detailed inventories of physical and biological parameters; much remains to be learned about the hydrological and ecological roles of springs in this landscape. Data for this report are available in the Springs Online database, which is maintained by SSI. Long-term continuous flow data were compiled from the U.S. Geological Survey's National Water Information System database.

We estimate that springs of the VRB collectively contribute more than 3850 L/sec (136 ft^3/s) of flow into the river annually. Flow and water quality vary spatially and temporally, and during the May-June dry period, virtually all VRB flow is derived from springs. Unfortunately, U.S. Geological Survey Verde River tributary flow measurements made during the dry month of June reveal persistent decline in springs discharge from 1990 to the present. This reduction in flow is attributable to little-regulated groundwater extraction, as well as climate-change-driven reduction in snowpack and decreased aquifer recharge.

The sum of all springs flows recorded during inventories and extrapolated to non-surveyed springs was 136 ft^3/s, indicating a substantial amount of water available for wildlife, riparian habitat, and baseflow to the Verde River. Springs water quality varied by elevation and by which aquifer the spring was draining. Specific conductance, a measure of the amount of dissolved solids in the water, was generally higher at low elevation springs where water had to travel the furthest from the groundwater recharge area to the spring. Spring water temperature was also warmer at the lower elevation springs. The majority of springs are rheocrenes (springs emanating from the bed of a channel) with a high proportion of hillslope and wet meadow springs (helocrenes).

Springs of the Verde River watershed support a wide array of wetland and upland plant and animal species. However, because May-June flows are almost or are entirely derived from springs, the aquatic species of the VRB are nearly all springs-dependent. These taxa range from rare springs-dependent plants, such as *Bidens laevigatum* (Asteraceae) at Del Rio Springs, to highly localized endemic leeches, amphipods, and water scorpions at Montezuma Well and other springs. Thus far, a total of 147 species of plants have been detected in the 133 springs surveyed, and SSI

has documented >100 invertebrate species and 129 vertebrate species through those surveys. Nonetheless, only a small proportion (<15%) of the springs in the VRB have been inventoried, and very few springs are monitored, making it difficult to provide a condition baseline assessment or to detect changes in individual springs assemblages due to anthropogenic environmental changes. Therefore, much remains to be learned about the relationship between springs and biodiversity in the VRB.

We conclude the report with recommendations to improve VRB springs stewardship. These include recommendations for future monitoring, restoration, and management actions. Six recommendations include: 1) filling data gaps in springs inventories, 2) using the Northern Arizona Regional Groundwater Model to determine vulnerable springs, 3) monitoring of flow and biota of large headwaters and representative springs, 4) restore over-used springs, 5) re-visit springs known to support rare and endemic species to monitor long-term population status, and 6) monitor springs ecosystem loss to provide information to management and policy agencies.

We hope that the results of this report enhance public and policy-maker appreciation of the unique and important role of springs and groundwater to the socio-ecological integrity of the Verde River.

Introduction

The Verde River basin (VRB) is one of the last perennial rivers in Arizona, but has undergone substantial changes as the population of Yavapai and Coconino Counties have increased, placing substantial pressure on ground and surface water resources (Blasch et al. 2006; Haney et al. 2008). Recent research related to the Verde River has focused on groundwater availability (e.g. Owen-Joyce and Bell 1983; Blasch et al. 2006; Pool et al. 2011), aquifer characteristics (e.g. Springer and Haney 2008; Wirt 2005a, 2005b), surface-groundwater interactions (e.g. Leake and Haney 2010; Leake and Pool 2010; VRBP 2015), human impacts (e.g. Bolin et al. 2008; VRBP 2015), and ecological assemblages in and near the water (e.g. Haney et al. 2008; Ruhí et al. 2016). The majority of research in the VRB has highlighted the vulnerability of this river system to harm from water over-allocation, over-use, and inadequate management and policy.

The VRB straddles the boundary between Arizona's two geologic provinces: the Colorado Plateau to the north, and the Basin and Range province that occupies southern and central Arizona (Fig. 1). The Mogollon Rim is a mega-ecotone separating Mexican and tropical flora and fauna from the boreal Nearctic region (Stevens 2012), and serves as the boundary between the two provinces. Geology, climate, and vegetation characteristics vary dramatically between these two aridland provinces. The Colorado Plateau occupies higher elevations, with greater precipitation (especially snowfall), and a geology dominated by basalt flows overlying Mesozoic and Paleozoic sedimentary strata. The major aquifers (water bearing geologic units) on the southern Colorado Plateau are late Tertiary basalts, the Coconino Sandstone (C) aquifer, and the Redwall-Muav Limestone (R) aquifer (Hart et al. 2002; Blasch et al. 2006). The Basin and Range province is an extensional, horst-and-graben terrain that is structurally controlled by normal faults and fractures, a process that has generated many north-trending mountain ranges, such as Mingus Mountain (Eaton 1982). The major water bearing geologic units in the Basin and Range section of the Verde River watershed include the Verde Formation (basin fill comprised of limestones, mudstones, conglomerate, and basalts) and Quaternary alluvial deposits (Blasch et al 2006). A generalized geologic cross section, including major aquifers and general water flow paths, is provided in Fig. 2.

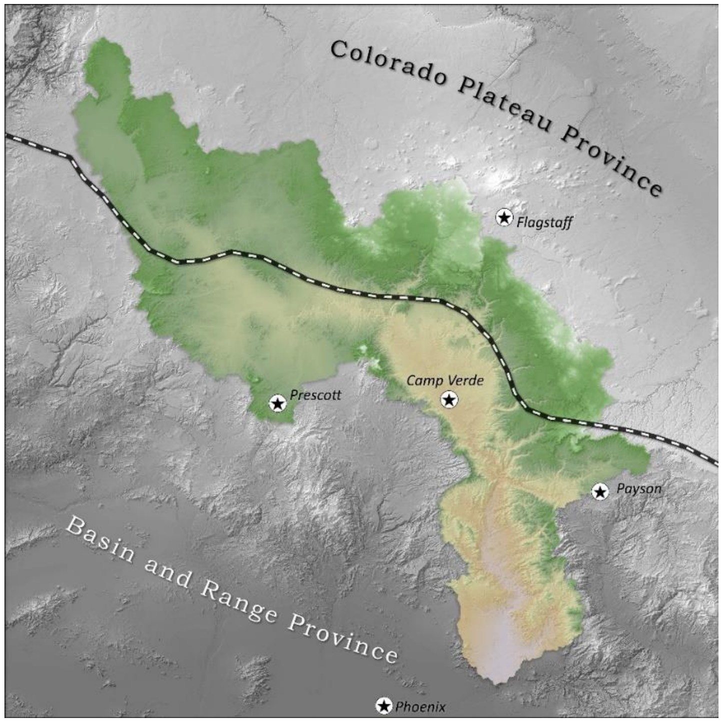


Fig. 1. The Verde River watershed, showing the general boundary of the Colorado Plateau and Basin and Range physiographic provinces.

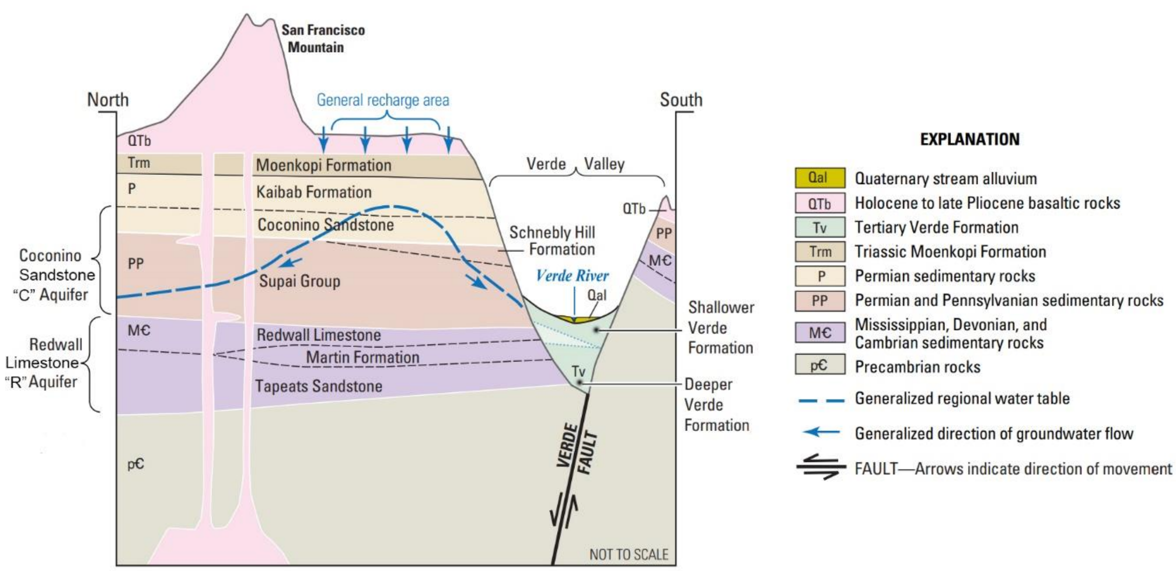


Fig. 2. A hydrogeologic cross section from the San Francisco Mountains south to the Verde River basin, including major aquifers (Blasch et al. 2006, modified by Garner et al. 2013).

Baseflow, and much of the biodiversity of the Verde River, are derived from the many widely scattered springs in the watershed (Fig. 3). The Springs Stewardship Institute (SSI) has reported that springs flow and water quality vary between the two physiographic provinces, with greater flow and lower specific conductance on the Plateau (Stevens et al. 2016b). The majority of groundwater contributing to Verde River baseflow is sourced on the Colorado Plateau, where snowpack is greater and the local geologic dip causes groundwater to flow southward, intersecting with Verde River valley (Fig. 2; Blasch et al. 2006). Basin and Range springs in the Verde River valley are more often locally sourced from the Verde Formation or from localized fractures, faults, and dissolution features in the south-dipping R-aquifer.

The impacts of groundwater depletion and pollution from human and climate causes can be readily detected at springs. These headwater sources act as "canaries in the coal mine", indicating the impacts of declining groundwater tables and/or groundwater contamination (Winter et al. 1998). Springs ecosystems are among the most biologically diverse features in arid regions (Stevens and Meretsky 2008). For example, Montezuma Well near Camp Verde supports the largest number of endemic and rare species of any site in North America to our knowledge (Blinn and Sanderson 1989; Blinn 2008; Stevens and Meretsky 2008), and is an exceptional ecosystem in the watershed. Springs ecosystems can support rare and endemic species found nowhere else on earth, as well as upland species that use springs for water, feeding, or habitat. Springs are oases in desert environments, and function as keystone ecosystems – small points on the landscape that are disproportionally diverse and ecologically interactive, for both wildlife and human uses (Kreamer et al. 2016).

Our goal in this report is to provide information to help the VRB community conserve and, where possible preserve and restore flow, water quality, fluvial habitats, and the diverse plant, fish, and wildlife populations in this remarkable river basin. Integration of the information presented in this report into the community and into policy may help Verde River basin residents more thoroughly understand the roles, distribution, and importance of springs in maintaining Verde River baseflow, water quality, and springs-dependent species populations. We intend to provide a basic framework for future water quality and quantity monitoring, as well as habitat mapping, assessment, and enhancement, by resource managers and concerned citizens.

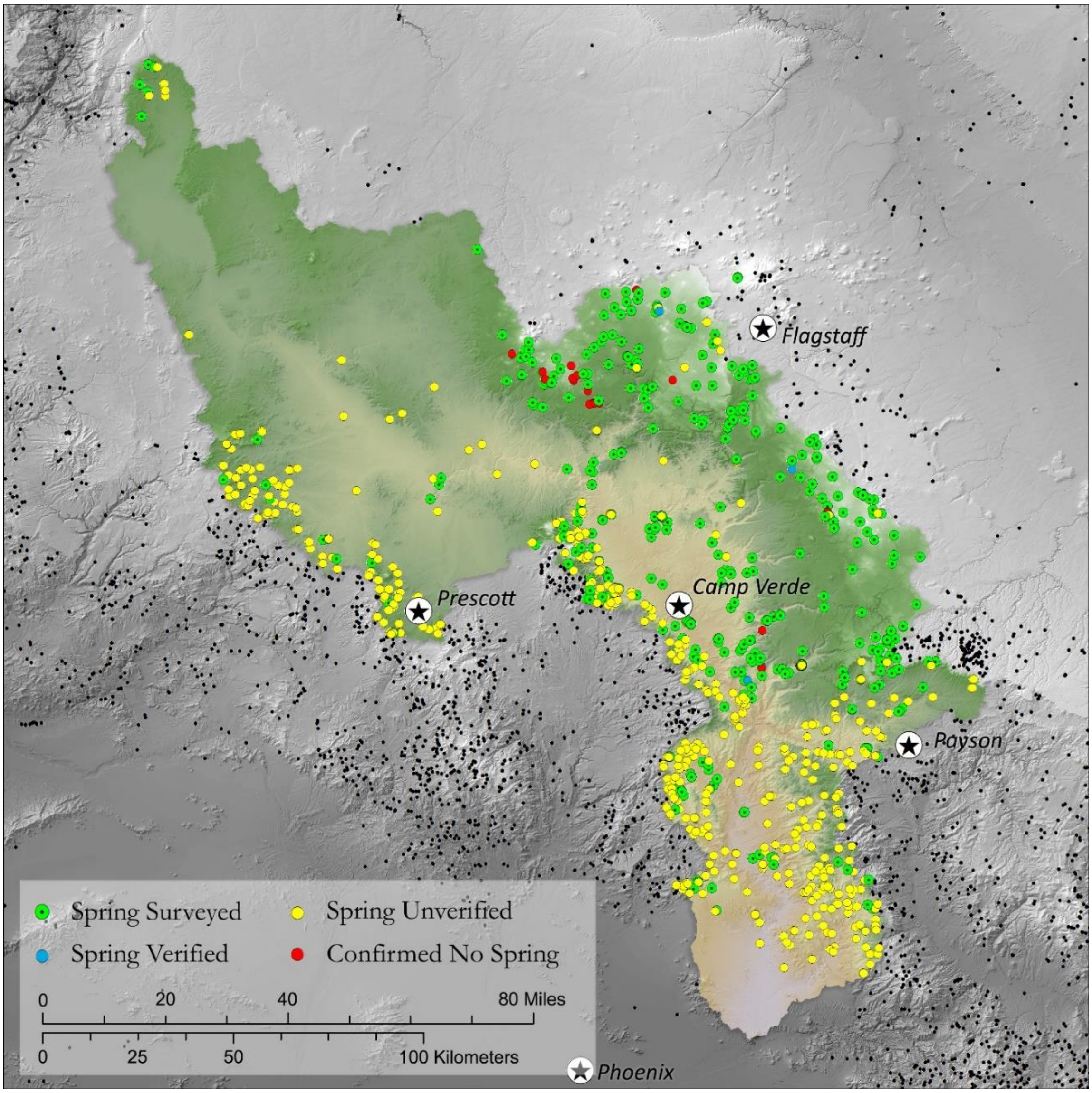


Fig. 3. The Verde River watershed with springs symbolized by survey level (from SpringsData.org, compiled spring 2018). Please note that the surface water watershed may be drastically different than the groundwater watershed/contributing area due to subsurface faults, fractures, and dissolution flow paths (Fetter 2001).

This report is offered as a tool for One for the Verde, its constituents, and the general populace to inventory, assess, plan, manage, and monitor springs water quality/quantity and ecosystem integrity (Appendices A, B). We provice basic information and introduce Springs Online (Springsdata.org) as an easy-to-use, secure, online platform for compiling, archiving, and easily reporting upon the diverse forms of information that may be deemed important by springs stewards. Future information and data collection can readily be entered by trained volunteers and partners who are monitoring springs ecosystems using the Spring Stewardship Institute inventory and assessment methods (SpringStewardshipInstitute.org).

The Springs Stewardship Institute and Springs Online

This report is written by the Springs Stewardship Institute for One for the Verde. The Springs Stewardship Institute (SSI), an initiative of the 501(c)3 nonprofit Museum of Northern Arizona, maintains a comprehensive, secure, and easy to use online springs ecosystem database (Springs Online, www.SpringsData.org), with information compiled from many sources, including federal, state, Tribal, and private research. Springs Online permits entry and archival of diverse inventory information (quantitative, qualitative, documents, photographs), data which are entered using SSI's standardized inventorying and monitoring protocols (www.SpringstewardshipInstitute.com, 2017; Fig. 3, 4). The SSI protocols and database have been developed, tested, reviewed, and refined over the last 20 years by many scientists, organizations, agencies, and Tribes.

