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MULTIDISCIPLINARY WORK TO DETERMINE HYDROLOGY OF ARID LAND SPRINGS AND HOW SPRING WATERS INFLUENCE WATER QUALITY AND ECOSYSTEM HEALTH FOR DESERT ENVIRONMENTS

Rebecca Jane Frus

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Rebecca Jane Frus
Candidate

Earth and Planetary Sciences
Department

This dissertation is approved, and it is acceptable in quality and form for publication:

Approved by the Dissertation Committee:

Dr. Laura J. Crossey, Chairperson

Dr. Clifford N. Dahm

Dr. Karl E. Karlstrom

Dr. Louis Scuderi

Dr. Gary Weissmann

MULTIDISCIPLINARY WORK TO DETERMINE HYDROLOGY OF ARID LAND SPRINGS AND HOW SPRING WATERS INFLUENCE WATER QUALITY AND ECOSYSTEM HEALTH FOR DESERT ENVIRONMENTS

By

Rebecca Jane Frus

B.S., Geological Sciences, Arizona State University, 2008
M.S., School of Earth and Space Exploration, Arizona State University, 2011

DISSERTATION

Submitted in Partial Fulfillment of the
Requirements for the Degree of

Doctor of Philosophy
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Albuquerque, New Mexico

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Dedication

I dedicate this work to my daughter, Elizabeth, and all of her girl cousins, Emma, Quincey, Parker, Elle, Kloey, Galilee, Sadie, Claire, Zoey, Violet, Penny and Juniper. In my youth there were no examples of women in science. I did not even know what science was when I started my undergraduate degree at the age of 29. A large part of the learning for my post-graduate education has been to understand the nature of science. I continue to learn more and more about what it means to be a scientist. I want all of the young girls in my family to know that they can do anything. That if they are interested, engaged and hardworking, they can have it all. They can be TRAIL BLAZERS! I also want to dedicate this work to my parents Bill and Rosemary Mathews for always expecting me to go to college, for supporting me when I quit a successful marketing career to pursue my education, and always telling me (and all of my brothers and sisters) that I was the smartest of their six kids.

Acknowledgments

I would like to acknowledge my advisor, Dr. Laura Crossey. I met Laura as I was finishing my master's degree and knew that I had found a mentor who would help me to understand the nature of science as well as celebrate being a woman and mother. I have appreciated her guidance, support and dedication to helping women and minorities find success in science. I also want to give special thanks to my husband and daughter, Adam and Elizabeth Frus. They have been the best field assistants, editors and cheer leaders! Special thanks for field and laboratory assistance including students from Earth and Planetary Sciences and Environmental Sciences at the University of New Mexico: Rebecca Wacker, Lauren Main, Chad W. Bryant, Pavel Vakhlamov, Chris McGibbon, Johanna Blake, Eric McKeage, Alexandra Priewisch, Alexander Nearson, Elizabeth Davis, Rachel Swatenson-Franz, Samuel Rhodes and Mariah Kelly; employees from the Forest Guild including, Eytan Krasilovsky and Matthew Piccarello; as well as volunteers from the Great Olds Broads for Wilderness including Susan Ostlie. In addition, I would like to thank other members of my committee who informed the work including Dr. Karl Karlstrom, Dr. Clifford Dahm, Dr. Louis Scuderi, Dr. Gary Weissmann, Dr. Rebecca Bixby, Dr. Ayesha Burdett, Dr. Gary Smith and Dr. Aurora Pun. Analyses were made with the help of Dr. Abdul-Mehdi Ali (Analytical Laboratory in the Department of Earth and Planetary Sciences), Dr. Viorel Atudordi and Dr. Laura Burkemper (Center for Stable Isotopes), and Dr. David Dettman (Environmental Isotope Lab). I would like to acknowledge the Cibola National Forest for financial, technical and logistical support. Specifically, I would like to thank Livia Crowley, Hydrologist for Cibola National Forest Supervisors Office for her mentorship and support of the work.

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Ph.D., Earth and Planetary Sciences, University of New Mexico, 2016

ABSTRACT

In the desert southwestern United States, water resources are stressed due to anthropogenic use, drought and climate change. Arid land spring sites are considered hotspots for biodiversity, providing refugia to aquatic habitats during dry seasons. To quantify the importance of desert land springs, this research applied an interdisciplinary approach to assess 78 springs of Cibola National Forest, New Mexico. Of specific importance are several springs that provide habitats for the endangered Zuni Bluehead Sucker (ZBS), Zuni Mountains, New Mexico. Inputs to the three remaining ZBS habitats include spring waters and shallow alluvium waters from stream channels upstream from spring discharge. This research used hydrogeochemical methods to determine flow paths, mixing scenarios, residence time and recharge mechanism for ground, surface and spring waters for the ZBS habitats. Continuous monitoring of physico-chemical parameters at the three ZBS habitats lead me to propose a water quality stability classification (WQSC) that differs upstream and downstream from spring inputs: 1) high WQSC (downstream from perennial spring), 2) medium WQSC (perennial waters upstream from spring) and 3) low WQSC (stream areas that dry). Sampling of biological communities showed that biodiversity varies with and may be influenced by the WQSC. Hydrogeochemical analysis indicate that springs are from confined regional and local aquifers. Isotopologues ($\delta^{18}O$, δD, ^{3}H) indicate that spring waters discharge from confined aquifers and are recharged primarily through snowmelt with a residence time greater than 70 years. In contrast, waters in the shallow alluvium are recharged from both snow and rain events. Geochemical mixing models explain seasonal inputs to ZBS habitats, where spring waters provide up to 99% of water during dry seasons. Continuous monitoring indicates that springs provide input of geochemically stable waters that maintain appropriate physico-chemical parameters (dissolved oxygen concentrations and specific conductance). In contrast medium WQSC areas become stagnant, anoxic and concentrated in ions. Areas with low WQSC dry completely. Biologic communities at different WQSC are significantly different from each other. Overall results show that springs of the Zuni Mountains are drying and those remaining are essential to water quality and biodiversity.

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Preface

The three chapters included in this dissertation are all independent works related to the common theme of spring water resources of Cibola National Forest and surrounding mountain areas. Each chapter is written as individual publications and therefore some materials will be repeated as necessary. Abstracts, introductions, site descriptions, methods, results, discussions and references are provided for each chapter. I conducted the majority of field and laboratory work found in each chapter. I was also the principle contributor on the writing and interpretation for each chapter. Each chapter has the collaborating coauthors listed and their specific contributions are detailed below.