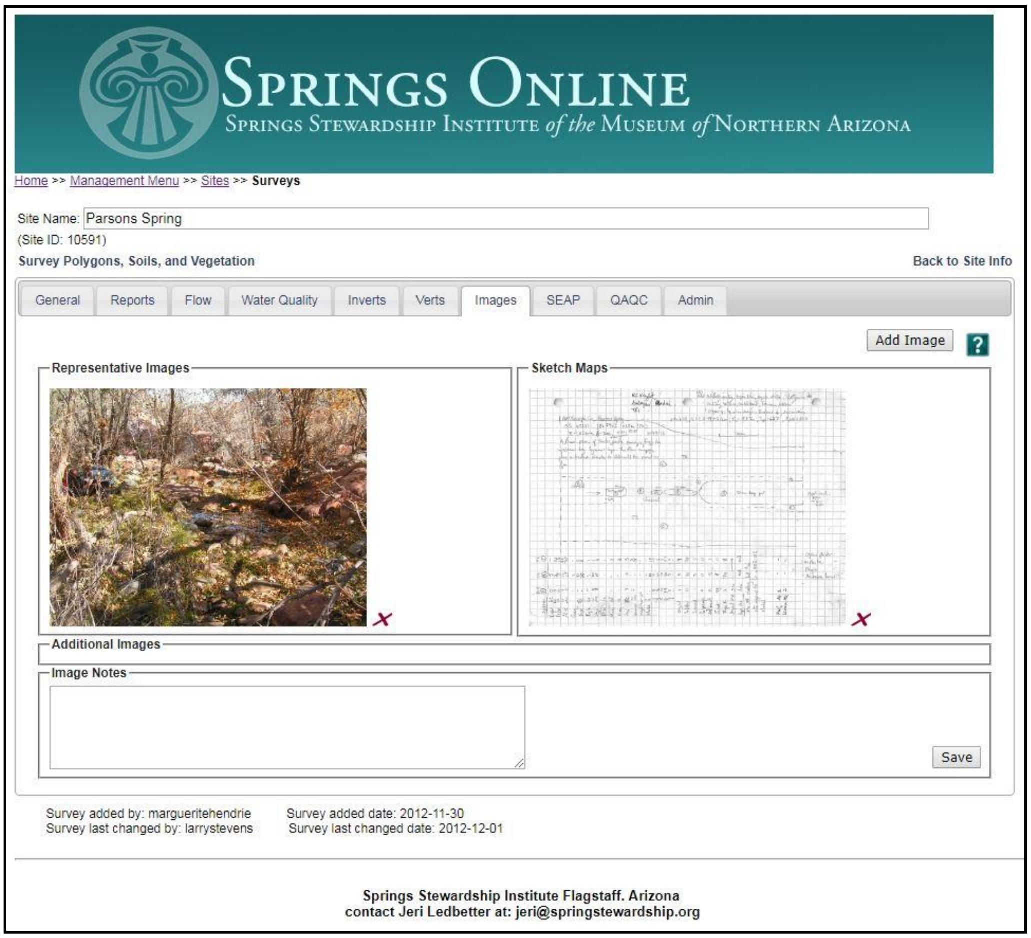


Fig. 4. A spring image and field map in the Springs Online database (www.SpringsData.org, Accessed 11/01/2017). This example, Parsons Spring, is one of more than 710 Verde River watershed springs in the Springs Online database. Information on Parsons Springs includes flow, water quality, spring associated plant and animal species, and human impacts.

A unique component of the Springs Online relational database is the opportunity to couple geographic and physical properties of VRB springs to analyze for biological and ecological patterns and trends, such as elevation-aspect influences on wetland vegetation or changes in flow or water quality over time. Springs Online also provides documentation of springs-dependent species distribution and conservation status. For this report, we compiled information from the literature and NatureServe on nearly 100 springs-dependent species in the VRB to provide lists and maps of the plants, invertebrates, and vertebrates that rely on Verde River springs. Many of those species are rare and some are unique to the VRB. For example, Montezuma Well (Fig. 5) supports at least six species found nowhere else on Earth. The biological data assembled helps identify vulnerable flora and fauna and can improve understanding of relationships among flow, water quality, and species distribution and status. These lists also can be readily updated with future monitoring data, allowing trend analyses of any monitored variable to inform adaptive management. Springs Online also can be used to provide guidance on adaptive management, restoration, and monitoring of springs ecosystems, as well as springs-dependent plants, invertebrates, fish and wildlife, and their habitats.

Fig. 5: Montezuma Well is one of the best known Verde River watershed springs and supports the highest concentration of unique species of any point in North America to our knowledge (source: 2008 inventory data in Springs Online, SpringsData.org).

This report provides links to the VRB Water-Resources Primer, an excellent resource for understanding the general and specific threats and hydrological processes occurring Basin Partnership (www.vrbp.org) or the Friends of the Verde River (https://verderiver.org/verde-river-basin-water-resources-primer-2/) and summarizes many of the recent hydrologic studies in the watershed. For more information about springs ecosystems, we recommend *Aridland Springs of North America* (Stevens and Meretsky, University of Arizona Press 2008) and *Ecological Implications of Verde River Flows*, a report prepared by The Nature Conservancy (Haney et al. 2008). Please feel free to contact SSI at Springstewardshipinstitute.org or questions or guidance.

Methods

Springs information was obtained from Springs Online (SpringsData.org), SSI's database, which provides geography and mapping services for springs distribution in the VRB and the associated summary files on springs flow, water quality, and biodiversity there. We quality-controlled available data, and conducted geographic analyses of springs distribution, water quality, flow, and associated aquatic, wetland, and riparian springs-dependent species. Data were compiled from many sources using ArcGIS, SQL, and Microsoft Excel, and were exported to an ESRI ArcGIS geodatabase for collaborative spatial analysis and use by SSI, VRB partners, and citizen scientists. Data in Springs Online are password-protected to ensure the security of intellectual property rights for the owner(s) of the springs and springs data.

Site-specific springs data were gathered using either the Springs Stewardship Institute's springs inventory protocols (Stevens et al. 2016) or the U.S. Forest Service's Groundwater Dependent Ecosystem (GDE) protocol (USFS 2012). Links to the SSI protocols and assessment techniques are included in the Appendices. Both protocols focus on physical and biological character at a springs ecosystem. Variables measured included water flow and quality, floral and fauna, aspect, slope, and surficial geomorphology, as well as the anthropogenic impacts and ecological integrity of the site. The composition of the field crews varied by the project and agency/organization conducting the survey, with most inventories conducted by two to four investigators.

Hydrographic analyses were conducted on each of the US Geological Survey's (USGS) stream gauges in the Verde River watershed over the period of record for each gauge. Stream gauge data were collected from the National Water Information System (waterdata.usgs.gov) and processed through R (R Core Team 2018) and Microsoft Excel to determine changes in streamflow over time. Two general analyses were conducted. 1) The peak snow melt flow by year was investigated to determine the impact of warming climate on snowmelt timing. Peak snow melt was determined using the one-day, three-day, and five-day averages between February 1st and May 31st each year. 2) The median June baseflow was analyzed to determine long-term changes in baseflow due to water diversion or use. June baseflow was calculated as the median flow for the entire month by year. June was selected because it is the driest month of the year and streams in Arizona typically are at or near baseflow throughout that month (Blasch et al. 2006). Hydrograph trends were compared with precipitation records as recorded at the Sedona airport (N 34°50.91', W 111°47.31’; 1472 m elevation) between 1970 and 2010 and compiled by the National Weather Service (https://w2.weather.gov/climate/local_data.php?wfo=fgz ; accessed July 2018;).

Results

Overview

The Springs Online (SpringsData.org) database now contains inventories and/or ecological assessment information on 820 VRB surveys of springs, including 717 springs with reported location data, and 133 springs with measured water flow and chemistry data (Fig. 3). A total of 945 springs, both verified and unverified, may exist within the watershed boundaries. Unverified springs are those reported by the National Hydrography Dataset or other remotely-determined sources using infrared or color analysis, but which have not been documented by in-person site visits.

Data on the 717 verified VRB springs include water flow and chemistry for 133 springs (database accessed March 2018; Fig. 3). The largest number of surveys at Del Rio (44) and Lindbergh (14) springs, and Montezuma Well (14). Most of the unverified springs occur near Prescott and along the western boundary of the watershed, and more inventory attention is warranted in those areas (Fig. 3).

Springs Flow and Water Quality

The sum of the average flow from 133 springs (14% of all springs in the watershed) is 2800 L/sec or 99.4 ft^3/s. While these data are synoptic and taken at multiple times of year over several years, they indicate the magnitude of groundwater provided to the Basin.

Another way to look at the magnitude of springs flow is to assign a value to the flow emanating from all springs within the basin. If we take the average (mean) flow for all the springs <50 L/sec (124 springs) and attribute that mean flow to the 708 verified springs (not including the nine springs that contain flow >50 L/sec) we estimate the total springs flow into the VRB basin. The average flow is 2.05 L/sec, which a total inflow of 1451 L/sec. The nine largest springs contribute a total of 2399 L/sec. All springs combined would therefore produce 3850 L/sec or 136 ft^3/s. Obviously, this is a crude estimation, and a large proportion of this springs water likely evaporates, is taken up and transpired by vegetation, or seeps back into the ground. Some springs, especially within the active channel of the river, may not be mapped or quantified. The purpose of this simple analysis is to show the magnitude of springs flow in the Verde River watershed, and that while a few large springs contribute the majority of the flow that there are hundreds of small springs that can support wildlife, native vegetation, and recreation.

A comparison of springs emanating south of the Verde River, compared to springs north of the Verde River may also be of interest. Northern springs are generally fed by the regional R aquifer while southern springs usually source from more local Verde Formation springs (Fig. 2). The median spring flow was the same for both north and south springs, however there are a few large springs that drain the northern watershed that influence the average (mean) spring flow and the standard deviation (Table 1). Southern springs also tended to be warmer and have higher specific conductance (dissolved solids) than northern springs (Table 1).

Table 1. Spring flow, in liters per second, specific conductance, in microsiemens per centimeter, and temperature, in Celsius, for springs north and south of the Verde River. The number of springs sites is provided (n) as is the standard deviation (STDEV) of each sample population.

		Spring flow		
	n	**average**	**median**	**STDEV**
North	166	15.62	0.17	99.87
South	60	3.88	0.17	13.09
		Specific conductance		
	n	**average**	**median**	**STDEV**
North	109	315	206	383
South	19	943	575	1209
		Temperature		
F	**n**	**average**	**median**	**STDEV**
North	138	16.0	15.3	5.0
South	23	22.3	20.9	5.5

Maps of the distribution of springs by flow, water pH, specific conductance, and water temperature are provided in Figs. 6, 7, 8, and 9. Specific conductance (SC) is a standardized measure of the amount of ionic conductivity in the water. SC is derived from electrical conductivity, the ability for electrical current to pass through water at a given temperature. The higher the conductivity the more dissolved solids, or ionic strength, that is in the water. SC provides a general understanding of how mineralized the water is, usually a sign of older water that has passed through a considerable amount of rock slowly gaining dissolved solids. The pH of the water allows us to

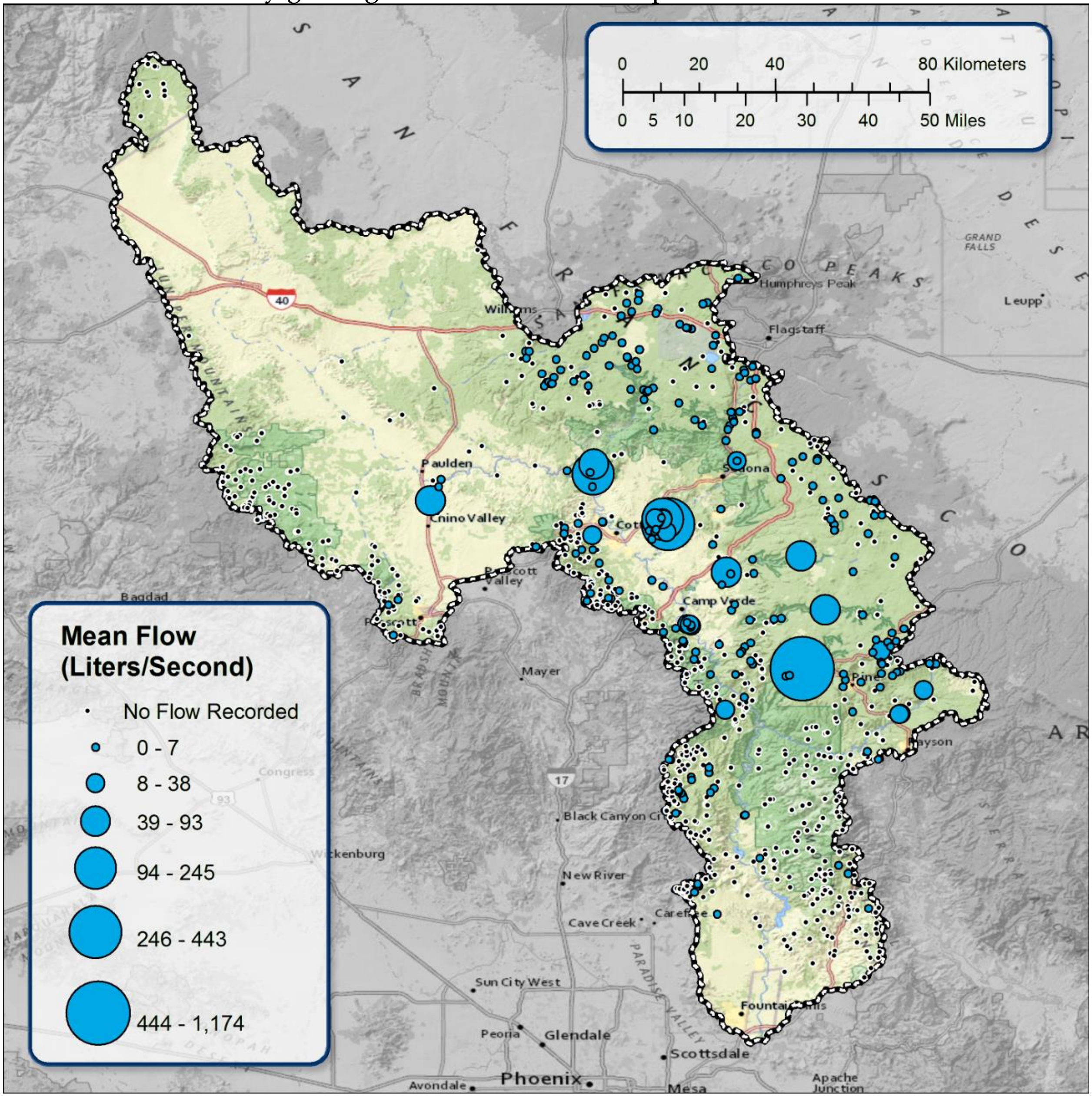


Fig. 6. Mean spring flow in liters per second at 135 springs. Springs with no measurements are shown as black dots, note the areas west of Paulden, AZ and the areas east of Cave Creek, AZ that have no flow information.

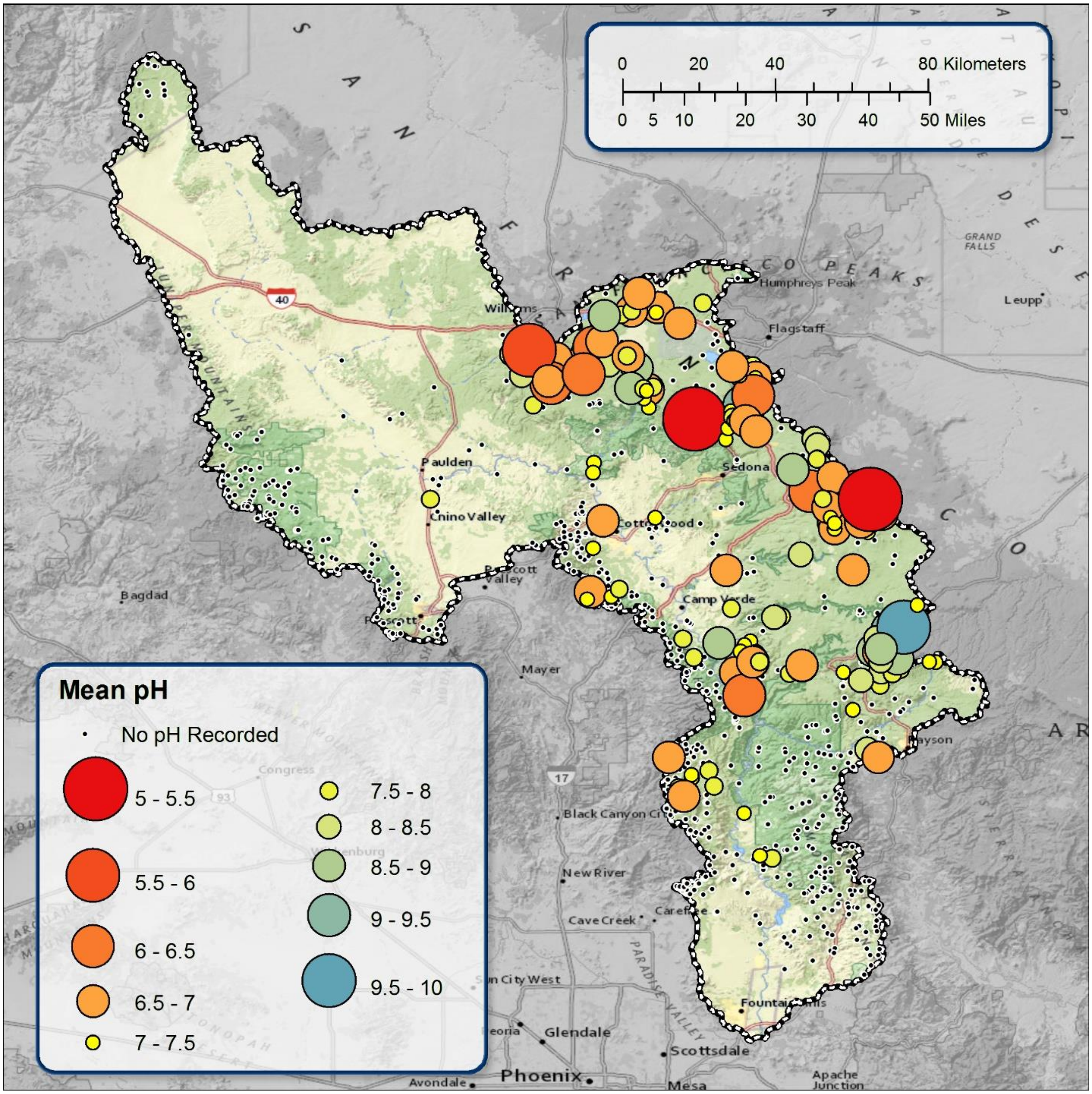


Fig. 7 Mean water pH measured at springs emergences as stored in Springs Online. Springs with no measurements are shown as black dots, note the areas west of Paulden, AZ and the areas east of Cave Creek, AZ that have no water quality information.