Chapter 1 presents the hydrogeochemical and continuous monitoring data for a spring at Agua Remora (AR), Zuni Mountains, New Mexico. The spring at AR is one of three remaining habitats to the endangered Zuni Bluehead Sucker (ZBS) (*Catostomus discobolus yarrowi*). The ZBS have seen a 90% reduction in habitat and AR is considered critical habitat. At the spring site are three perennially wet pools, two are downstream from the spring discharge and one is upstream from the spring discharge. The pools below the spring discharge are able to support ZBS populations (fish), while the pool upstream from the spring is unable to maintain ZBS populations (fishless). Major ion concentrations and physico-chemical parameters indicate that the spring waters and the waters found in the fishless pool are from different sources. Geochemical mixing models were used to identify seasonal inputs into the fish habitats, where the spring provides as much as 99% of waters during dry seasons. Hydrogeochemical data were gathered on regional ground water aquifers and compared to waters found at the AR site. Regional hydrochemistry results indicate that the spring waters are a mixture of Triassic Chinle and Permian Abo (80/20) aquifers, while the fishless waters are from the shallow alluvium. Isotopologues ($\delta^{18}O$, δD) of AR ground and surface waters identified that the spring waters are recharged primarily through snowmelt while the fishless waters are recharged through both snow and rain events. Tritium (^{3}H) was also used to determine that the ground water at AR spring has a residence time of more than 70 years. Continuous monitoring of dissolved oxygen levels for the fish and fishless pool shows that the spring discharge provides reaerated waters to the fish pool, while the fishless pool becomes stagnant and anoxic. This work was used by the United States Fish and Wildlife Service (USFWS) to help determine that ZBS habitats are spring fed. This work is also important to the Forest Service as it provides understanding about flow paths, residence time, and recharge mechanisms for the spring at AR. Coauthors who contributed significant ideas, analytical facilities and assistance on the chapter include Laura Crossey, Clifford Dahm, Karl Karlstrom and Livia Crowley. Laura provided assistance with hydrochemical interpretations, Clifford contributed to understanding physico-chemical differences and help with the statistics, Karl provided invaluable feedback on geologic maps and cross sections and Livia gave priorities for the work and critical editing on the written section. I have submitted this paper to the journal Ecohydrology.

Chapter 2 of this dissertation presents continuous monitoring data of physico-chemical parameters and biological community differences at three ZBS habitats. Using physical and chemical parameters of specific conductance, dissolved oxygen and water temperature measured across seasonal variations we propose a water quality stability classification (WQSC). Areas downstream from springs have the highest WQSC with little changes to specific conductance and dissolved oxygen throughout the seasons. Waters characterized by medium WQSC become stagnant, increase in specific conductance due to evaporation and become anoxic in dry seasons. Low WQSC are found in areas that dry completely during the dry season. Sampling of aquatic biological communities along the WQSC shows that the three communities are significantly different from each other. The multidisciplinary approach was used to quantifying the hydrochemical differences within the WQSC and to understand aquatic biological communities' differences within the WQSC. This work will be used by USFS and USFWS to manage spring habitats and provides a WQSC that can be compared to other sensitive arid land locations. Rebecca Bixby supervised initial collection of biological samples. Rebecca Bixby and Ayesha Burdett significantly contributed to this manuscript by analyzing and interpreting biologic data as well as edits to the written manuscript. Louis Scuderi provided guidance on analysis and interpretation of statistical methods for continuous monitoring data. Laura Crossey and Clifford Dahm assisted in editing and refining the overall concept of the work. Journals that are being considered for submission of this manuscript include the Journal of Arid Lands.

Chapter 3 of this dissertation is a final report on the current state of springs within Cibola National Forest. The work was performed from 2012 to 2015 and included visits to the Zuni, Mount Taylor and Sandia Mountains. 78 springs were visited, with several springs being visited more than once. A spring assessment was performed for each spring including GPS location, geology, geomorphology, spring type and wetland habitats. Of the springs that were visited 46% were dry, with Mount Taylor springs having 67% dry, Zuni Mountain springs having 63% dry, and Sandia Mountain springs having 13% dry. For the springs that were wet, water samples were collected for hydrogeochemical analysis to determine flow path, residence time, recharge mechanisms and physico-chemical conditions. Results indicate that a majority of springs are from confined aquifers that are recharged primarily from snowmelt. These results, coupled with ongoing drought and climate change projections provide important information to the USFS on the current and probable future of spring flow on Forest Service lands. Coauthors including Laura Crossey and Karl Karlstrom contributed by introducing me to field and sampling protocols, assisted in prioritizing field work, guided interpretations and kept my spirits high. Livia Crowley contributed to the research by providing access to Forest Service data and materials, defined priority areas for the work and helped with edits. A final report will be printed and bound for Cibola National Forest.

Chapter 1: Desert Spring's Influence on the Habitat of the Endangered Zuni Bluehead Sucker (*Catostomus discobolus yarrowi)*

Authors: Frus, R.J., Crossey, L.J., Dahm, C.N., Karlstrom, K.E., Crowley, L.

Abstract

Located on the southeastern part of the Colorado Plateau, the Zuni Mountains are home to the endangered Zuni Bluehead Sucker (ZBS) (*Catostomus discobolus yarrowi*). The ZBS have seen a loss of more than 90% of habitat in large part due to the drying of surface waters. For four years hydrogeochemical analysis was performed at a perennial spring-fed habitat, Agua Remora (AR). Seasonal concentrations of Mg^{2+} are used to determine that spring waters ($spring_{ave}$=5.6 mg/l (s=0.4)) and upstream fishless surfaces waters ($fishless_{ave}$=10.7 mg/l (s=1.2)) are from different sources. The downstream fish pools (LFP_{ave}=7.4 mg/l (s=0.6)) are a mixture of these two water sources with the spring water contributing up to 99% during drier seasons. Stable isotopes (δD and $\delta^{18}O$) indicate that the spring is recharged primarily through snowmelt. The fishless pool is a mixed recharge of rain and snow. Continuous monitoring of dissolved oxygen (DO) concentrations ($fishless_{mean}$=1.599 mg/l and LFP_{mean}=5.742 mg/l) shows that the fishless site is a low oxygen water body unable to support ZBS. The LFP maintains appropriate DO concentrations due to discharging spring waters reaerating downstream habitats. Geochemical modeling and tritium results (^{3}H=1.5 TU) indicate spring waters are a mix of regional groundwaters and recharged over 70 years ago. Consequently, the spring waters at the Agua Remora site are necessary for the survival of the species. Actions to maintain water levels, where possible, will be necessary to maintain perennial flow from the hillslope spring.

Introduction

Persistent aridity in the 21st century (MacDonald, 2010) has caused available water in the semi-arid southwestern United States to decline, and not recover (Overpeck and Udall, 2010). As human population continues to grow and expand, urban, agricultural and rangeland areas continue to deplete water supplies that are already stressed (Zektser et al., 2005). Over pumping ground water supplies has led to significant drops in local and regional water tables, which has produced large sink holes and fissures that are found throughout the desert Southwest (Jacobs and Holway, 2004). The combination of these land management practices with severe drought and increasing air temperatures (Overpeck and Udall, 2010) has caused many springs of the Southwest to dry (Unmack and Minckley, 2008). Recently springs have been recognized by management agencies as important indicators of ground water sustainability. Baseline inventories of these resources are now being completed on some public lands to measure future impacts to ground water availability and habitats that depend on them (Springer and Stevens, 2009).

Spring waters sustain ecosystem habitats that concentrate and isolate unique species relative to the surrounding desert environment. Both ephemeral and perennial desert springs and resulting wetlands have been identified as biodiversity hotspots (Stevens and Meretsky, 2008a). These hotspots have been recognized by managers of public lands in the western U.S. including the Grand Canyon landscape where spring wetlands maintain 11% of the plant species but account for less than 0.01 percent of the area (Perla and Stevens, 2008). Ash Meadow National Wildlife Refuge also established minimum ground water levels at Devils Hole to support the spring-dependent pup fish (Minckley and Deacon, 1991; Minckley and Douglas, 1991). Outside of parklands, managers of public lands in the Sonoran Desert recognize that during dry months low flow springs and seeps can support both warm and cold water fish species (Pool and Olden, 2014). With the loss of surface water discharge from springs due to ground water use and drought conditions, desert fish and other species are at risk of losing critical habitat and possible extinction (Ruhí et al., 2014).