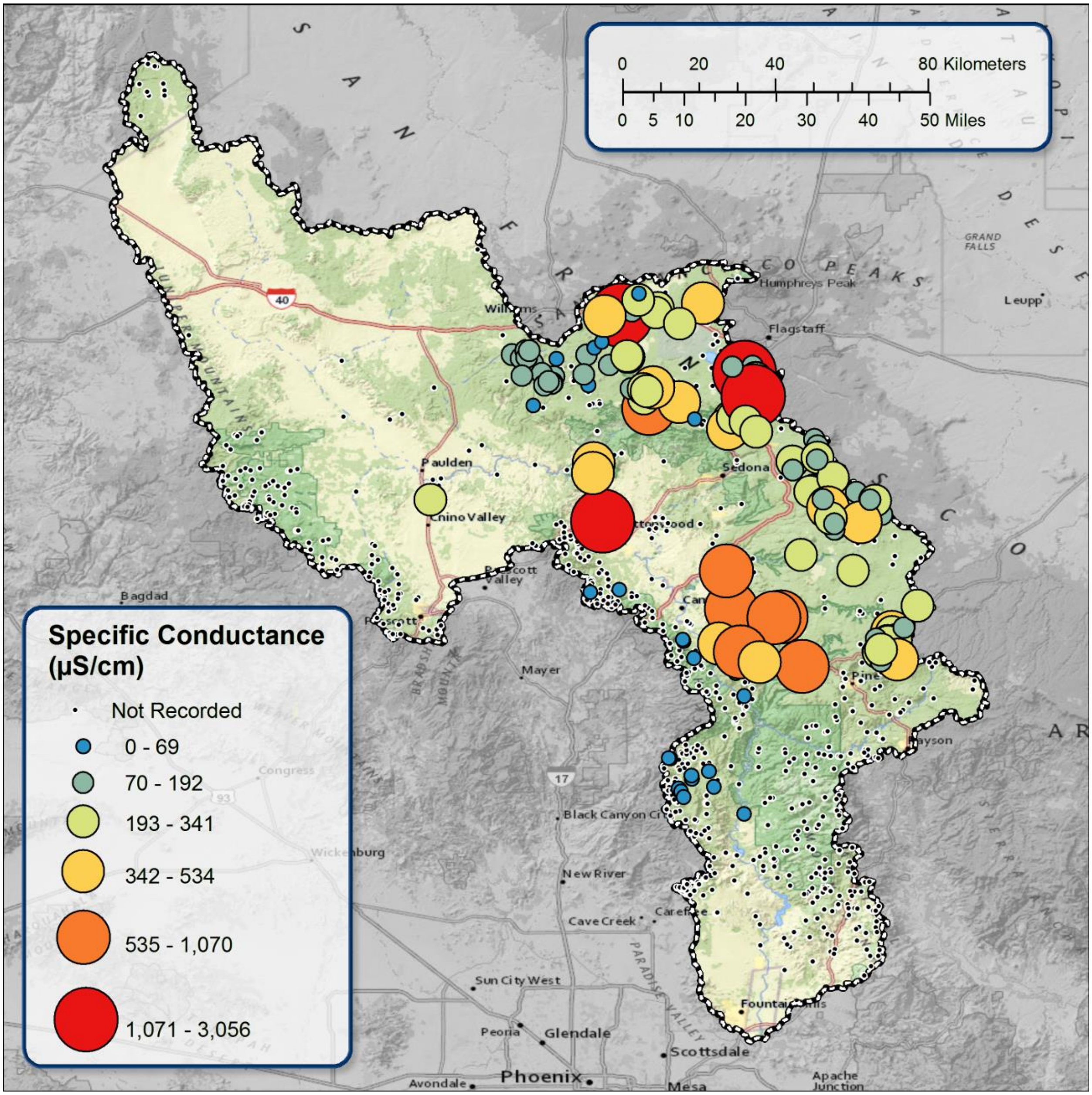


Fig. 8 Mean specific conductance for springs as stored in Springs Online. High values generally indicate long flow pathways and/or passage through highly soluble geologic units. Springs with no measurements are shown as black dots, note the areas west of Paulden, AZ and the areas east of Cave Creek, AZ that have no water quality information.

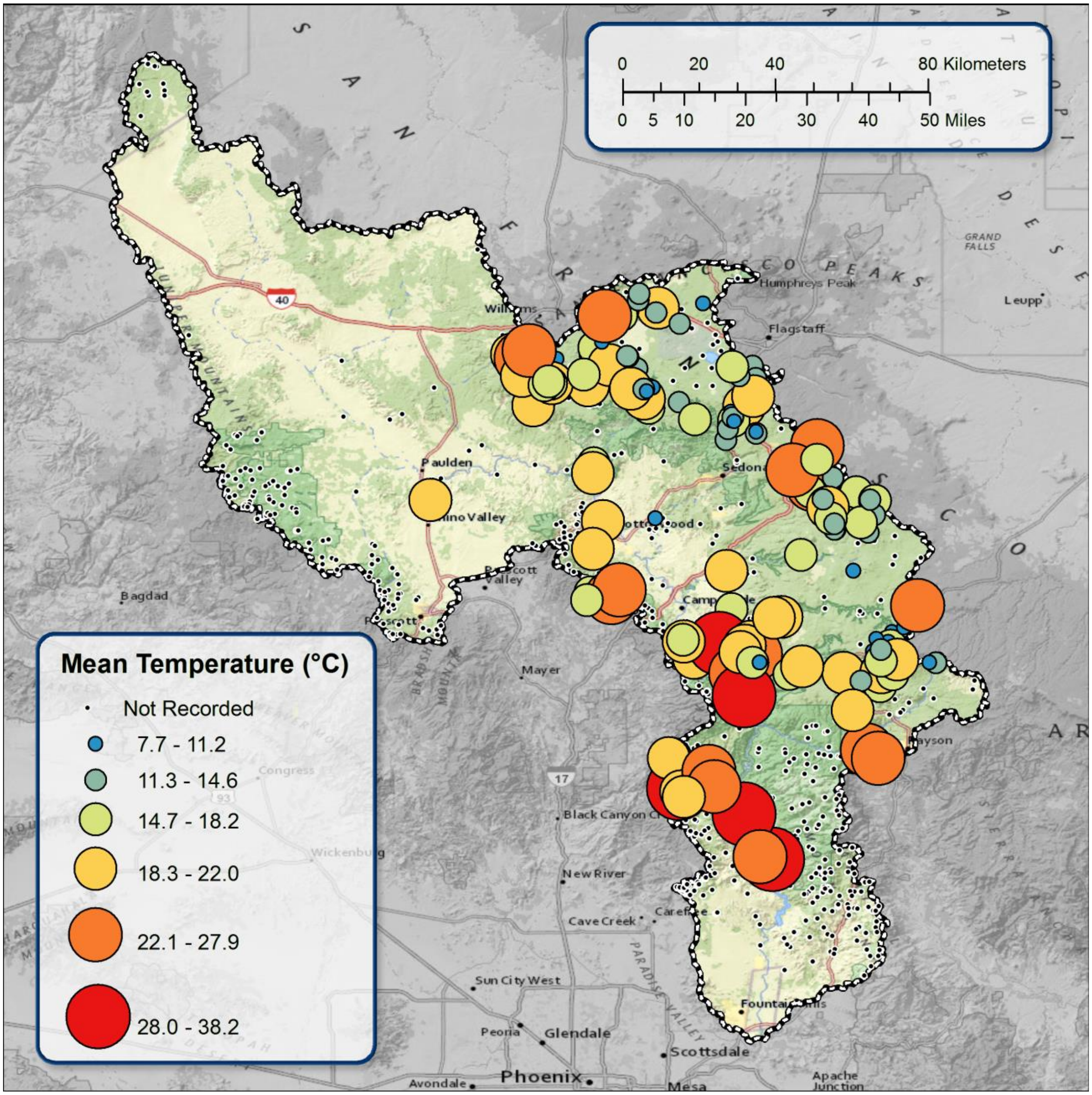


Fig. 9. Water temperature at springs emergence. Springs with no measurements are shown as black dots, note the areas west of Paulden, AZ and the areas east of Cave Creek, AZ that have no water quality information.

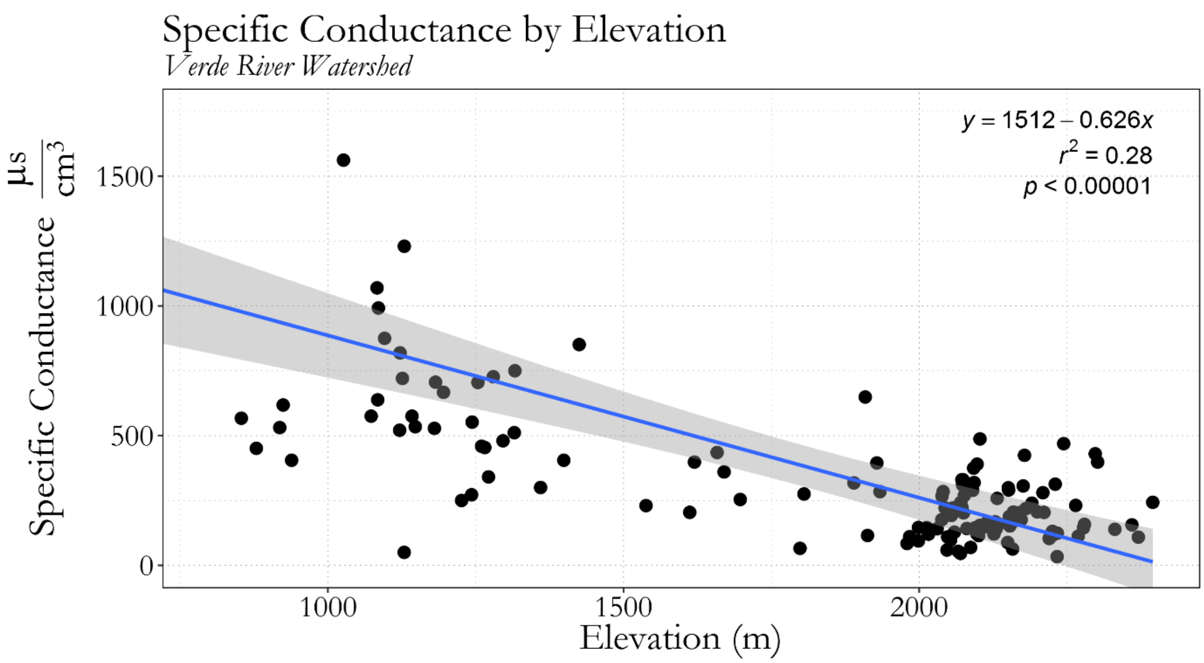
understand how acidic or basic the water is. Water temperature is important for aquatic habitat and also for determining aquatic chemical processes (as is pH).

Weak trends exist when comparing elevation to specific conductance or water temperature, trends that have been observed for many springs throughout the Southwest. In general, lower elevation springs have higher specific conductance (a measure of dissolved solid concentration) due to longer flow paths and residence time, higher temperature, and more neutral pH (Figs. 8, 9, 10). Springs in the Juniper

Mountains northwest of Prescott and Mogollon Rim springs south of Payson are both under-represented in terms of water flow and chemistry (Figs. 10, 11, 12). The following graphs, however, indicate that springs at lower elevations in the Basin are likely sourced from older waters, rather than directly from high elevation springs.

The SC of springs in the Verde River watershed generally follow an elevational trend with springs in high elevations containing less dissolved solids than those in lower elevations (Fig. 10). Springs that did not follow this trend include Mineral, Griffiths, and Kelly Seep springs, all with SC above 1500 µs/cm and at elevation above 2000 m. High elevation springs with high SC may be contaminated with road salts (likely at Griffiths due to location near Highway 89a), or other human activities. A graph of SC versus elevation is provided in Fig. 10, note that the graph does not include the three springs above 1500 µs/cm, nor any springs where a value of 0 was recorded.

A)



B)

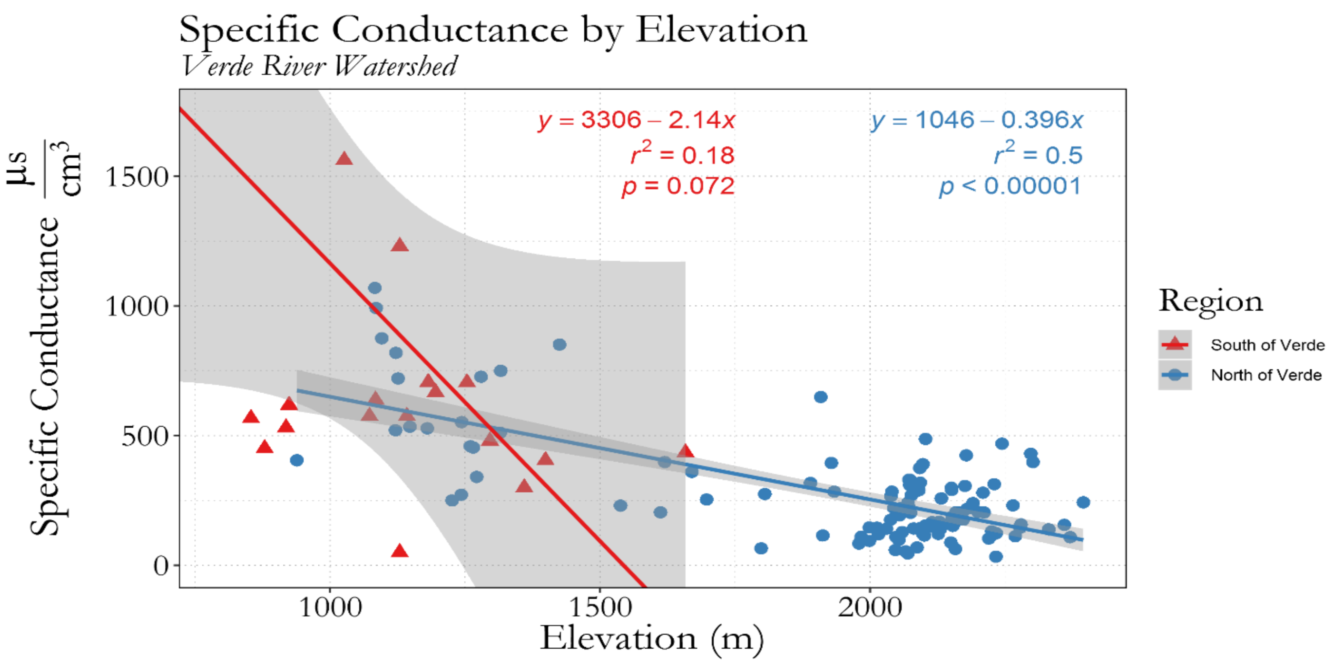
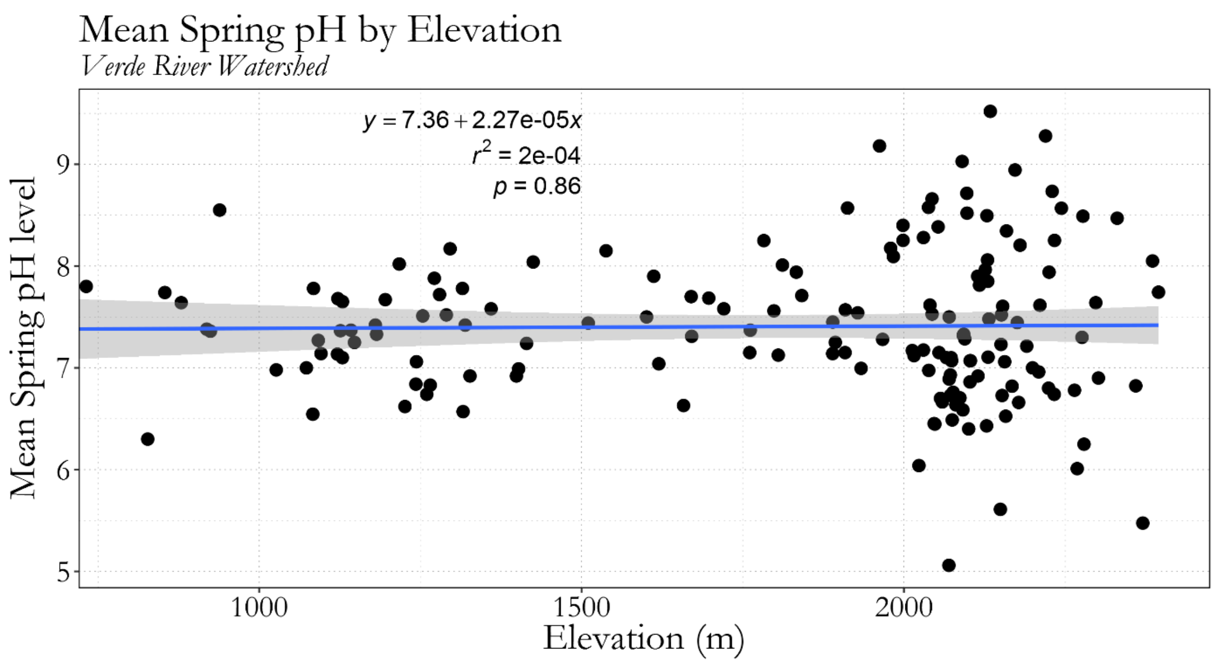


Fig. 10. Spring water specific conductance by elevation. A) is a graph of all sites, B) is a graph of springs by region, either North or South of the Verde River. Note the expected increase in conductance in the low elevation springs. Two outlier (specific conductance above 1700 µs/cm3) springs were removed from the graph for clarity.