The Zuni Bluehead Sucker (ZBS) (*Catostomus discobolus yarrowi*) is a small (average length 200 mm) algae eating fish (Figure 2). ZBS is the only remaining species of Bluehead Sucker still found in the Zuni River. ZBS is federally listed as Endangered by the US. Fish and Wildlife Service (USFWS, 2014). This desert fish has only four populations remaining in the wild, all within the Zuni Mountains, New Mexico. One ZBS population is located on lands managed by the Cibola National Forest. The population is isolated to a 200 m stretch of perennial spring fed waters in Agua Remora (AR).

The goal of this paper is to characterize the importance of the spring discharge to the survival of the ZBS. We report on spatial and temporal hydrogeochemical processes of the ground and surface waters within the 200 m ZBS habitat. A multi-tracer approach (major ion chemistry, δD and δ18O, ^{3}H) is used to identify geologic and hydrologic controls at the site. Continuous monitoring of dissolved oxygen is gathered for understanding the spring waters impacts on the habitat. To help quantify AR seasonal variations in water quality and availability, recharge conditions, flow paths, and residence time were used. Information on the AR site and how spring waters contribute to critical habitat will help with management of ZBS and its habitat.

Study Area

We report here on a low-flow (<80 cm^3/sec) spring located on the Colorado Plateau in west-central New Mexico (Figure 1A), where perennial waters in an ephemeral stream have provided a refugia for ZBS. The Zuni River drainage is a tributary to the Little Colorado River (HUC6 150200) (Propst, 1999; Propst et al., 2008, 2001), with its headwaters in the Zuni Mountains, west of the Continental Divide. The area has seen a 90% reduction in ZBS habitat (Gido and Propst, 1999; USFWS, 2014) and populations are limited to four spring-fed sections of the Rio Nutria (Carman, 2004; Gilbert and Carman, 2013; Turner and Wilson, 2009; Unmack and Minckley, 2008). In 2014, the ZBS habitat was designated critical by the U.S. Fish and Wildlife Service due to habitat destruction, stream drying, predation by nonnative species, and small population sizes with restricted ranges (USFWS, 2014, 2013).

Located in the upper Rio Nutria, AR is an ephemeral stream with four perennially wet pools and a perennial hillslope spring (see Springer and Stevens, 2009) (Figure 1b). The AR spring has a grassy seep area that is 3 m higher and 6 m away (north) from the stream channel. The seep area has 2-4 small (<1 m) channels where spring waters emerge and flow into the stream channel. The largest of the seep channels is where water samples were collected and discharge was measured. The stream channel contains pools upstream (one) and downstream (three) from the area where the spring enters. The pools range in size (width 1-3 m x length 3-20 m, depth 0.2 – 2 m) but have similar geometries because they were dug by a backhoe to capture spring flow (Hunter-Lynn, 2013). The ZBS are only found in the section of the stream downstream from the spring discharge (Carman, 2004). The pool upstream from the spring discharge (Figure 1B, fishless) is unable to support fish populations, even if introduced (Carman, 2004; Gilbert and Carman, 2013).

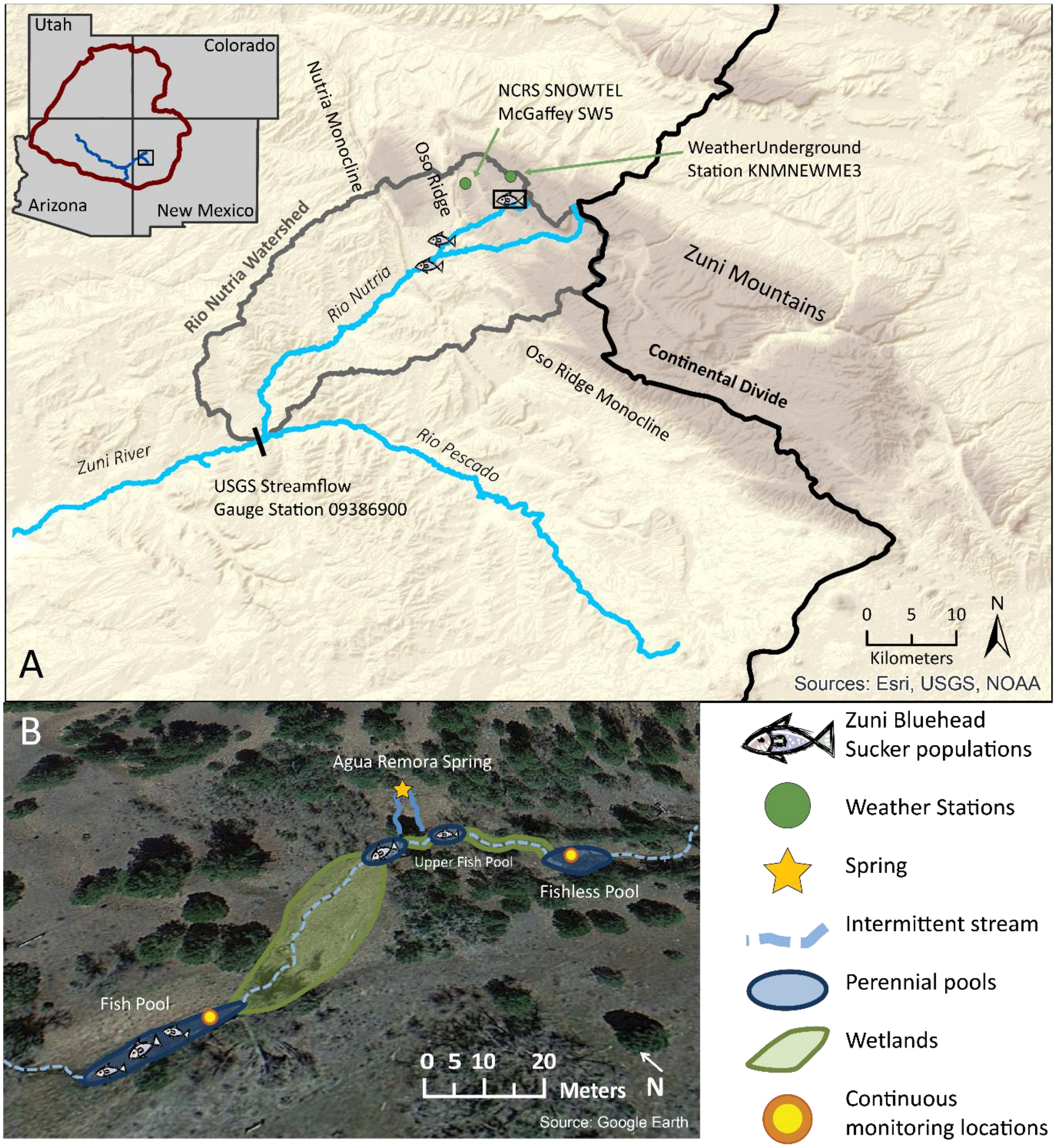


Figure 1. Maps of site. Inset. Southwestern USA 4-Corners region. Red indicates boundaries for the Colorado Plateau, blue is the Little Colorado River. A) Zuni Mountains and tributaries of the Zuni River with fish population locations. B) Agua Remora site with perennial spring (star) and perennial pools (blue), sample and continuous monitoring sites (circle).

Photo, New Mexico Game and Fish

Figure 2. Image of an adult Zuni Bluehead Sucker (*Catostomus discobolus yarrowi*).

The stream channel, including the pools, have bedding materials of grus (weathered granite) that are cobble and sand size. The sections of stream between the pools have surface water intermittently. Upstream from the spring discharge are granite boulders (0.5 – 1.5 m) in the stream channel, with a wetted perimeter no larger than 2-3 m wide. Downstream from the spring is a meadow (15 m wide) that is grassy year-round but has intermittent surface water in a small channel that runs along the northern edge. Downstream from the lowest pool the stream dries. All of the pools are shaded by large Ponderosa pine trees.

Climate

Annual precipitation (350mm) graphs in the region are typically bimodal, with recharge peaks occurring as snowfall (112 mm, 25% of annual) from January through March and as monsoonal rainfall (131 mm, 29% of annual) from August through September. Weather stations for the western Zuni Mountains have been recording daily precipitation measurements from 1949 to January 2014 by a National Weather Service volunteer (Figure 1A, MCGAFFEY 5 SE). In August 2014, daily precipitation values began to be recorded by a Forest Guild weather station (Figure 1A, KNMNEWME3). The weather stations are located within the higher elevations of the Rio Nutria watershed, within 5 km of the AR site.

The sources of precipitation events for the Zuni Mountains can vary with El Niño/Southern Oscillation (ENSO) being a driving factor for interannual variability (Giannini et al., 2001). Additionally, storms in the Gulf of Mexico can provide up to 30% of seasonal rainfall totals for New Mexico (Newton et al., 2012). In the Southwest, this variability has led to very wet periods of the early 20th century (Seager et al., 2005) as well as to the drought conditions of 1998-2002 (Hoerling and Kumar, 2003; Hoerling et al., 2014). Large rain and snow events are able to infiltrate shallow aquifers, but snow precipitation is the primary source for infiltration and recharge of confined aquifers of the desert Southwest (Anderson et al., 2003).

A USGS streamflow gauge station at Ramah (Figure 1a USGS Ramah 09386900) measures daily discharge on the Rio Nutria upstream of the Nutria Monocline. The streamflow gauge is located within the Rio Nutria watershed, 20 km downstream from the weather stations. The streamflow gauge an annual discharge average of 51.7 m^3/sec (USGS Ramah).

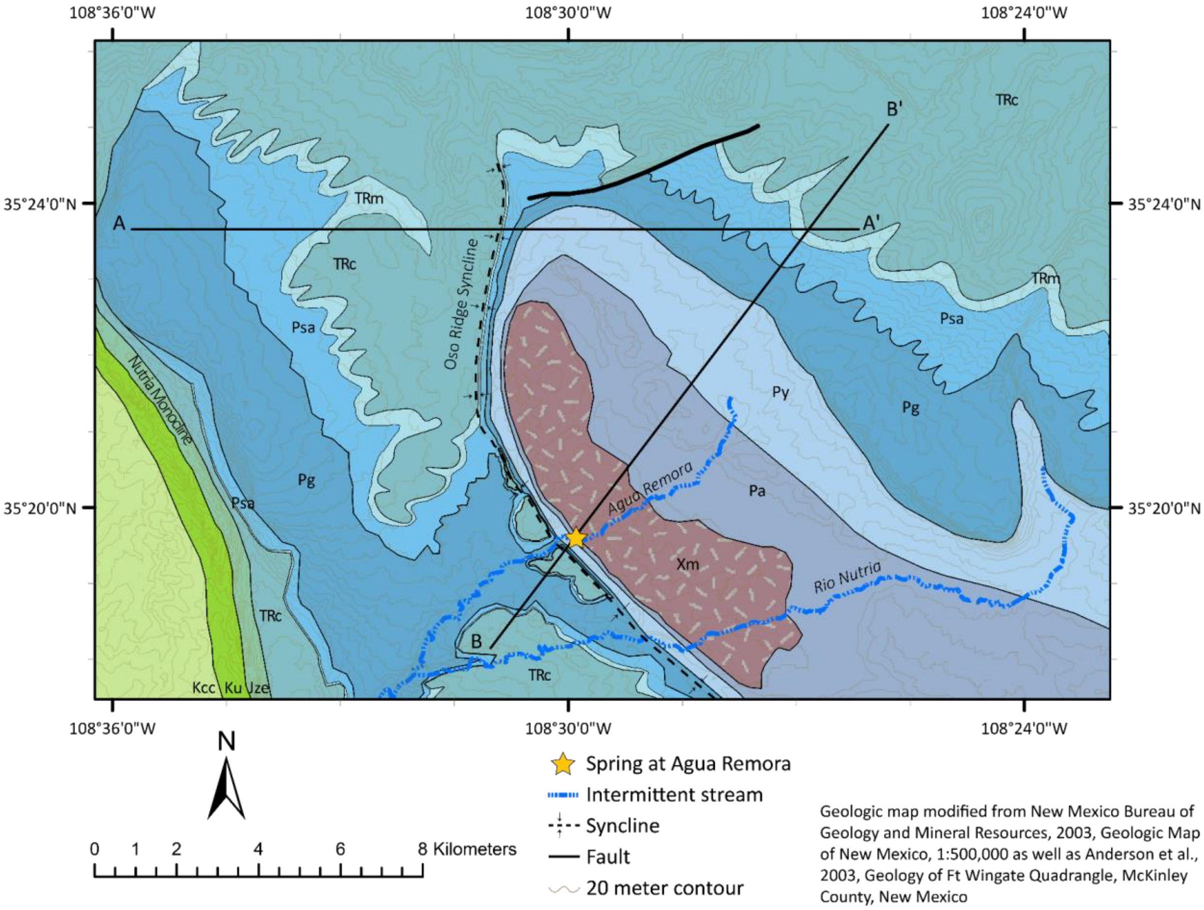
Hydrogeologic Setting

Water chemistry can be impacted by the geologic history of the rocks (Springer and Stevens, 2009; Wilson, 2004). Geologic structures, such as faults, can act as barriers and conduits to vertical groundwater flow (Apaydin, 2010; Banerjee et al., 2011; Connell, 2011; Crossey et al., 2006; Gudmundsson, 2000; Stevens and Meretsky, 2008a) and can allow for mixing of waters from different sources (Glynn and Plummer, 2005; Plummer et al., 2004). In areas with upwelling waters along fault zones, spring densities can be high in relation to adjacent non-faulted areas (Hubbs, 1995). Spring water chemistry can identify discrete hydrochemical zones (Banerjee et al., 2011; Crossey et al., 2009, 2006; Newell et al., 2005; Williams et al., 2013) making springs ideal indicators for mixing of ground waters from underlying geological structures (Manga, 1999, 1996).

The Zuni Mountains have a northwest-southeast trending core of uplifted basement rocks including 1655 Ma year old quartz monzonite (Xm) (Strickland et al., 2003). The Precambrian basement is overlain unconformably by Permian strata (Krainer et al., 2003) (Figure 3) indicating the Zuni Mountains were an uplifted region during the Pennsylvanian Ancestral Rocky Mountains. Additional deformation and fault movement took place during the Laramide orogeny about 70 Ma. The overall geometry of the Zuni uplift is a broad arch or domal anticline with steeply dipping bedding of monoclines along the northeast and southwest sides (Karlstrom et al., 1997; Kelley, 1967; Strickland et al., 2003). The steeply dipping limb of the southwestern monocline is Oso Ridge (Figure 3 and 4), which is primarily formed of thinned Permian rocks which dip as much as 75 degrees to the west (Anderson et al., 2003, 1998).