The pH of spring water is not related to elevation (Fig. 11) and ranges generally from slightly acidic (pH of 6) to alkaline (pH of 9). A handful of springs are more acidic or alkaline, mostly above 2000 m elevation (Fig. 11). Temperature of springs waters is related to elevation with cooler waters in the higher elevations and warmer waters at low elevations (Fig. 12).

A)



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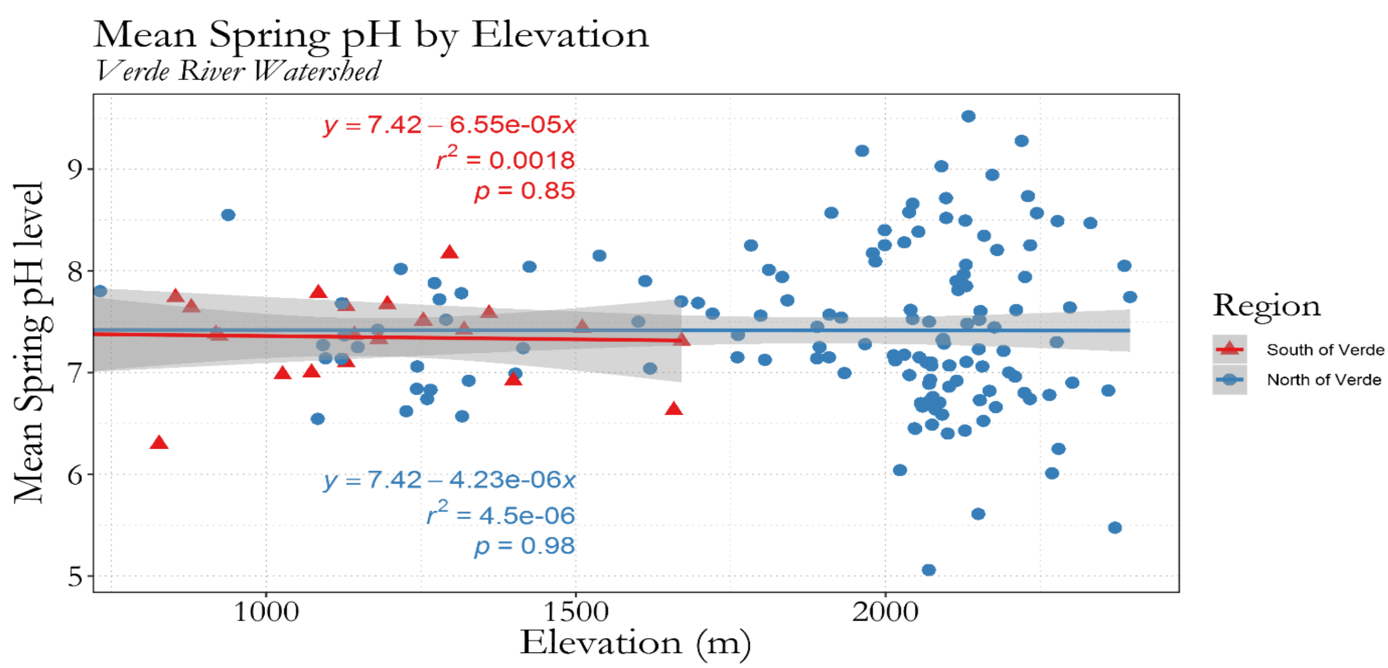
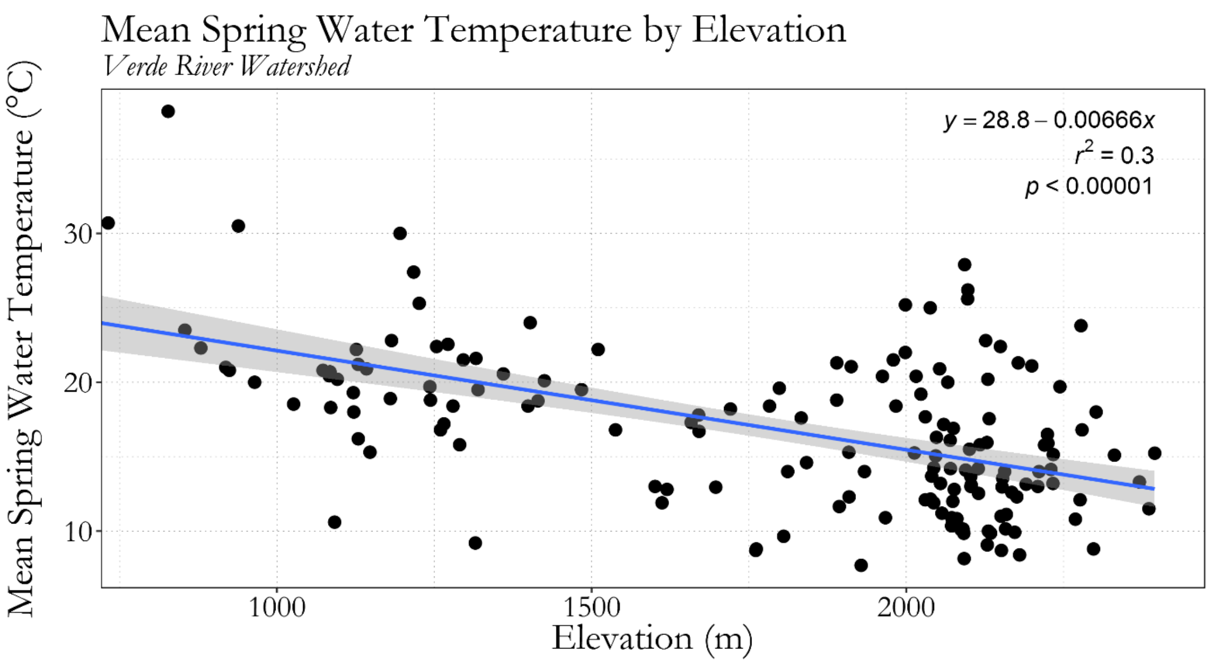


Fig. 11. Mean spring water pH by elevation for all springs (A) and for springs by location relative to the Verde River (B). Note the greater range of pH values in the higher elevations relative to the low elevation springs.



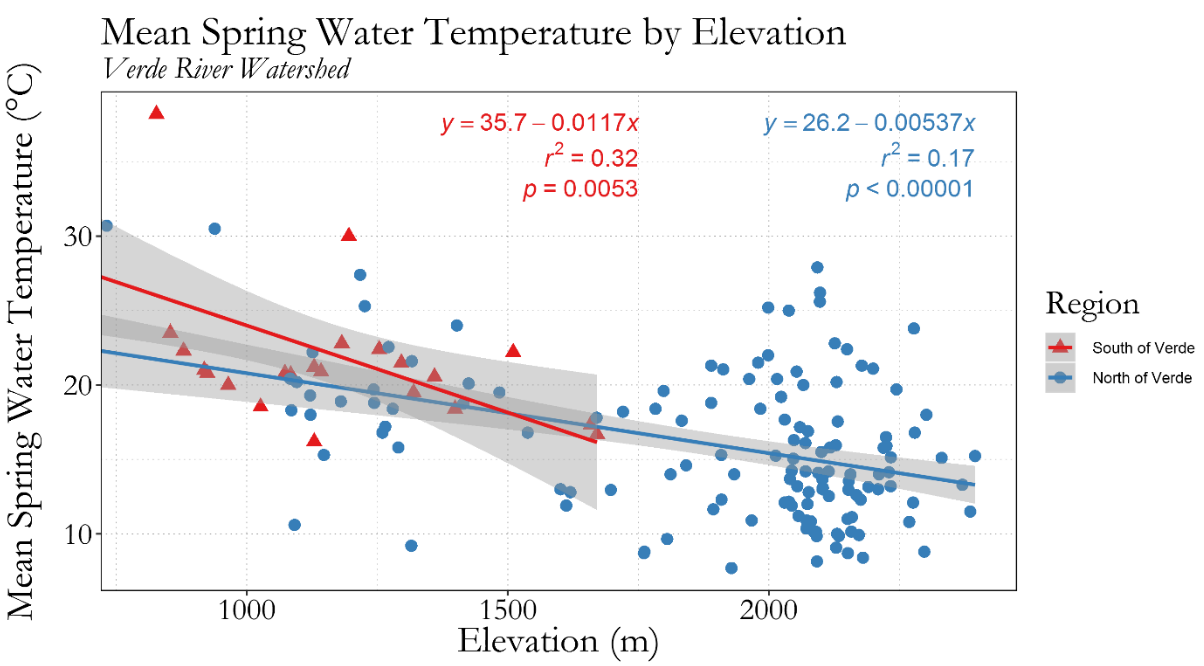


Fig. 12. Spring water temperature (C) by elevation.

Understanding the general trend in water temperature and SC with changes in elevation is important for groundwater source and withdrawal protection, contaminant risk assessment, and for educating the public about the groundwater character of the VRB. Warmer water, and water with higher SC, typically have longer flow paths than colder less mineralized water.

Stream Flow Trends: Earlier Snowmelt Periods and Lower Baseflow

Analyses of USGS stream flow data indicates that, over the years, the date of peak spring time stream flow (indicating snowmelt) is shifting earlier in the year for many spring fed tributaries of the Verde River, and June (the driest month) baseflow contributions are decreasing. An earlier snowmelt indicates a warming trend, an adverse condition for springs flow since snow can recharge groundwater supplies much more efficiently than rainfall (Gee and Hillel 1988; Winograd et al. 1998). Spring fed tributaries to the Verde River show the strongest trends towards an early spring snowmelt (Figs. 13, 14, 15, 16).

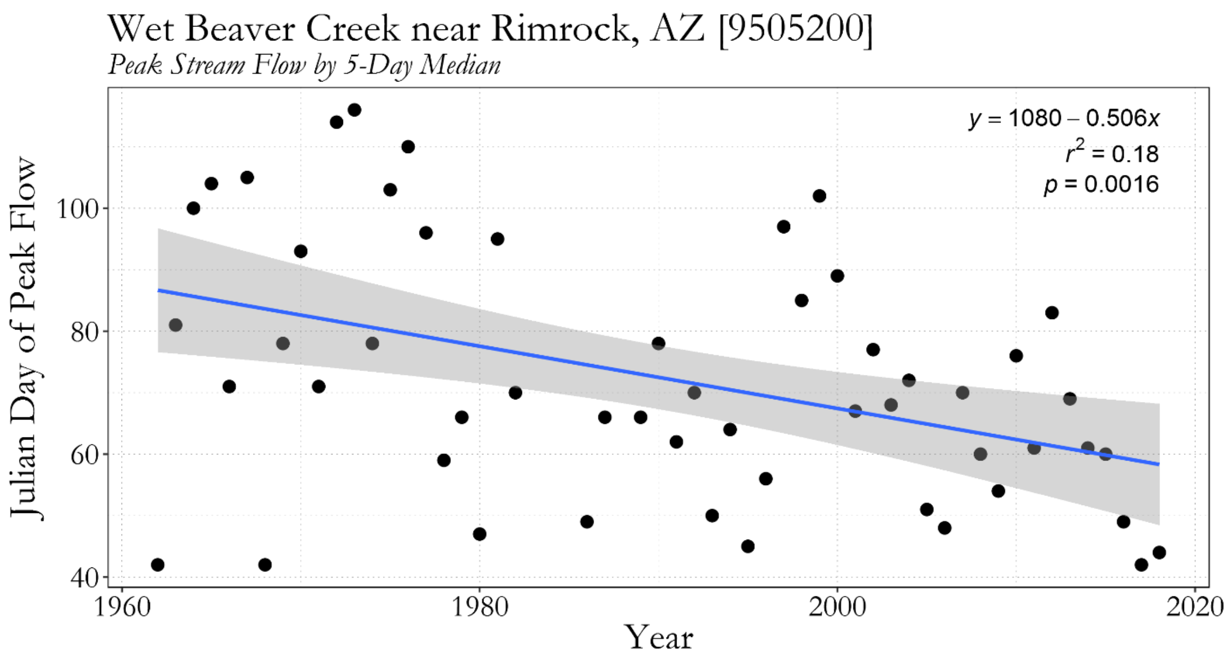


Fig. 13. Peak snowmelt flow over a five day period at the Wet Beaver Creek stream gauge. Peak spring snowmelt runoff occurs nearly one month earlier than at the beginning of the period of record (1960). The blue line indicates the trendline, the grey boundaries indicate the confidence error.

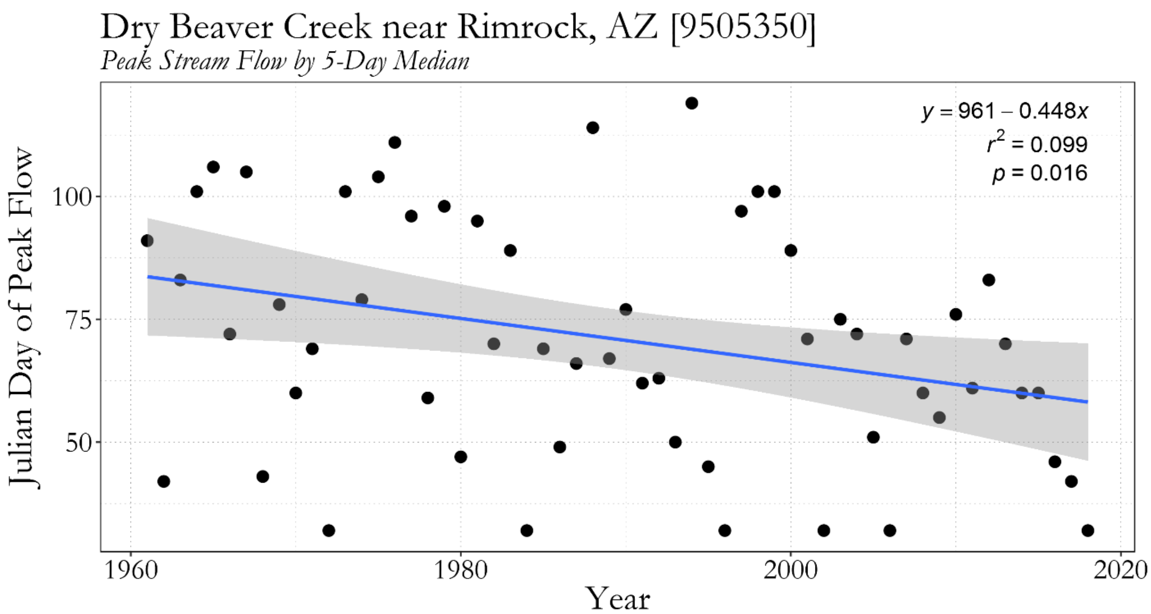


Fig. 14. Peak snowmelt flow over a five day period at the Dry Beaver Creek stream gauge. Peak spring snowmelt runoff occurs nearly one month earlier than at the beginning of the period of record (1960). The blue line indicates the trendline, grey boundaries indicate confidence error.