Geologic evidence indicates the Zuni Mountains have undergone repeated deformation and magmatism from the early Proterozoic through the Cenozoic times. The deformation of the bedding has created pathways for vertical movement of fluids along faults. The hydrogeology of the western Zuni Mountains reflects the complex geologic history of the area (Figures 3 and 4). As ground water flows through aquifers, the water chemistry can be altered by rock-water interactions (Crossey et al., 2009; Drever, 1982; Glynn and Plummer, 2005; Wilson, 2004) where older waters have more time to interact with lithology resulting in higher salinity and total dissolved solids (Phillips et al., 2013; Plummer et al., 2004) relative to rain water.

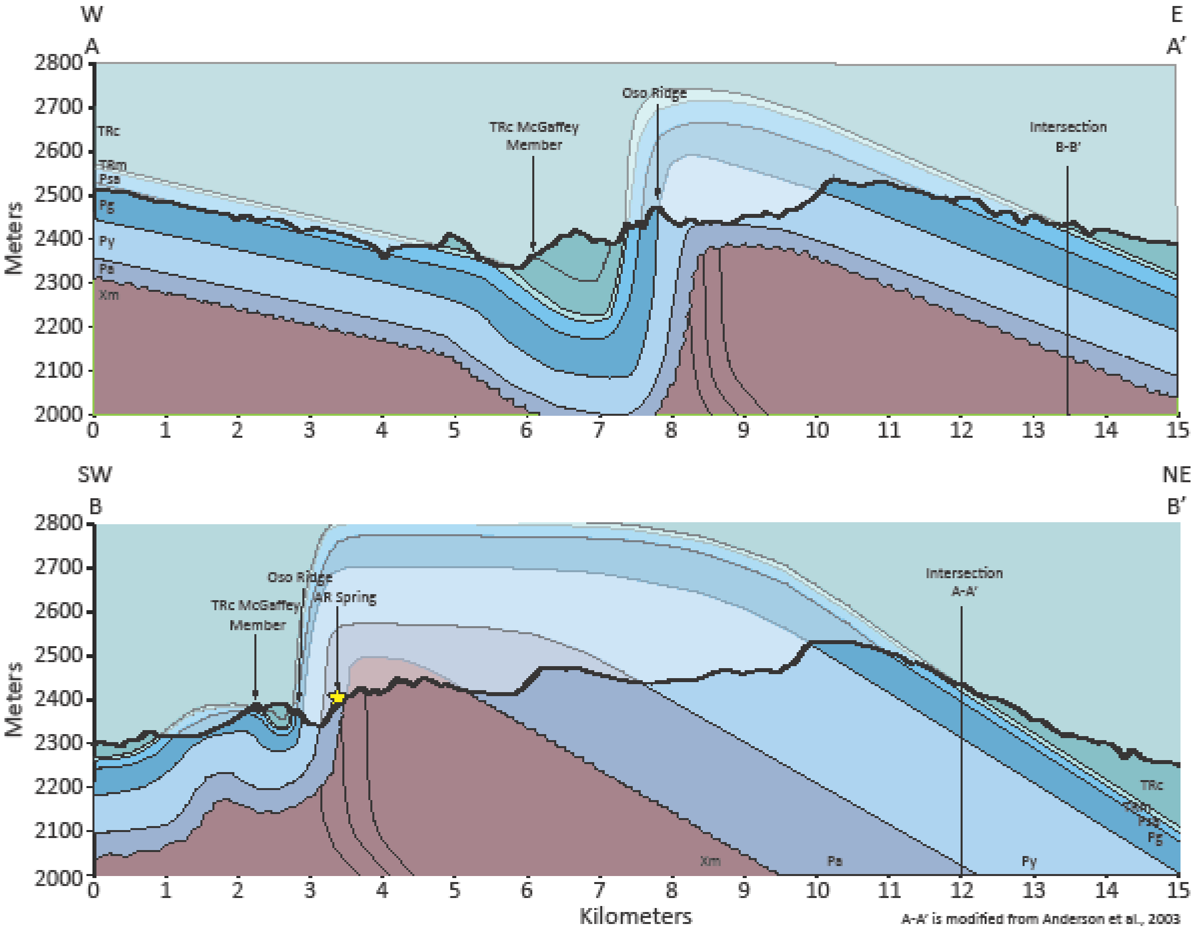
The Xm rocks are not considered a major ground water resource, except where fractured along fault zones or weathered along erosional unconformities. The Xm is locally overlain by Permian strata of the Abo Formation (Pa) (Figure 5).



Geologic map modified from New Mexico Bureau of Geology and Mineral Resources, 2003, Geologic Map of New Mexico, 1:500,000 as well as Anderson et al., 2003, Geology of Ft Wingate Quadrangle, McKinley County, New Mexico

Figure 3. Geologic map of Northern Zuni Mountains. Yellow star indicates spring at Agua Remora where ZBS population is found.

Regionally, Pa is 200 m thick consisting of mudstones, siltstones and sandstones (Anderson et al., 2003; Armstrong et al., 1994; Baars, 1974; Baldwin and Rankin, 1995; Colpitts, 1969). The Yeso Formation (Py) (200-300 m) conformably overlies Pa (Figure 5) and has a sandstone basal unit with large-scale cross-bedding and an upper member of interbedded reddish-colored siltstones, shales and sandstones with thin beds of limestone and evaporite (Anderson et al., 2003; Baars, 1974; Baldwin and Anderholm, 1992; Baldwin and Rankin, 1995; Connell, 2011). Both Pa and Py produce poor quality ground water due to low permeability and porosity, as well as high salinity due to the concentration of evaporites within each of the units (Baldwin and Rankin, 1995; Connell, 2011; Cooley et al., 1969; Hood and Kister, 1962).



A-A' is modified from Anderson et al., 2003

Figure 4. Cross sections of Zuni Mountains across Oso Ridge and AR spring site. Locations of A-A' and B-B' are shown on Figure 4.

In conformable contact with Py (Figure 5), the Glorieta Sandstone (Pg) is a white, fine-to medium grained, cross-bedded siliceous sandstone that regionally is up to 60 m thick (Anderson et al., 2003; Baars, 1974; Colpitts, 1969; Connell, 2011). Above Pg is the San Andres Formation (Psa). Psa is a 20-40 m thick fossiliferous gray limestone with interbedded sandstones (Anderson et al., 2003; Baars, 1974; Connell, 2011). The Psa and Pg are hydrologically connected (Psg) and is the most productive aquifer that provides the best water quality in the region (Anderson et al., 2003; Baars, 1974; Baldwin and Anderholm, 1992; Baldwin and Rankin, 1995; Colpitts, 1969; Connell, 2011; Robertson et al., 2013).

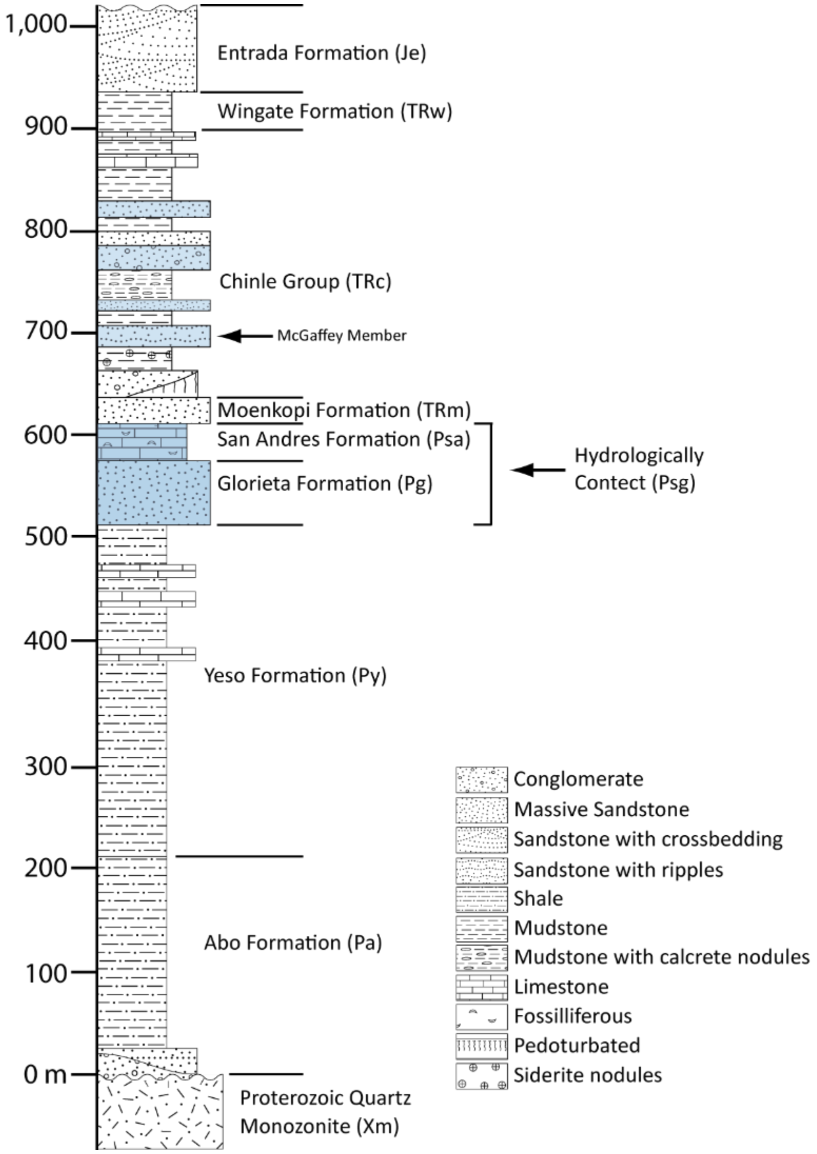


Figure 5. Stratigraphic column of the Zuni Mountains with hydrologically permeable layers in blue. Modified from Robertson et al., 2013.

Overlying the Permian strata locally is the Triassic Moenkopi (TRm) and Chinle Group (TRc). The Tm is relatively thin (<25 m thick) dark-red micaceous sandstones interbedded with mudstones and siltstones (Connell, 2011; Repenning et al., 1969) and considered a poor source for ground water (Cooley et al., 1969). The TRc can be as much as 600 m thick regionally and is dominated by mudstones and siltstones with some sandstones and carbonates (Heckert and Lucas, 2003). The different sections of the TRc are exposed at distinct locations throughout the western Zuni Mountains including the McGaffey Member, which is a white well-sorted sandstone that forms cliffs found near the AR site (Heckert and Lucas, 2003; Robertson et al., 2013). The different TRc sections are known to locally store water that ranges in water quality and hydrologic capabilities (Robertson et al., 2013).

Quaternary alluvial aquifers also store and provide water locally in the Zuni Mountains. The alluvium is found in stream channels and in valley bottoms not occupied by streams. Alluvial aquifers transport and store high intensity rain event waters and spring snow melt (Harrington et al., 2002). Ground water supplies in alluvial aquifers are not only recharged through different precipitation events, but are also affected by interactions with the atmosphere during dry times where waters are lost due to evapotranspiration (Barnes, 1988).

To further understand spatial and temporal processes within the semi-arid landscape that impact the ZBS and its habitat, we examined Agua Remora, one of four remaining habitat sites. Agua Remora spring (AR) discharges at the contact between the Proterozoic basement rocks and the Permian Yeso, just east of the Oso Ridge Monocline (Figure 3 and 4). Using the best available geologic evidence, results in the cross-section are inferred with a fault at depth resulting from the reverse fault structure. The faulting dies out before reaching the surface as is common in monoclines (Erslev, 1991; Paul and Mitra, 2012). Ground waters vertically flow up this fault structure and are expressed at the surface at the AR spring site. Upstream from the spring, the stream channel is composed of shallow grus alluvium with granite bedrock (Xp) exposed. Downstream from the spring, the channel incises the Abo and Yeso Formation (Pa and Py) and during wet times becomes much more muddy and silty. Agua Remora channel then cuts thru Oso Ridge and remains in the bedded Glorieta Sandstone (Pg) and San Andres Limestone (Psa) until its confluence with the Rio Nutria 10 km to the southwest.

Methods

To describe the temporal and spatial variations in the waters at AR, seasonal visits (springtime (n=4), summer (n=3), fall (n=3) and winter(n=3)) began in May 2012 through May 2015. Initially, collection sites were established within the stream channel where ZBS are found. In addition, a shallow (1 m) temporary well was installed at the spring site for collection of spring waters. In May 2013, the site protocol was changed so as to determine the influence the spring waters have on the ZBS habitat. Sample sites were established within the stream channel with one above (Fishless) and one below (Lower Fish Pool) the spring discharge (Figure 1). Sample waters were collected from the spring (n=15), the fishless pool (Fishless; n=12), the lower fish pool (LFP; n=14) as well as water from several local precipitation event (Rain; n=7) seasonally from springtime 2012 to springtime 2015. At each seasonal visit, two 125 ml polypropylene bottles were used to collect waters from each site using USGS protocols (Myers, 2006). One bottle was filled without treating the water and gathered with no head space (sample used for alkalinity, anion and isotope analysis). The second bottle had water filtered through 0.45 µm hydrophilic polyethersulfone filters in the field and immediately treated with ~1 mm of concentrated nitric acid (69.5% HNO_3) (sample used for cation analysis). In addition, in October 2014 a third 500 ml polypropylene bottle of untreated sample water was collected at the spring site with no head space (sample used for tritium analysis). Samples were stored and transported in a designated cooler with ice. Upon returning from the field, samples were stored in a refrigerator in the water chemistry lab on University of New Mexico campus.

Alkalinity was determined in the lab using the endpoint titration method (APHA, 1999) with the necessary volume of weak acid (0.02% H_2SO_4) as is necessary for the method. Cation concentrations were analyzed using Inductively Coupled Plasma/Optical Emission Spectroscopy (ICP/OES) (Martin et al., 1994) and for anion concentrations using Ion Chromatography (IC) (Hautman and Munch, 1997) in the Department of Earth and Planetary Sciences at the University of New Mexico, Albuquerque, New Mexico. Charge balance of major ions was then computed with all surface and ground water samples (n=42) to be less than ±5%. Duplicate analysis was routinely performed on 10% of the samples, and external reference standards were used to assure accuracy. Geochemical modeling of results was performed in Geochemist WorkBench (Bethke, 2008).

Isotopologues of liquid water (δD and $\delta^{18}O$) were analyzed using untreated surface waters, spring waters and precipitation event waters. Laser ring-down cavity spectrometry (Gupta et al., 2009; Romanini et al., 1997) was performed at the Center for Isotopic Studies at the University of New Mexico where the weighted mean values are reported. Mean tritium content, weighted for volume, was determined by the Environmental Isotope Lab at the University of Arizona using a LKB Wallac Quantulus 1220 spectrophotometer (Eastoe et al., 2012) with a detection limit of 0.6 TU ±2σ for low-counting samples, and applies for 9-fold enrichment and 1500 minutes of counting.