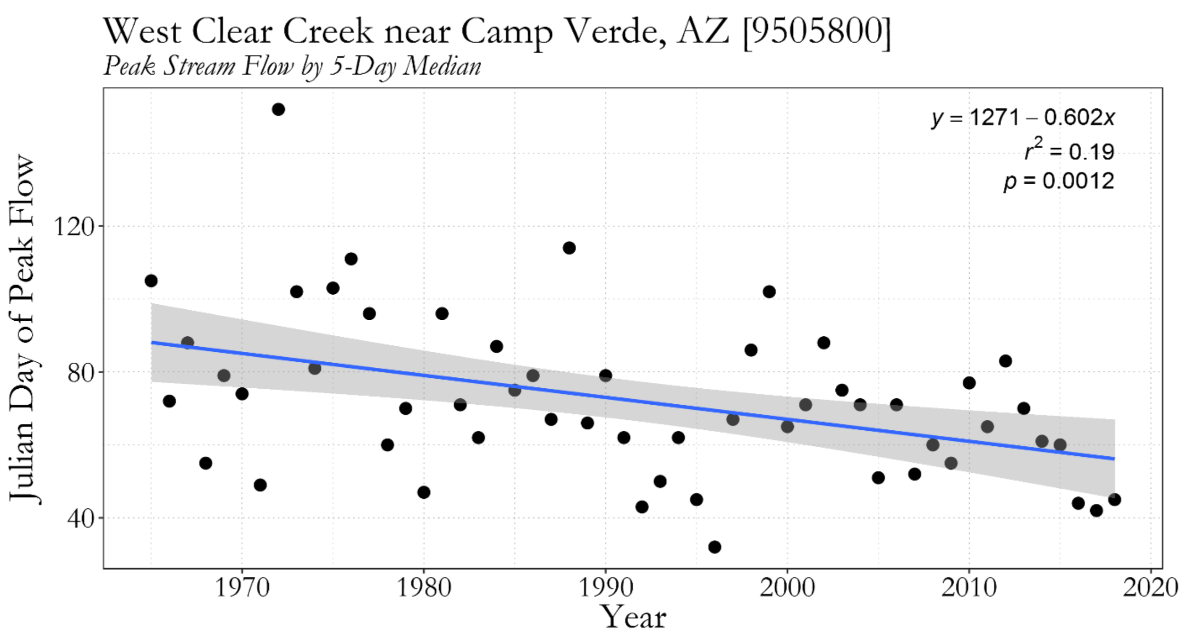


Fig. 15. Peak snowmelt flow over a five day period at the West Clear Creek stream gauge. Peak spring snowmelt runoff occurs nearly a month earlier than at the beginning of the period of record (1965). The blue line indicates the trendline, the grey boundaries indicate the confidence error.

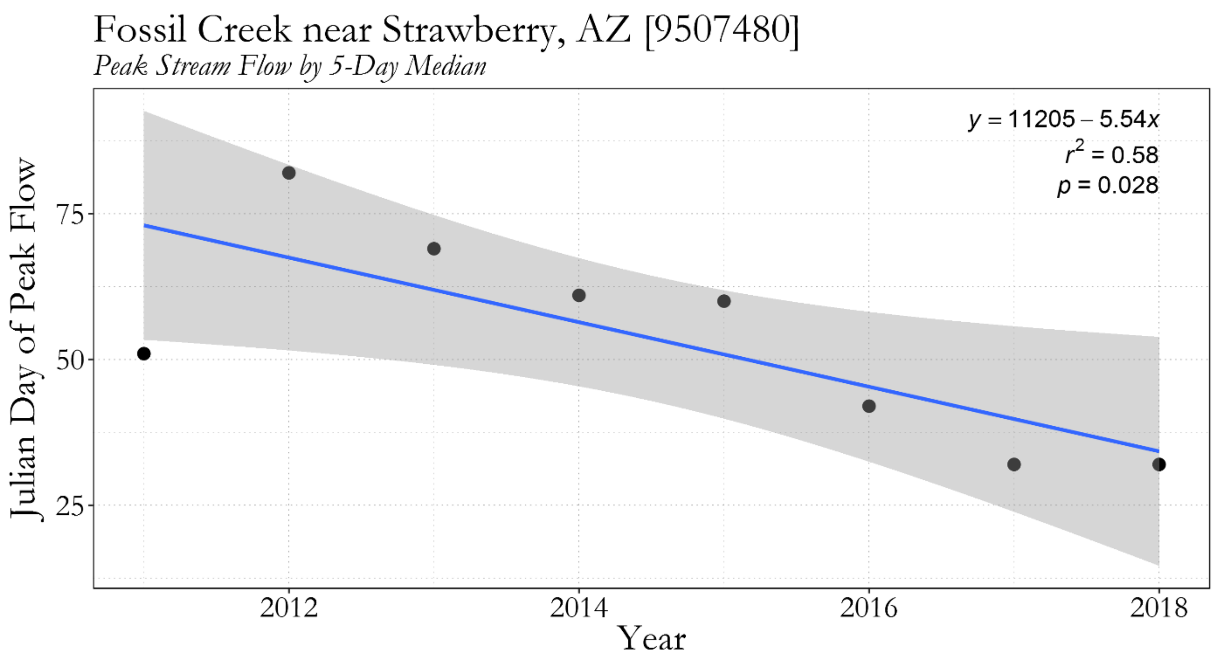


Fig. 16. Peak snowmelt flow over a five day period at the Fossil Creek stream gauge. Peak spring snowmelt runoff has occurred drastically earlier since 2011 but caution should be exercised when using such a low sample size. The blue line indicates the trendline, the grey boundaries indicate confidence error.

The snowmelt trends point to the negative impact of climate change on the spring fed tributaries of the Verde River. The June baseflow trends show the impact of water diversions and aquifer drawdown on springs contributions to tributaries of the Verde River. Dry Beaver Creek, included in the snowmelt analysis above, is not shown due consistently zero June median flow. June flow trends were compared to the long term precipitation monthly average at the Sedona Airport (1970-2010). There were no statistically significant trends or patterns in either June average precipitation ($p = 0.26$, $R^2 = 0.03$) or the total annual precipitation ($p = 0.20$, $R^2 = 0.02$), indicating that precipitation has not varied significantly during the period that June flows have decreased.

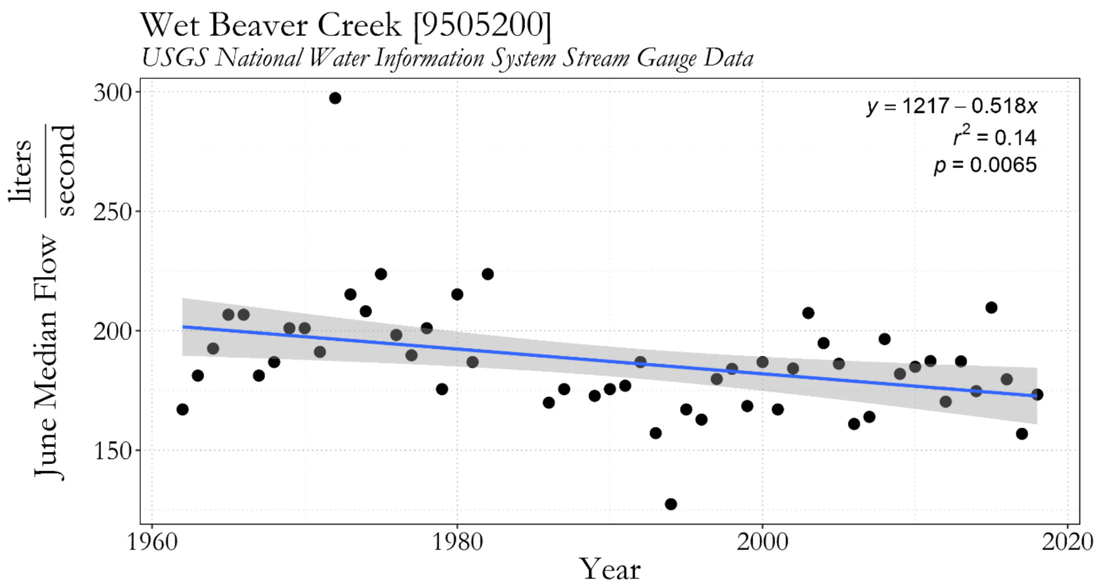
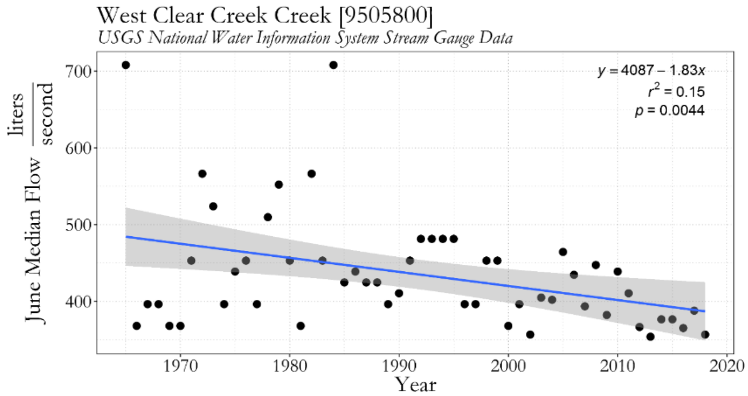
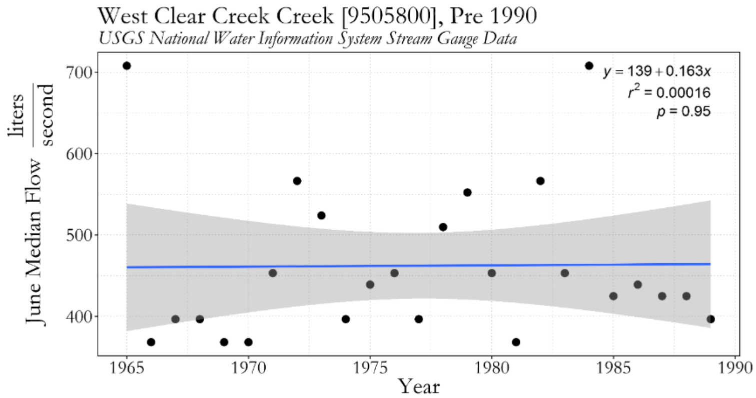


Fig. 17. June median flow at Wet Beaver Creek. The baseflow has reduced by nearly 25 L/sec over the period of record.





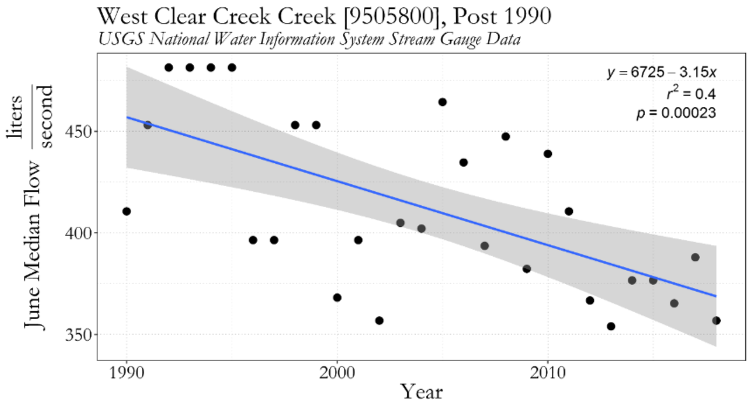


Fig. 18. June median flow at West Clear Creek. Top - the period of record; Middle - 1965 to 1990; Bottom - 1990 to the present. The largely springfed baseflow at this gauge has declined by nearly 100 L/sec over the period of record.

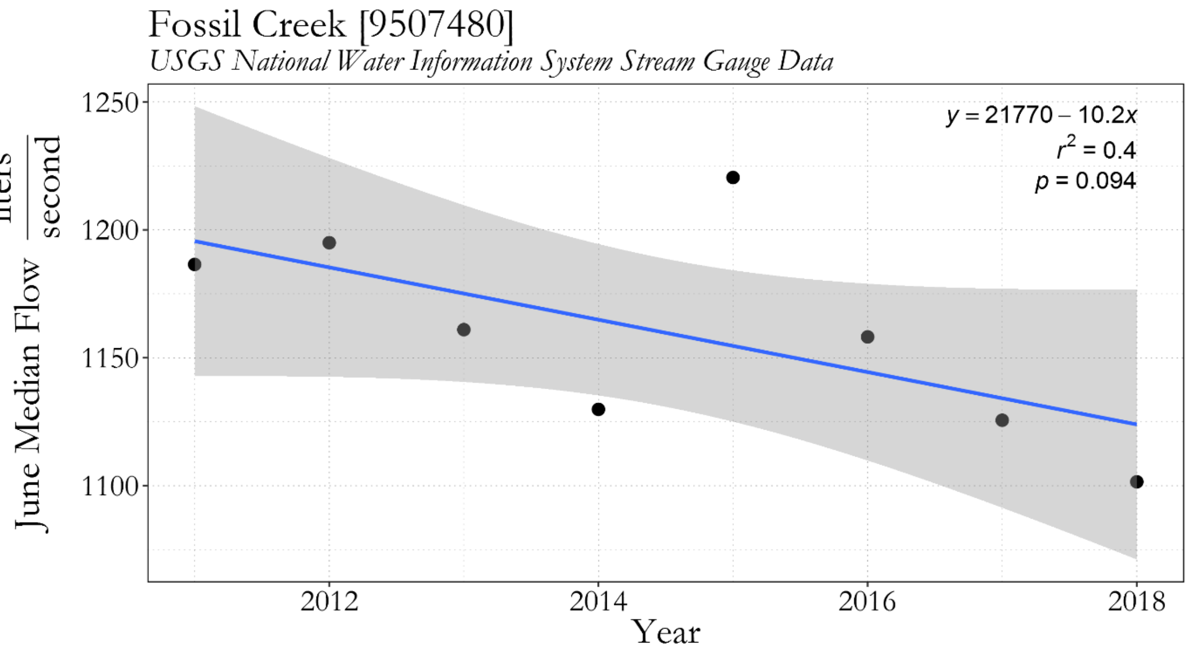


Fig. 19. June median flow at Fossil Creek. The baseflow has reduced by nearly 100 L/sec over the brief period of record. Note that the regression is not statistically significant (p = 0.15), and that the period of record is very short.

The June baseflow analysis can be influenced by rainfall in the low elevations or in the mountains that bound the southern portion of the watershed. Nonetheless, the June dry season analysis is most likely to best reflect changing groundwater conditions. The baseflow of the Verde River is virtually entirely derived from groundwater through springs, and declines in flow like those depicted above translate into reduced mainstream flow, with relatively strong trends in the upper and middle reaches of the river (Figs. 20, 21, 22). The weaker trend in the lower Verde reach near Tangle Creek also reflects increased irrigation withdrawal and evapotranspiration impacts on the mainstream over the period of record (Fig. 23).

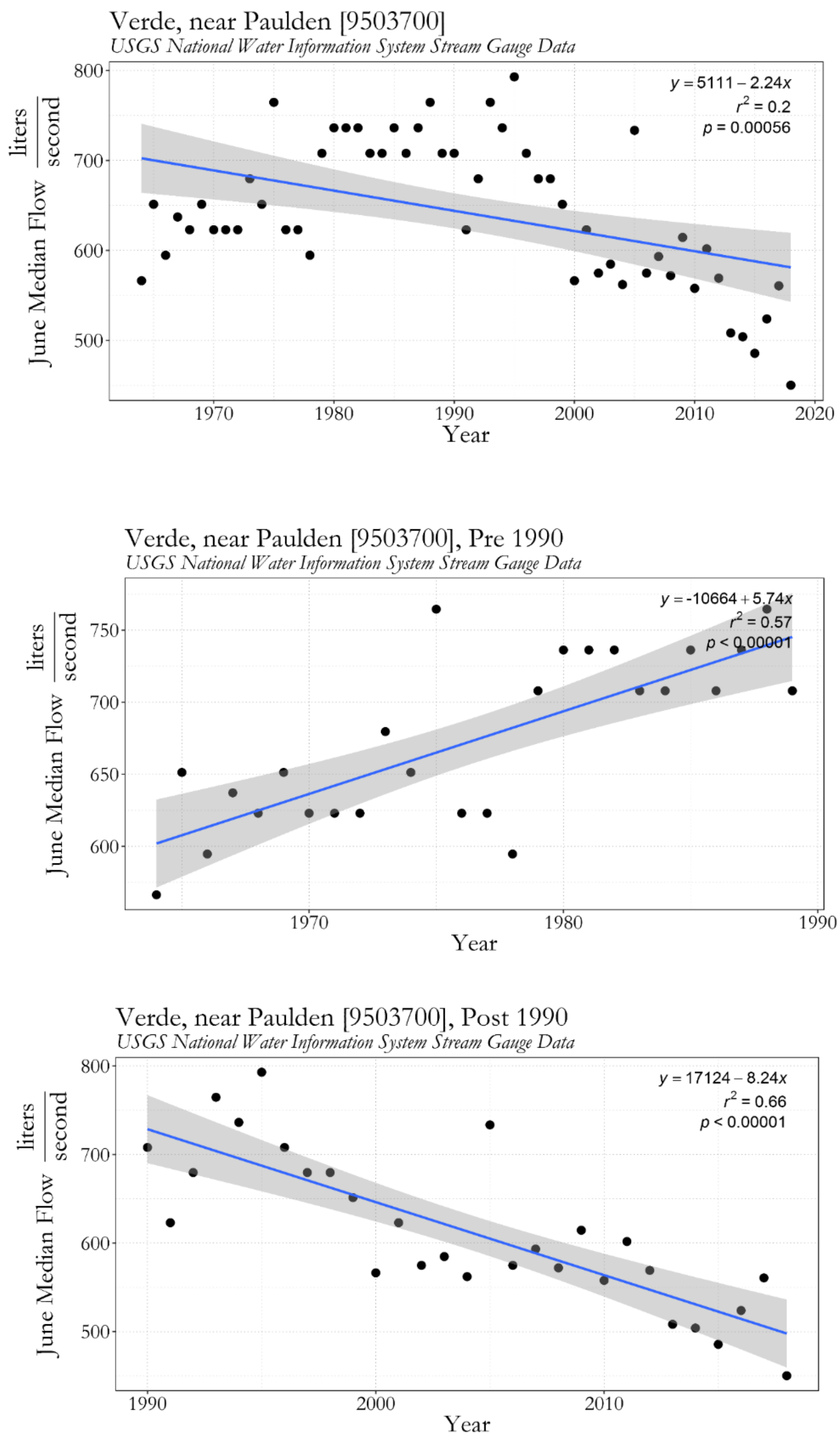


Fig. 20. June median flows (approximating baseflow) in the upper Verde River near Paulden. Top - the period of record; Middle - flows before 1990; Bottom - flows after 1990. Note the statistically significant decline in flow of over 200 L/sec since 1990 over the period of record.