Physico-chemical parameters were gathered at the spring well and other surface water locations using either an Oakton ph/CON 300 meter and/or Yellow Springs Instruments (YSI) Professional Plus meter. The Oakton ph/CON 300 is a waterproof microprocessor-based meter that used a conductivity electrode (0 to 199.9 mS/cm, ±1%) and a single junction 12 mm pH electrode (-2.00 to 16.00 pH, ±0.01 pH) with built-in temperature sensor (0.0 to 100.0 °C, ±0.5 °C). Specific conductance (normalized to 25 °C) was calculated using the measured conductivity (C) divided by 1, minus the manufacturer's temperature coefficient (Tc = 2.1% per 1 °C) multiplied by the difference in the measured temperature (T_1) and 25 °C ($\Delta T = 25 - T_1$). The specific conductance equation ($SP = (C/(1-(Tc)(\Delta T))$) was provided in the Oakton manual (Oakton, 2000). The YSI Professional Plus handheld multiparameter meter was used with a Quatro cable that included a specific conductance sensor (0 to 200 mS/cm, ±0.5%), a pH glass combination electrode (0 to 14 pH units, ±0.2%), a galvanic dissolved oxygen sensor (0 to 20 mg/l, ±2%) and a field-grade water temperature probe (-5 to 70°C, ±0.2°C). Prior to field work, all probes were calibrated using manufacturers guidelines (pH and SC). In the field the dissolved oxygen optical sensor was again calibrated using the local barometric pressure in 100% water-saturated air.

In situ measurements of dissolved oxygen concentrations were made using Yellow Spring Instruments model 6920 V2 sondes (YSI Incorporated, 2009). Measurements were made at 30 minute intervals from 27 May 2013 to 19 December 2013 and redeployed from 23 May 2014 to 25 February 2015. Due to the remoteness of the location, equipment checks and calibrations of the Yellow Springs Instruments were performed every three months with 100% water-saturated air on the optical DO sensor (Canada, 2012; USEPA, 2002; Wagner et al., 2006). Continuous monitoring measurements were uploaded to an external Yellow Springs Instruments 650 multi-parameter display system. AQUARIUS software (Wagner et al., 2006) was used to perform quality assurance (corrections are documented), address equipment failure, erroneous values during calibration visits and to run statistical analysis. Measurements were verified based on calibration data and field parameter measurements made during calibrations. Equipment failure for the Fishless site included 13 September 2013 at 19:00 through 19 December 2013, 28 August 2014 02:00 through 12 October 2014 16:00 and 14 January 2015 13:00. Equipment failure for the LFP site includes 23 May 2014 through 9 July 2014, 4 September 2014 12:00 through 12 October 2014 16:00 and 8 January 2015 at 16:30. Complete data are available in Appendix II and III.

Results and Discussion

Agua Remora site waters

Waters were collected seasonally (May 2012 to February 2015) at the AR site. To characterize the seasonal variations in water quality, major ions (Table 1) for the different collection sites were plotted on a Piper diagram (Piper, 1944) to allow for comparison (Figure 6b). Spring waters (black) vary little between seasons, fishless waters (white) vary over the seasons while the lower fish pool (gray) was intermediate. A whisker-plot (Figure 6a) is representative of the major ion variability between the sites. The fishless pool variability encompasses the springs’ values in most of the major ions, except magnesium (Mg^{2+}) shows distinct concentrations for the spring and fishless waters. This evidence is used to interpret the spring waters are a different water source than the waters in the stream (fishless) and that the LFP is strongly influenced by the spring waters.

Table 1. Water Quality of Agua Remora Site, Zuni Mountains, New Mexico

Sample ID	Sample Location	Sample Date	North* DMS	West* DMS	Elevation m	Type
D1207007	AR Lower Fish Pool	5/17/2012	35°19'36.04"	108°30'00.22"	2342	stream
D1207034	AR Lower Fish Pool	7/4/2012	35°19'36.04"	108°30'00.22"	2342	stream
D1207049	AR Lower Fish Pool	9/1/2012	35°19'36.04"	108°30'00.22"	2342	stream
D1207055	AR Lower Fish Pool	12/2/2012	35°19'36.04"	108°30'00.22"	2342	stream
D1307063	AR Lower Fish Pool	5/27/2013	35°19'36.04"	108°30'00.22"	2342	stream
D1307085	AR Lower Fish Pool	7/22/2013	35°19'36.04"	108°30'00.22"	2342	stream
D1307095	AR Lower Fish Pool	9/7/2013	35°19'36.04"	108°30'00.22"	2342	stream
D1307097	AR Lower Fish Pool	12/19/2013	35°19'36.04"	108°30'00.22"	2342	stream
D1407111	AR Lower Fish Pool	5/23/2014	35°19'36.04"	108°30'00.22"	2342	stream
D1407114	AR Lower Fish Pool	7/9/2014	35°19'36.04"	108°30'00.22"	2342	stream
D1407120	AR Lower Fish Pool	10/12/2014	35°19'36.04"	108°30'00.22"	2342	stream
D1507130	AR Lower Fish Pool	2/21/2015	35°19'36.04"	108°30'00.22"	2342	stream
D1507137	AR Lower Fish Pool	4/3/2015	35°19'36.04"	108°30'00.22"	2342	stream
D1507150	AR Lower Fish Pool	5/31/2015	35°19'36.04"	108°30'00.22"	2342	stream
D1207006	AR Spring	5/17/2012	35°19'36.71"	108°29'57.35"	2348	spring
D1207033	AR Spring	7/4/2012	35°19'36.71"	108°29'57.35"	2348	spring
D1207050	AR Spring	9/1/2012	35°19'36.71"	108°29'57.35"	2348	spring
D1207056	AR spring	12/2/2012	35°19'36.71"	108°29'57.35"	2348	spring
D1307060	AR Spring	5/27/2013	35°19'36.71"	108°29'57.35"	2348	spring
D1307083	AR Spring	7/22/2013	35°19'36.71"	108°29'57.35"	2348	spring
D1307093	AR Spring	9/7/2013	35°19'36.71"	108°29'57.35"	2348	spring
D1307098	AR Spring	12/19/2013	35°19'36.71"	108°29'57.35"	2348	spring
D1407108	AR Spring	5/23/2014	35°19'36.71"	108°29'57.35"	2348	spring
D1407113	AR Spring	7/9/2014	35°19'36.71"	108°29'57.35"	2348	spring
D1407121	AR Spring	10/12/2014	35°19'36.71"	108°29'57.35"	2348	spring
D1407124	AR Spring	10/18/2014	35°19'36.71"	108°29'57.35"	2348	spring
D1507127	AR Spring	2/21/2015	35°19'36.71"	108°29'57.35"	2348	spring
D1507139	AR Spring	4/3/2015	35°19'36.71"	108°29'57.35"	2348	spring
D1507151	AR Spring	5/31/2015	35°19'36.71"	108°29'57.35"	2348	spring

* The North American Datum (NAD83) is used as the horizontal control datum.