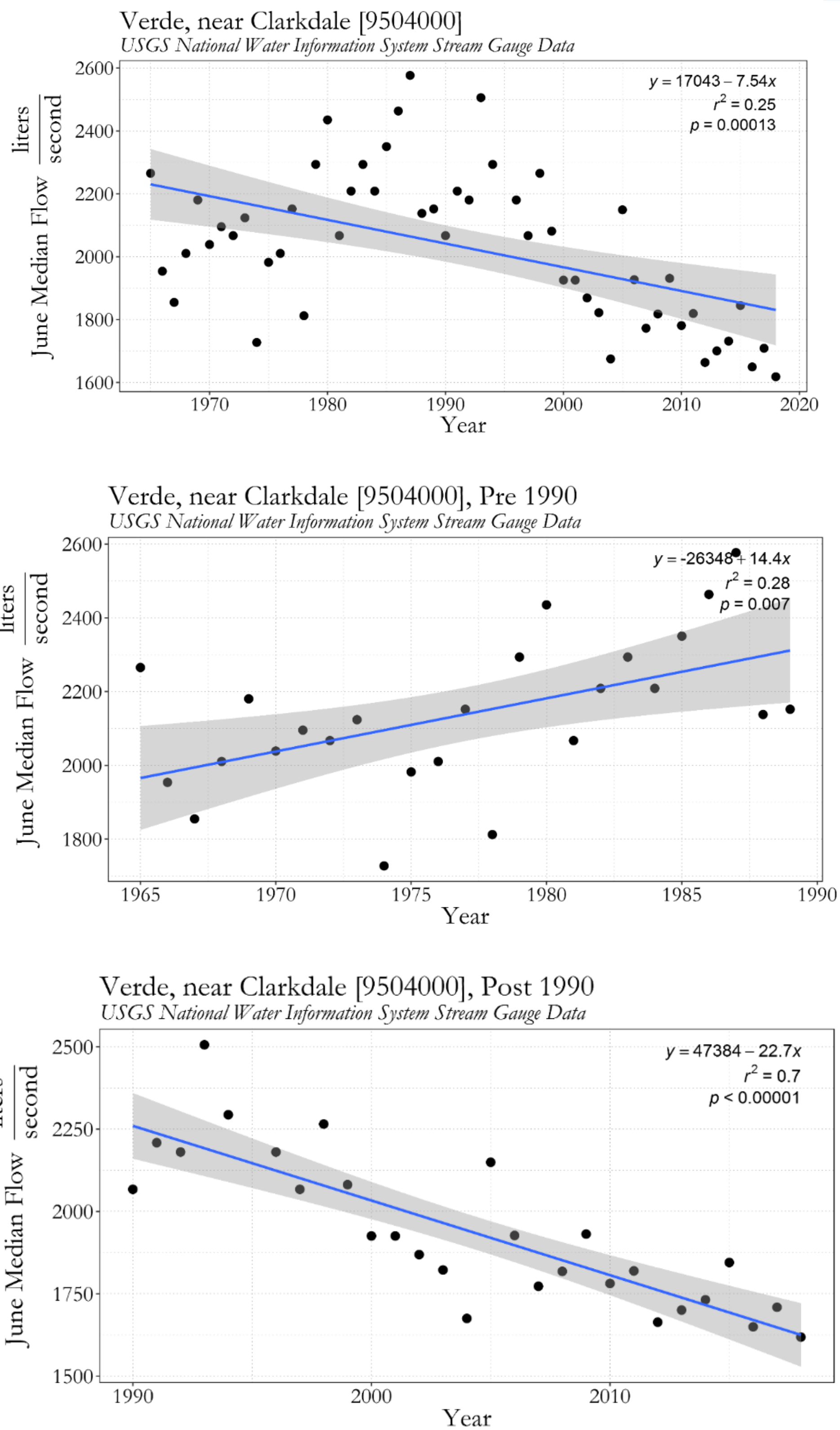


Fig. 21. June median flows (approximating baseflow) in the middle Verde River near Clarkdale, AZ. Top – the period of record; Middle - pre-1990; Bottom - Post-1990. Note the statistically significant decline in flow over the period of record, with a decline of over 400 L/sec post 1990.

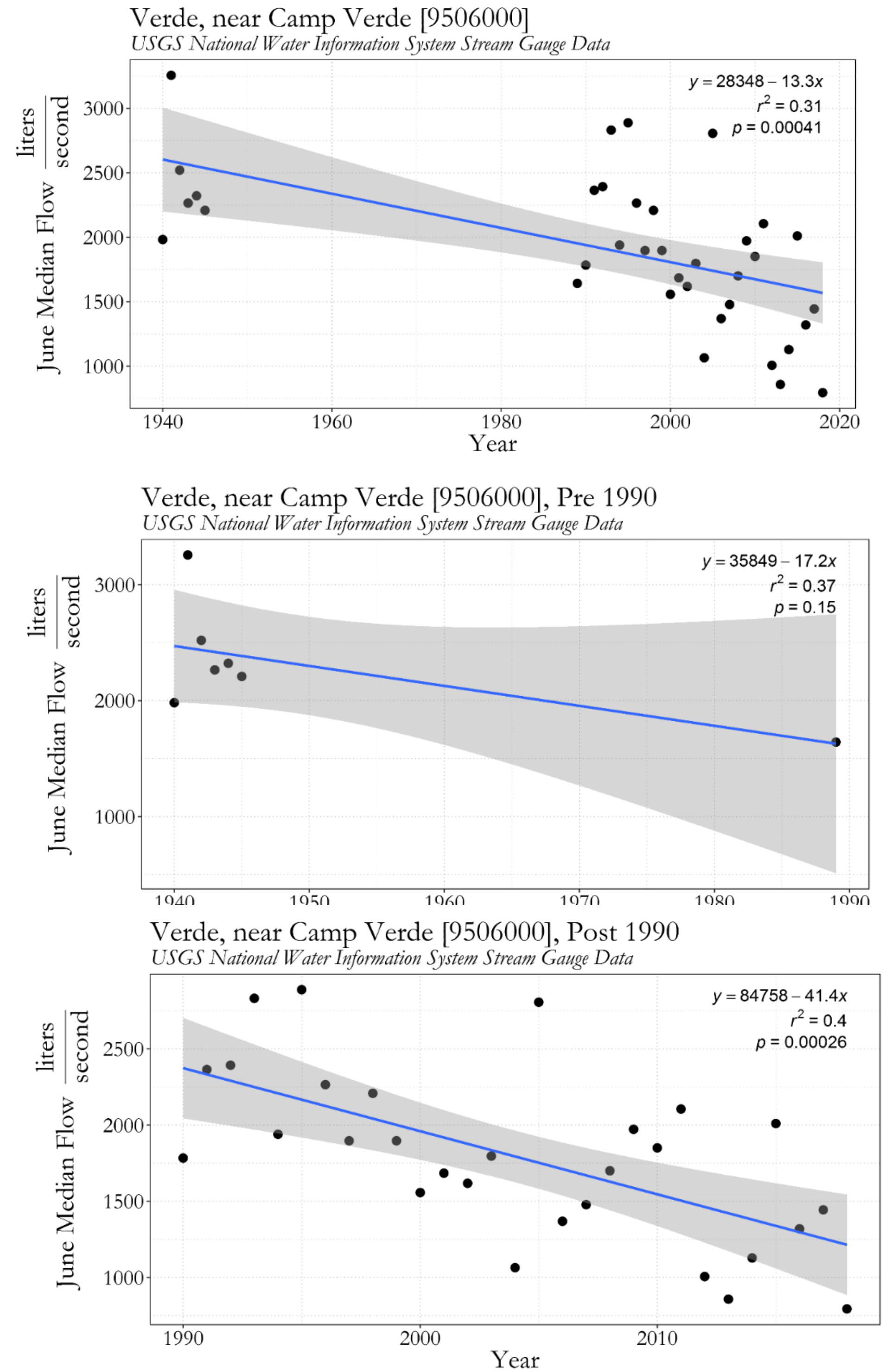
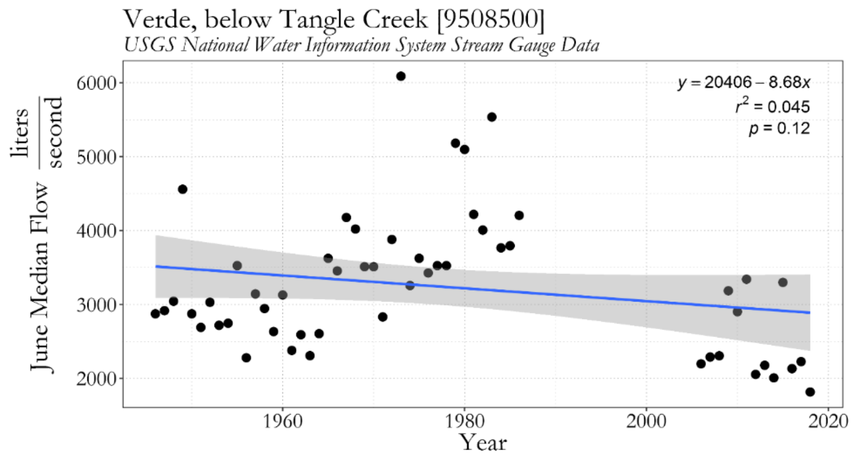
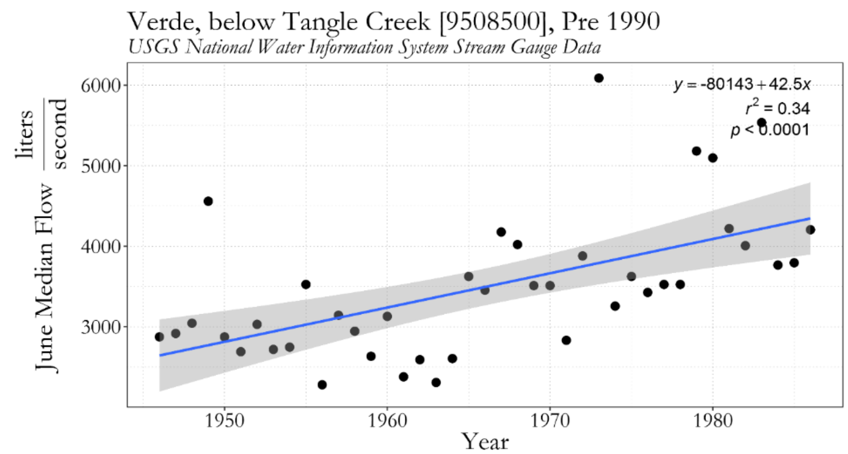


Fig. 22. June median flows (approximating baseflow) in the Verde River near Camp Verde. Top – The period of record; Middle - Pre-1990 ; Bottom - Post-1990. Note the statistically significant decline in flow over the period of record, with a decrease of over 1000 L/sec since 1990.





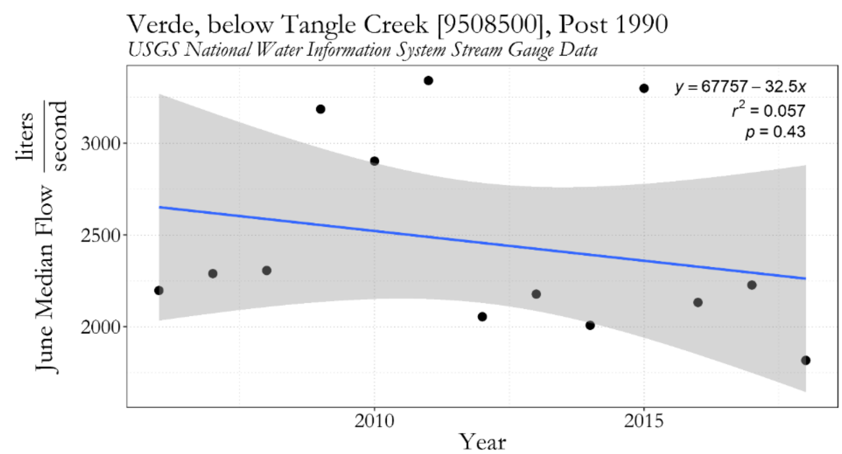


Fig. 23. June median flows (approximating baseflow) in the lower Verde River near Tangle Creek. Top - The period of record; Middle - Pre-1990; Bottom - Post-1990. The decline in baseflow is not statistically significant ($p = 0.10$), but still shows a general decline in baseflow for the lower portion of the Verde River since 1990.

Springs Geomorphology – Spheres of Discharge

Springs Online inventory data include the emergence environment for 255 VRB springs. Springs can be categorized based on 12 distinct emergence environments termed "spheres of discharge" (Springer and Stevens 2009). Each sphere of discharge has a characteristic geomorphology (Fig 24, 25). For example, "hanging gardens" are springs that occur on vertical or overhanging cliffs and usually consist of linear drip lines along a geologic contact. This is in contrast to hillslope springs that occur on sloped surfaces and emerge either from a geologic contact, a fracture, a fault, or a seepage area. Understanding the sphere of discharge for individual springs is helpful for springs ecosystem assessment, restoration, and protection.

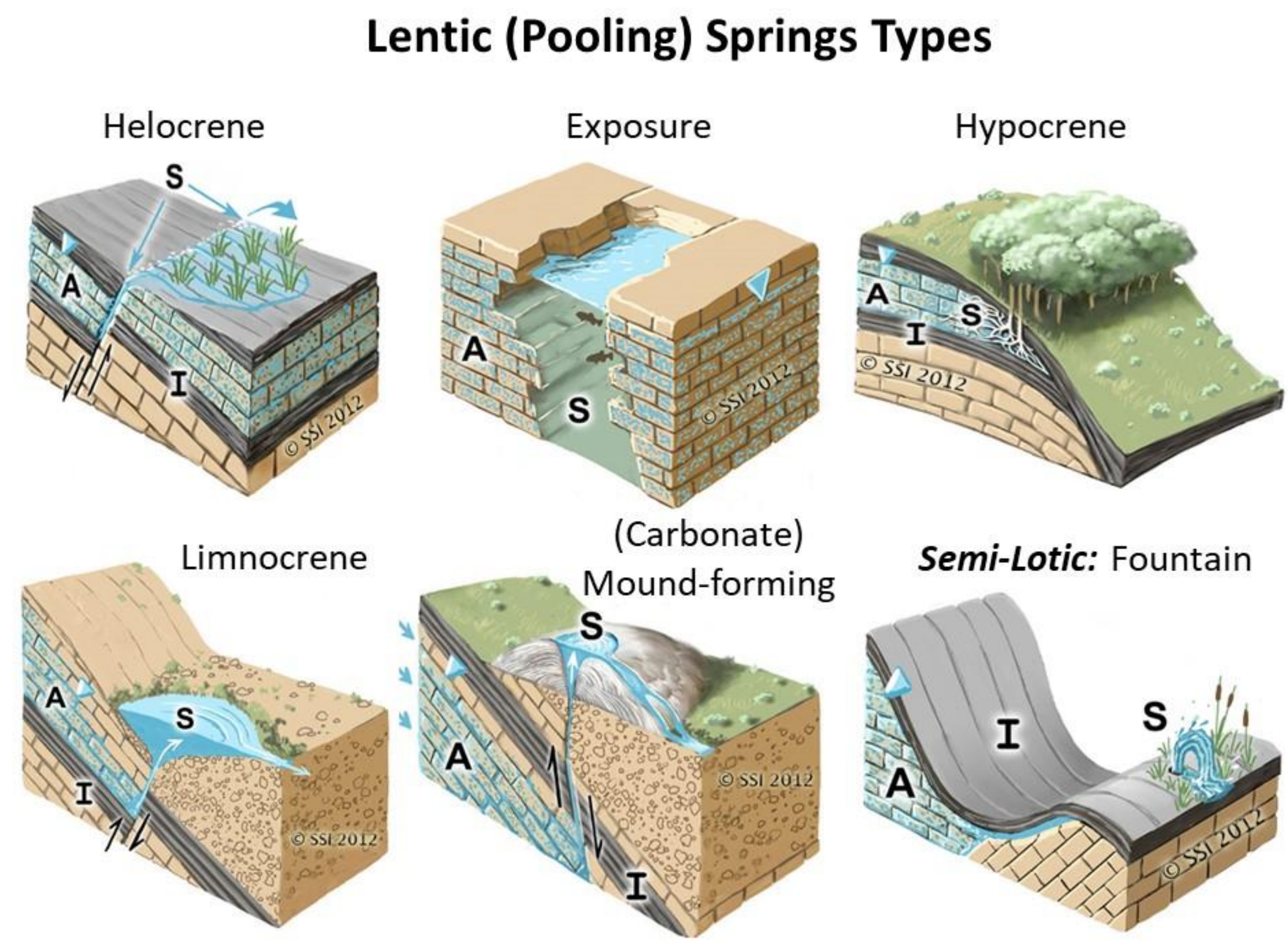


Fig. 24. Lentic (non-flowing) springs types from Springer and Stevens (2009). The "A" stands for aquifer, "S" for springs source, and "I" for the impervious aquitard layer. More information can be found at SpringStewardshipInstitute.org

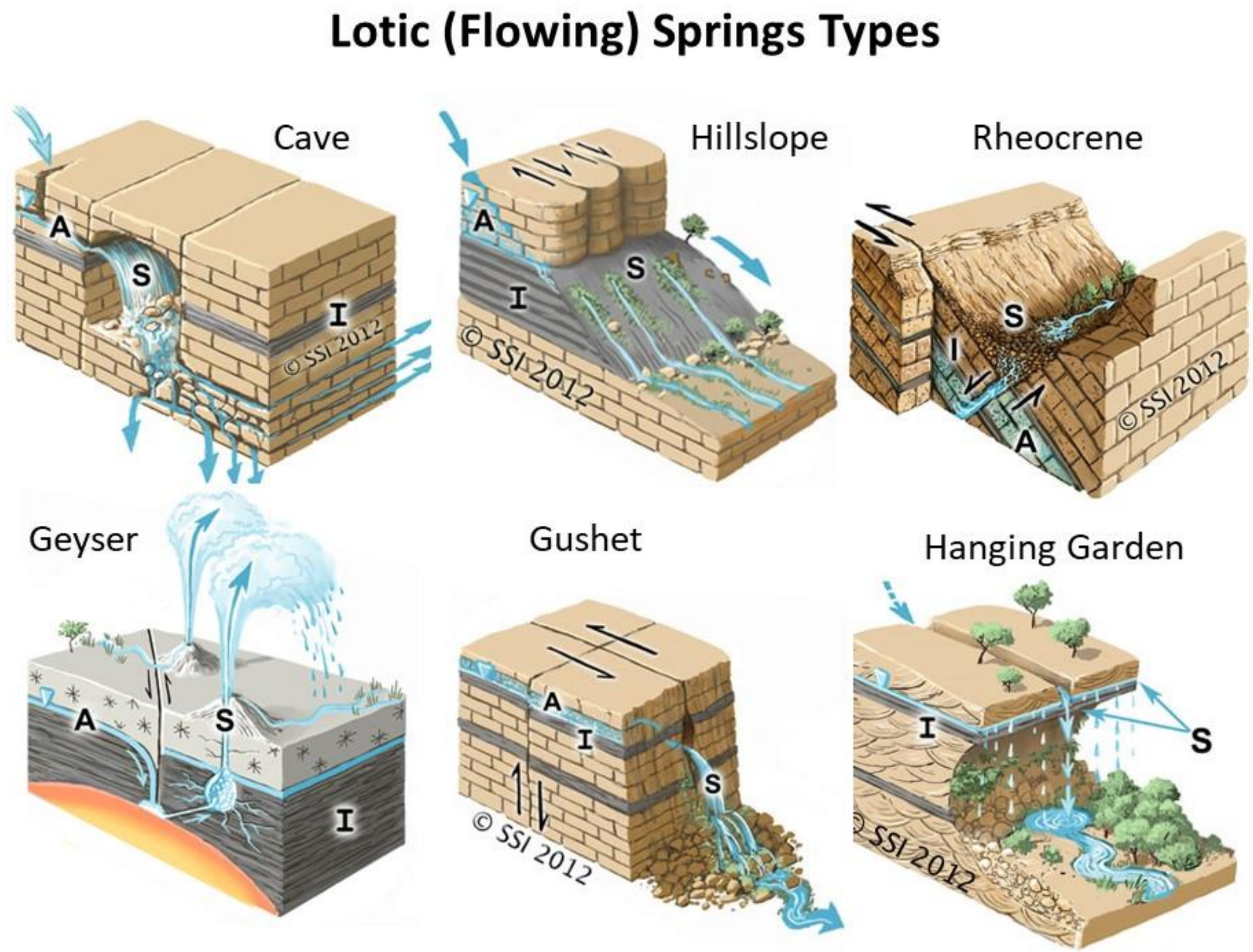


Fig. 25. Lotic (flowing) springs types from Springer and Stevens (2009). The "A" stands for aquifer, "S" for springs source, and "I" for the impervious aquitard layer. More information can be found at SpringStewardshipInstitute.org

Ten of the 12 globally recognized springs types occur in the VRB, with only geyser and fountains not found, but including several anthropogenic springs types, such as excavated ponds (anthropogenic limnocrenes; Table 2). Anthropogenic springs are water sources that emerge due to human development, such as livestock water tanks and troughs, and canals. Also, there are only a few reported paleosprings (Pleistocene or early Holocene springs that no longer flow) in the VRB, but more are to be expected in and around the Pliocene Verde Formation.

The VRB assemblage of springs is strongly dominated by rheocrene springs (45%) that emerge in established channels. For example, Parsons Spring in Sycamore Creek Wilderness Area provides most of the baseflow to that stream. Parsons Spring emerges over a distance of about 50 m, approximately 6 km upstream from the creek's confluence with the Verde River. Hillslope springs also are abundant, making up 23%

of the inventoried springs thus far, but are only slightly more common than are helocrene wet meadow springs (19%). Further effort to distinguish floodplain from uplands hillslope springs may assist with identification of sites that support springs-dependent species. Other springs types are rare, with only 5% of Verde River watershed springs occurring as pool-forming limnocrenes, although those that have been studied have elevated levels of endemic invertebrate species (Blinn 2008). Based on current level of knowledge, cave, exposure, gushet, hanging garden, and hypocrene springs types are relatively rare in the VRB (Table 2).

Table 2 Summary of spheres of discharge expressed by springs in the Verde River watershed. Percent of total only reflects those springs for which there is spring type information (255 of 945 potential springs).

Springs Type	Number	Percent of total
Rheocrene	114	45
Hillslope	59	23
Helocrene	49	19
Limnocrene	13	5
Anthropogenic	9	4
Gushet	3	1
Cave	2	1
Hanging garden	2	1
Hypocrene	2	1
Exposure	1	0.4
Mound	1	0.4
Total Inventoried	255	100

Springs-dependent Species (SDS)

Overview: Springs of the Verde River watershed support a wide array of wetland and upland plant and animal species. However, because May-June flows are almost or are entirely derived from springs, the aquatic species of the VRB are nearly all springs-dependent. Thus far, a total of 147 species of plants have been detected in the 133 springs surveyed thus far, and SSI has documented >100 invertebrate species and 129 vertebrate species through those surveys. Nonetheless, only a small proportion (<15%) of the springs in the VRB have been inventoried, and very few springs are monitored, making it difficult to provide a condition baseline assessment or to detect changes in individual springs assemblages due to anthropogenic environmental changes. Therefore, much remains to be learned about the relationship between springs and biodiversity in the VRB.

SDS Flora: Springs-dependent species (SDS) in the VRB are known from numerous taxon-based studies and inventories (Table 3). Data from 55 floristic inventories of springs and expert knowledge of Verde Valley plant assemblage has revealed only a few rare SDS plant species, and no endemic SDS plants. One unusual species is Smooth Beggartick or Burmarigold (*Bidens laevis*: Asteraceae), an aquatic composite that is relatively common in the southeastern USA and in the Los Angeles area in California, but which occurs in the Southwest at only a few springs and along a few river shorelines. One VRB population occurs at Del Rio Springs north of Chino Valley. Another unusual SDS plant species is Helleborine Orchid (Orchidaceae: *Epipactis gigantea*; Fig. 26). While the range of this species extends throughout the Intermountain West, it typically only occurs at springs, so its actual habitat area is extremely small. Other SDS of plants include: Beautiful Spikerush *(Eleocharis bella)*, Golden Columbine (*Aquilegia chrysantha*), Hairy Waterclover (*Marsilea vestita*), and Nebraska sedge (*Carex nebrascensis)*, as well as other herbs and gramminoids.

Fig. 26. Helleborine orchid (Orchidaceae: *Epipactus gigantea*), photo from Wikimedia Commons, accessed April 2018.

Macroinvertebrates: Macroinvertebrate inventories have revealed a large number of unusual, rare, and endemic SDS of macroinvertebrates, detected at more 65 VRB springs, and other data have been compiled from an array of studies on individual taxa.

- ***Leeches (Hirudinida):*** Several species of leeches have been identified in the VRB, including the endemic erpotobdellid *Motobdella montezumensis*, a genus and species known only from Montezuma Well. A population of the glossiphonid *Helobdella stagnalis* and *Glossiphonia* nr. *elongata* also occur in Montezuma Well.
- ***Aquatic Snails (Mollusca: Gastropoda):*** At least three endemic hydrobiid springsnails have been reported in the Verde Valley: Brown Springsnail (*Pyrgulopsis sola*), Montezuma Well Springsnail (*Pyrgulopsis montezumensis*), and Page Springsnail (*Pyrgulopsis morrisoni*). These species are or were found only at or immediately around their springs type localities. The status of the first species is uncertain.
- ***Crustacea:*** Amphipoda: The hyallelid scud, *Hyallela montezuma* occurs only in Montezuma Well, and the *Hyallela azteca* population there may also be another unique taxon. In addition, the cyclopid zooplankter, *Tropocyclops prasinus* mexicanus also appears to be a rare SDS taxon.
- ***Ephemeroptera (Mayflies):*** While many mayfly species occur in the VRB, most are widespread and/or not springs-dependent. However, *Moribaetis mimbresaurus* (Baetidae) is found only at 2-3 springs in the headwaters of Oak Creek, and is the only representative of this South American genus in USA.
- ***Odonata (Dragonflies and Damselflies):*** A recent survey of VRB dragonflies recognized 57 species, most of which are widespread and catholic in habitat preference (Stevens and Bailowitz 2009; R.A. Bailowitz, written communication). However, several SDS Odonata occur in the VRB, including: Apache Spiketail (Cordulegastridae: *Cordulegaster diadema*), which oviposits at springs sources in upper Oak Creek; several *Argia* dancer species that occur primarily along springbrooks, including Amethyst, Aztec, Dusky, Fiery-eyed, Lavender, Springwater, and Violet Dancers (*Argia pallens, A. nahuana, A. translata, A. oenea, A. hinei, A. plana, A. fumipennis*, respectively). In addition, Pima Dancer damselflies (*Argia pima*) are found in the springfed upper Wet Beaver Creek, representing a range extension and the furthest north locality for this species. Persephone's Darner (Aeshnidae: *Aeshna persephone*) is a large dragonfly species that prefers wooded, desert canyon springfed stream habitats. It has been recognized as a species of management concern for Coconino National Forest, but its population status remains uncertain in the VRB headwaters.
- ***Aquatic and Semi-aquatic Hemiptera (ASH):*** Based on the compendium by Stevens and Polhemus (2008), many predaceous ASH species occur in the VRB, and many are SDS. A total of 59 ASH have been reported from the Verde Valley. Two endemic SDS are known, including Montezuma Well Water-scorpion

(Nepidae: *Ranatra montezuma*) and the saldid shorebug, *Rupisalda saxicola*). Among the rare SDS in the VRB are: *Belostoma bakeri* (Belostomatidae), *Buenoa scimitar* (Notonectidae), *Hebrus majo* (Hebridae), and *Microvelia glabrosulcata* (Veliidae). In addition, Stevens and Polhemus (2008) noted that the Verde Valley supports about 40% of Arizona's ASH diversity, most of which occur at springs and in springbrooks.

- ***Beetles (Coleoptera):*** Only a single endemic SDS beetle is known from the VRB. The aquatic elmid beetle, *Huleechius marroni* is found only at Tonto Bridge Lower Spring in the East Verde drainage. Several rare SDS have been reported at VRB springs, including the hydrophilids *Anacaena signaticollis*, *Crenitulus debilis,* and *Laccobius ellipticus*, as well as the large dytiscid, *Cybister fimbriolatus*. Largely unstudied in the VRB, several terrestrial riparian beetle taxa are likely to occur and may be of management concern. Carabid ground beetles in the genus *Nebria* are particularly prone to endemism in the Intermountain West, and more intensive investigation of that genus in the VRB may be expected to yield new taxa.
- ***Dobsonflies (Megaloptera):*** While the Teax Dobsonfly (Corydalidae: *Corydalus texanus*, is common both at springs and in the Verde River and its tributaries, the higher elevation *Neohermes filicornis*, which has been collected at Parsons Spring in Sycamore Creek is uncertain.
- ***True Flies (Diptera):*** Many aquatic and semi-aquatic flies exist in the VRB, but collections in the basin thus far have been insufficient to recognize the likely many rare and unique species found there.
- ***Caddisflies (Trichoptera):*** Oak Creek is renowned for supporting the greatest diversity of caddisflies of any stream of its size in the Southwest. Blinn and Ruiter (2009) documented 58 species among 30 genera and 16 families there. While most taxa are not restricted to springs, the flow of Oak Creek is largely dependent on headwater springs, and therefore the habitat for these taxa is dependent on springs. Of those reported in the Verde Valley, *Metrichia arizonensis is endemic to springfed Fossil Creek, and M. nigritta* is tightly restricted to springs in Fossil Creek and Montezuma Well.
- ***Moths and Butterflies (Lepidoptera):*** Two newly described species of crambid aquatic moths (*Petrophila anna* and *P. cornvillia*) were recently described from the springflow-dominated Oak Creek (Solis and Tuskes 2018). The larvae feed on aquatic vegetation, and the adults are encountered along stream margins.

Fish

At least 13, and perhaps as many as 16 species of native fish formerly occurred in the VRB (Stevens et al. 2008), of which several likely were at least partially SDS. Seven of the eight cyprinid species, including *Agosia, Gila, Meda, Rhinichthys*, and *Tiaroga* minnows may have used springs directly. Although poorly studied, many freshwater fish species may imprint on distinctive springs water quality and rely on springs for identifying spawning sites. The VRB native fish fauna is in extreme decline, with only a few species remaining in the headwaters reaches. At least 30 non-native game, bait, and nuisance fish species have replaced the native taxa and now are numerically and biomass dominants in the VRB. Exotic fish taxa include a wide array of piscivorous and highly competitive species.

Herpetofauna

Stevens et al. (2008) reported at least 56 amphibian and reptile taxa in the VRB, of which four of the six amphibians, the single native turtle, and at least two snake species are considered to be at least weakly SDS. While *Lithobates* and *Hyla* frogs tend to disperse widely, their breeding often is focused on springs-supported wet meadows and ponds. Sonoran mud turtles (*Kinosternon*) are riverine, but individuals regularly move into Montezuma Well to breed. Two *Thamnophis* garter snake species (*T. rufipunctatus* and *T. eques*) occupy springbrook habitats, and a third species (*T. elegans*) is commonly encountered in headwater springs and springfed wet meadows in the VRB.

Birds

While the avian diversity of the Verde Valley is nationally renowned and sufficiently large to annually attract springtime festivals of bird watchers, the only truly springs-dependent bird species in the VRB is the American Dipper (Cinclidae: *Cinclus mexicanus*), which makes a nest of moss behind springfed waterfalls.

Mammals

A number of aquatic and wetland mammals occur or formerly occurredin the Verde Valley. Montezuma Well is the type locality for the Sonoran River Otter (*Lutra canadensis sonora*), the now-extinct endemic Colorado River subspecies. However, neither otter, beaver, or muskrats can be regarded as SDS.

Discussion

Much attention has been paid to the Verde River over the last five decades. The river is one of only a handful of large perennial rivers in Arizona, and is gravely imperiled by water withdrawals for agriculture and the growing human population of the Verde Valley, Prescott, Sedona, and Flagstaff areas (Haney et al. 2008; Garner et al. 2013; VRBP 2015). The Verde Valley currently has an Arizona Active Management Area that encompasses the tri-city area around Prescott, a state designation intended (but unsuccessful) to protect groundwater from over use (www.azwater.gov). Springs are the surface expression of groundwater, and are therefore readily impacted by groundwater withdrawal and contamination (Winter et al. 1998; Stevens and Meretsky 2008). The inventory and monitoring of springs flow, water quality, and ecosystem health is still rare, however, partly due their unique location on the landscape at the fringe of both the surface water and groundwater regulatory environment. Springs still garner little regulatory, funding, or research attention despite the fact that springs ecosystems harbor over an order of magnitude more biodiversity than upland Arizona habitat, are the sources of all perennial streams in the state, and can provide an assessment of aquifer health and function (Stevens and Meretsky 2008; Giardina 2012; Stevens et al. 2016a).

Several popular and well-known springs ecosystems exist in the VRB, including Montezuma Well, Parsons Spring (lower Sycamore Creek), the springs complexes of Fossil Creek, and the Verde Hot Springs near Childs, AZ. These springs serve not only as critical ecosystems in otherwise arid landscapes but also as drinking supplies and well known recreational areas. A recent study found that, when asked, Americans valued springs as one of the most important resources in the Grand Canyon region (Mueller et al. 2017). The recreational values of the Verde Hot Springs, Fossil Creek, Montezuma Well, and other springs sites within the Verde River watershed have not been quantified, but likely are substantial. Continued water withdrawals will degrade these springs in the VRB. Of equal, if not greater, concern is the impact of water withdrawal and climate change on less well known springs ecosystems. The VRB may contain >900 springs, many of which are small and easily damaged or destroyed with little notice. Routine and regular monitoring, inventorying, and assessment of a representative set of springs should help catch impacts to these special ecosystems before they become too severe to restore or remediate. For example, the impact of water withdrawals from new wells on nearby springs could be documented and provided to the State and County for future decision-making and aquifer protection. The stream flow analysis provided in this document is a good first start for determining long term impacts of water use and climate change, however, these stream gauges are often not near springs sources, meaning that interpretation can be influenced by surface processes. The implementation of continuous flow monitors at a representative set of springs may provide an early warning system for aquifer impairment, but such monitoring data are rare. The majority of continuous data is collected at stream gauge sites, which may provide some insight into aquifer functionality but can also be influenced by surface water diversions, rainfall runoff, and human effluent inflows. Without regular and routine springs and groundwater monitoring there would be no documentation of deteriorating springs flow and/or impacts to the ecosystem. This is just one example of the importance of regular and routine monitoring, inventorying, and assessment. There are virtually no limits to the benefits of having robust, defensible datasets that can support springs, water, and biological stewardship, especially in an imperiled watershed like the Verde River.

Long-term stream gauge records indicate that changing climate is having an impact on spring dominated tributaries (see Figs. 13-16). The earlier snowmelt peak flows are similar to trends found near the Grand Canyon (Schenk 2018) and support the findings of climate models that indicate that high elevation areas of the Southwest will likely change from a snow dominated winter precipitation cycle to rain (Mote et al. 2005; Cayan et al. 2013). The loss of snowpack is worrisome as the majority of groundwater recharge occurs due to snowmelt. Summer monsoons and rain events tend to provide extremely short term surface water runoff and do not contribute much to the long-term water availability. Drought and changing climate has already been attributed to the loss of some small volume springs in the nearby Grand Canyon (Tobin et al. 2018) and is likely impacting springs in the Verde River watershed as well.

The baseflow of the Verde River has been impacted by water diversions and wells (as described in Wirt 2005a; Leake and Poole 2010; Nelson and Yunker, 2014; VRBP 2015; and others). A full discussion of the influence of wells on the main stem Verde River is beyond the scope of this limited report. There have been several synthesis papers on the topic, however, including the Verde River Basin Water-Resources Primer (VRBP 2015), the USGS synthesis on upper and middle Verde River hydrogeology (Blasch et al. 2006), and the Arizona Department of Water Resources review of the Verde River watershed (ADWR 2000), to name just a few. There are also several academic journal articles that discuss the impact of groundwater withdrawals on springs and surface water, both Verde River specific and in a more regional setting (e.g. Leake and Pool 2010; Marshall et al. 2010; Garner et al. 2013; Smith 2013).

The analyses of the June median flow data at a series of USGS stream gauges presented in this report, show through long-term unbiased datasets what has already been predicted, modeled, or observed in other hydrologic syntheses. Consistent long-term trends of diminishing baseflow portend a grave future for the VRB because they show little to no positive effect of the last two decades of research, outreach, and policy concern. Continual reduction in groundwater inputs will likely lead to the dewatering of many small springs, and habitat contraction or loss of larger springs ecosystems. Previous baseflow studies have focused primarily in the upper Verde River where the loss of perennial water in the main stem is obvious (e.g. Wirt and Hjalmarson 2000; Wirt 2005a,b; Blasch et al. 2006). The reduction in flow downstream (as shown in Figs. 17 through 23) show that the trend is widespread and not unique to Prescott and Chino Valley water use. The persistent drop in baseflow throughout the river system is worrisome since the Verde River relies on increasing amounts of baseflow with distance downstream. Two synoptic river float trips were conducted in 2007 and 2011, both showing a gradual increase in baseflow contribution to the river from Clarkdale, AZ to 50 river miles downstream (Garner and Bills 2012). The widespread loss of groundwater contributions to the river means that ecological impacts of reduced water availability may occur at multiple springs and tributaries at a time. Responding to widespread de-watering is much more difficult than identifying and remediating point source issues.

Table 3 summarizes the results of this report in terms of baseflow loss and compares the observed reductions in baseflow to modelled reductions using the Northern Arizona Groundwater Flow Model. The modeled prediction for 2010 to 2019 are under the unchanged human stress model run (Garner et al. 2013; VRBP 2015). The statistical regression estimates from this report estimate a greater loss of baseflow per year at both Clarkdale and Camp Verde compared to the regional groundwater flow model. Future losses may accelerate due to increased population and agricultural pressure and/or potential lag in the response time of springs to human stressors.

Table 3. Calculated annual additional (compounding) baseflow loss from the June streamflow regressions (Figs. 17-23), compared to the annual base flow reported in Garner et al. 2013 and the modeled baseflow reductions originally reported in Garner et al. 2013 and summarized in the Verde River Basin Water-Resources Primer (VRBP 2015).

				VRBP 2015	VRBP 2015
	This report			Table 7.1	Table 7.2
	Reduction in		Garner et al. 2013	**1991-2005**	**2010-2019**
	Acre-ft		**Average**	**Reduction in Acre-ft**	
	per yr		**annual base flow (Acre-ft)**	**per year**	
Wet Beaver Creek	13.3				
West Clear Creek	46.8				
Fossil Creek	261.5				
Verde River nr Paulden	57.5		16,000 - 21,700		
Verde River nr Clarkdale	192.8		40,000 - 60,000	67	60
Verde River nr Camp Verde	314.5		48,000 - 145,000	227	140

As of this writing is not possible to quantify with precision the relative influence of individual stressors on the aquifer and related springs flow. Climate change, as observed in the earlier snowmelt in Fig. 13 to 16, and drought, likely contribute to the lower base flow during the period of stream gauge records. Continued, and increasing, groundwater extractions are also likely decreasing the aquifer storage. All of these stressors can be quantified, however there is still some uncertainty to the response and residence times of the groundwater, especially for individual springs.

Groundwater, or aquifer, response time is defined as the time required for a response to be seen at a spring or well from an aquifer recharge or dewatering event. A response time may be the same as the residence time, the amount of time it takes for a particle of water to move through an aquifer, but in many cases may be different (see

Fetter 2001). An increase of water pressure, through precipitation or water additions, may push out old water through a spring or well; oftentimes, springs water is composed of a mixture of both young and old waters from local and longer-distance sources (e.g. Kazemi et al. 2006; McMahon et al. 2011). While “young” and “old” are relative terms, they general pertain to water that are a decade or two in the ground (young) versus old water that can take thousands of years, or longer, to travel through an aquifer (e.g., 13,300 yr at Montezuma Well). Fig. 27 provides a simplified diagram of potential groundwater pathways draining from the Colorado Plateau. Recent studies of stable isotopes in the Verde River watershed indicate that many springs are fed by a mix of young and old waters (Wirt and Hjalmarson 2000; Zlatos 2008; Springer et al. 2017). In the nearby Grand Canyon, also a part of the Colorado Plateau, evidence of both extremely fast (on the order of weeks) groundwater movement (Schindel 2015; Jones et al. 2017; Tobin et al. 2018) using water temperature, springs flow, and dye tracing, as well as evidence for some of the same springs of groundwater that is several thousands of years old (Pool et al. 2011; Beisner et al. 2017). The combination of several aquifers, several geological units, and water of different ages, makes it difficult to determine springs response to any one particular stressor (Huntoon 1995). The Verde River watershed is also complicated due to its position on the edge of both the Colorado Plateau and the Basin and Range province.

The VRB straddles the Colorado Plateau and Basin and Range physiographic provinces, a location that creates a complex watershed, which drains an array of geologic strata and perched aquifers. An analysis of springs draining the Colorado Plateau versus the Basin and Range (Table 1) indicates that Verde Basin springs draining the Basin and Range tend to be warmer, more mineralized, and more likely to be small, in terms of flow. The Verde watershed contains nearly every type of spring found on the Earth (Table 2) and serves as an important ecological transition zone between the higher elevation plateaus and mountains and the lower elevation Sonoran Desert. Springs sites in the Verde River watershed likely serve as oases for migratory animals moving between the high lands and the desert (and vice versa). The protection of springs as habitat is just as important as using springs as indicators of groundwater withdrawal and impacts to the surface river system. The unique, endemic, and rare species that rely on springs have only begun to be quantified by ecologists and biologists. Species loss is a valid concern in the VRB and elsewhere, where considerable pressure is being placed on groundwater availability and quality.

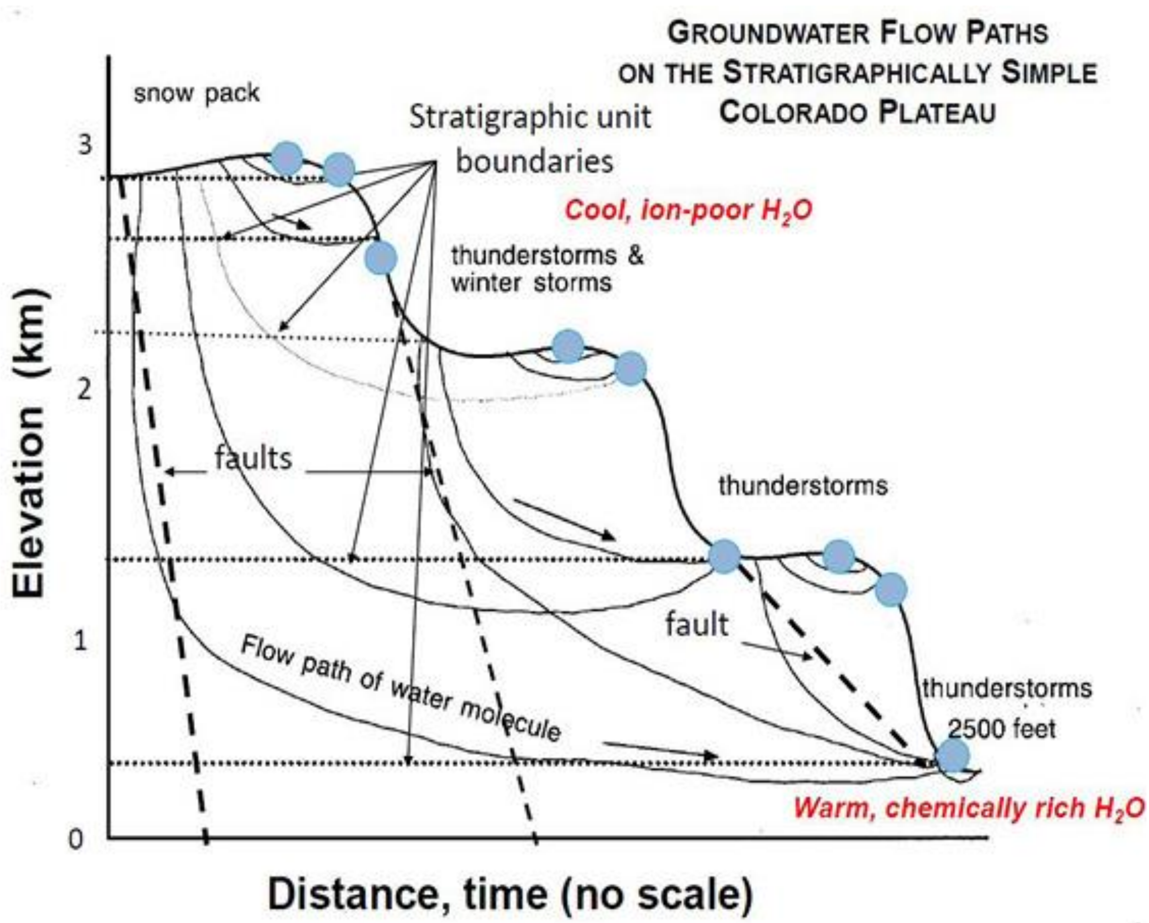


Fig. 27. Hypothetical groundwater flow paths and springs emergences (blue dots) in the Colorado Plateau. Figure from Stevens et al. 2016b, modified from Grand Canyons Wildland Council 2002.

Protecting springs ecosystems is likely much more cost effective than attempting to restore these ecosystem after the damage has been done. Case studies of springs restoration in Arizona show that individual springs require considerable amount of planning, permitting, stakeholder engagement, and funding to be successful (Stevens et al. 2016b). Once de-watered a spring may never recover, and the loss of organic soils, endemic plant and animal species, and microhabitat diversity may be irreversible. Trampling of springs sites by cattle, elk, humans, or other may also be difficult to remediate due to the damage to soil integrity and native plant and animal assemblages. In many cases springs rehabilitation (the management of a spring to obtain a certain threshold ecological utility) is more realistic than a restoration to pre-disturbance condition (Dufour and Piégay 2009; Stevens et al. 2016b). The Springs Stewardship Institute has assisted several agencies and organizations make decisions on appropriate and effective goals for springs ecosystem rehabilitation.

We hope this summary report focused on springs of the VRB will help focus future inventorying, monitoring, and assessment of springs to provide an early response to threats to the Verde River. The perennial springs of the Verde River are important for maintaining the river's baseflow, water quality, and riparian ecosystem.

Conclusions, Next Steps

As many as 945 springs ecosystems may exist in the VRB, of which approximately 700 have been verified as to location, and 133 have been subjected to flow, geochemistry, and biological inventory. Verde River springs provide multiple benefits to society and nature, including recreation, clean and abundant water, and ecological hotspots where plant and animal species abound. Results presented in this report indicate that springs provide up to 3850 L/sec of baseflow to the Verde River including providing perennial water to tributary creeks including Sycamore, Oak, Wet Beaver, West Clear, and Fossil Creeks, among others. The majority of flow emanates from springs on the North or East side of the valley derived from the regional R and C aquifers of the Colorado Plateau. Numerous small springs exist on the south side of the Verde River Valley and tend to be mineralized and warmer. These springs emanate from the Verde Formation or localized fractures in the south dipping R aquifer.

An analysis of USGS stream gauges indicates that springs are being stressed by climate change through earlier snowmelt conditions, and also by groundwater withdrawal. Reduction of baseflow is evident throughout the basin at both tributaries and the mainstream. The impact of increased groundwater withdrawal coupled with climate change is likely widespread across the watershed. Springs ecosystems will likely experience, or are experiencing, reduced flow that will reduce the size and diversity of individual ecosystems. Springs support a number of endemic and rare species as well as provide a food base for a substantial amount of upland species.

Following the results of this report, the Springs Stewardship Institute recommends a series of actions as budgets and personnel allow.

1) Continue to inventory and assess springs in under-represented areas of the Verde River watershed. These are identified in Fig. 3 and include areas north of Prescott, AZ and south of Payson, AZ.
2) Use the Northern Arizona Regional Groundwater Model and the distribution of springs in Springs Online to determine which springs are most likely to be impacted by future groundwater withdrawals.
3) Develop and implement a monitoring plan to continuously monitor flow and water quality at a subset of the most important and representative springs, including those that provide the perennial headwaters of the major Verde River

tributaries. While focusing on these larger springs, the monitoring effort also should include an array of representative smaller springs that are not being monitored.

4) Plan and restore springs affected by overgrazing, trampling, and localized water diversions to increase ecosystem resilience in the face of regional pressures (groundwater withdrawal and climate change). In many cases, such restoration projects are simple and inexpensive as fixing fencing, or building a stepping stone trail to provide access but limit hillslope erosion.
5) Revisit and monitor springs that already have been identified as supporting rare or endemic species. Conduct appropriate research to learn critical constraints on those populations, and monitor those springs at appropriate time intervals to determine and ensure the health and sustainability of those populations.
6) Inventory and list springs ecosystem loss in terms of area, microhabitats, soils, flora, and fauna to demonstrate to policy and regulatory agencies ecological damage.

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Appendices (provided as electronic links)

Appendix A: Springs Inventory Protocols.

Most recent field sheets and protocol instructions can be found online here: http://springstewardshipinstitute.org/protocols/.

Appendix B: Springs Ecosystem Assessment Protocols.

Most recent field sheets and protocol instructions can be found online here: http://springstewardshipinstitute.org/springs-1.

Appendix C: Springs Flow and Water Quality

Please see SpringsData.org, Verde River project data.