Table 1. Water Quality of Agua Remora Site, Zuni Mountains, New Mexico (continued)

Sample ID	pH	Water Temperature °C	Dissolved Oxygen mg/l	Specific Conductivity µS/cm	Dissolved solids mg/l	$\delta^{18}O$ ‰ SMOW	δD ‰ SMOW	d-excess
D1207007	7.31	17.0	n.a.	406	288.6	-11.21	-84.53	5.12
D1207034	7.13	17.7	n.a.	577	369.6	-11.38	-86.56	4.50
D1207049	7.05	16.9	6.3	563	393.4	-11.81	-87.86	6.60
D1207055	5.93	3.2	n.a.	615	363.5	-12.82	-94.05	8.51
D1307063	7.58	12.7	4.9	432	336.9	-11.63	-88.64	4.43
D1307085	6.38	18.0	n.a.	539	365.4	-11.87	-88.90	6.03
D1307095	7.70	14.9	6.3	550	376.7	-11.77	-86.67	7.51
D1307097	7.79	3.9	9.0	427	298.9	-12.05	-87.02	9.36
D1407111	6.60	13.5	7.9	456	319.8	-11.38	-85.41	5.60
D1407114	6.75	15.4	5.5	543	402.0	-12.32	-89.83	8.71
D1407120	7.49	9.0	6.7	536	380.2	-12.68	-89.34	12.09
D1507130	7.80	4.2	9.7	377	255.9	-12.89	-92.40	10.72
D1507137	7.59	6.6	6.3	292	227.2	-12.39	-86.57	12.55
D1507150	7.51	13.5	8.9	376	285.8	-12.32	-87.00	11.60
D1207006	7.05	11.3	n.a.	501	347.0	-12.65	-93.28	7.89
D1207033	7.52	11.4	2.4	521	351.1	-12.62	-92.70	8.25
D1207050	7.24	15.5	3.9	534	340.9	-12.14	-91.66	5.42
D1207056	8.94	8.1	n.a.	510	352.3	-12.69	-92.98	8.58
D1307060	7.63	11.9	3.1	479	384.3	-12.75	-93.25	8.74
D1307083	6.63	17.4	n.a.	500	348.8	-12.74	-93.44	8.47
D1307093	6.89	14.1	0.1	569	353.7	-13.23	-93.48	12.35
D1307098	7.22	5.5	0.9	565	358.2	-12.84	-94.83	7.87
D1407108	n.a.	11.1	4.9	504	349.1	-12.62	-92.57	8.37
D1407113	7.25	11.5	1.6	439	410.2	-12.97	-93.86	9.90
D1407121	7.81	10.8	4.8	238	372.2	-13.00	-93.13	10.86
D1407124	7.83	10.9	1.6	482	360.7	-13.21	-92.90	12.81
D1507127	7.07	6.3	0.2	543	356.5	-12.55	-92.03	8.39
D1507139	7.36	8.9	0.1	501	388.3	-13.48	-94.32	13.53
D1507151	6.83	6.8	0.1	522	342.4	-13.13	-94.33	10.72

Table 1. Water Quality of Agua Remora Site, Zuni Mountains, New Mexico (continued)

Sample ID	Ca^{++} mg/l	Mg^{++} mg/l	Na^{+} mg/l	K^{+} mg/l	HCO_3^{-} mg/l	SO_4^{--} mg/l	Cl^{-} mg/l	Mass Balance** %
D1207007	26.9	6.8	43.6	1.7	131.8	58.4	10.8	2.11
D1207034	29.6	7.0	64.8	2.0	144.6	98.5	16.5	0.36
D1207049	29.9	6.7	79.4	1.8	167.3	84.1	18.4	4.98
D1207055	32.2	7.8	70.4	2.2	116.2	130.8	19.8	1.71
D1307063	32.4	7.4	50.7	1.6	141.6	85.0	11.4	0.64
D1307085	32.0	6.6	71.0	2.3	142.0	103.5	17.8	2.89
D1307095	32.7	7.1	68.8	1.5	148.9	90.1	15.4	4.96
D1307097	30.3	7.9	37.7	1.6	136.7	64.0	9.2	0.10
D1407111	31.5	7.3	53.9	1.5	147.8	70.2	11.8	3.90
D1407114	34.6	8.0	72.4	1.8	158.0	108.4	18.6	1.92
D1407120	33.6	7.6	69.7	2.4	114.3	123.7	20.6	3.46
D1507130	29.0	8.7	30.2	1.7	120.8	46.4	9.0	4.83
D1507137	25.5	7.3	19.9	1.5	119.5	40.8	6.4	-3.67
D1507150	30.4	8.3	34.7	1.8	144.6	47.9	8.4	1.97
D1207006	29.7	5.3	65.1	2.1	128.7	92.7	16.3	3.26
D1207033	28.9	5.2	63.3	2.2	128.5	96.6	15.7	1.25
D1207050	31.3	5.5	60.4	2.0	130.7	86.2	15.9	3.31
D1207056	32.4	5.8	64.3	2.3	129.0	94.7	14.6	4.72
D1307060	31.7	5.4	73.0	1.9	133.0	115.6	15.4	2.26
D1307083	32.1	5.5	65.7	2.1	136.7	94.1	15.5	3.44
D1307093	31.9	5.4	66.1	1.7	132.4	95.1	16.1	3.70
D1307098	31.2	5.3	67.6	1.9	131.2	94.7	15.5	4.44
D1407108	31.7	5.4	64.0	1.9	127.5	91.0	14.6	4.98
D1407113	33.0	6.1	68.7	2.2	151.0	123.4	16.8	-3.09
D1407121	32.9	6.1	60.7	1.8	123.9	116.8	16.6	-1.04
D1407124	32.8	6.2	59.6	2.2	127.8	97.9	20.6	0.86
D1507127	34.5	6.1	63.7	2.1	129.4	95.4	16.4	4.97
D1507139	30.9	5.4	63.4	2.1	133.6	127.1	16.3	-4.96
D1507151	31.9	5.6	58.6	2.0	133.6	96.7	11.5	1.30

** Mass Balance Equation:

100***(**(2*Ca++(mg/l)/40.08)+(2*Mg++(mg/l)/24.305)+(Na+(mg/l)/22.99)+(K+(mg/l)/39.0983)-(HCO3-(mg/l)/61)-(Cl-(mg/l)/35.453)-(2*SO4-(mg/l)/96.06)**) / (**(2*Ca++(mg/l)/40.08)+(2*Mg++(mg/l)/24.305)+(Na+(mg/l)/22.99)+(K+(mg/l)/39.0983)-(HCO3-(mg/l)/61)-(Cl-(mg/l)/35.453)-(2*SO4-(mg/l)/96.06)**)**

Table 1. Water Quality of Agua Remora Site, Zuni Mountains, New Mexico (continued)

Sample ID	SiO_2(aq) mg/l	F^- mg/l	Br^- mg/l	Fe^{++} mg/l	SI Calcite log Q/K	SI Gypsum log Q/K	SI Quartz log Q/K	CO_2(g) fugacity
D1207007	8.9	3.3	0.1	0.2	2.42E-01	5.22E-03	2.07E+00	5.03E-03
D1207034	8.4	4.0	0.3	0.0	1.74E-01	8.74E-03	1.90E+00	7.94E-03
D1207049	8.3	4.4	1.3	0.1	1.61E-01	7.55E-03	1.94E+00	1.06E-02
D1207055	4.6	4.3	0.5	0.0	1.51E-03	1.34E-02	2.00E+00	2.17E-02
D1307063	6.0	3.2	0.1	b.d.	5.01E-01	8.58E-03	1.67E+00	2.85E-03
D1307085	5.3	4.1	0.4	0.1	1.98E-02	9.95E-03	1.18E+00	2.60E-02
D1307095	9.6	4.2	0.2	0.1	7.49E-01	8.80E-03	2.43E+00	2.36E-03
D1307097	10.2	2.6	0.4	0.1	5.77E-01	6.74E-03	4.26E+00	1.55E-03
D1407111	8.2	3.4	0.2	0.1	3.69E-02	7.17E-03	2.22E+00	1.87E-02
D1407114	8.8	4.0	0.4	0.3	6.92E-02	1.09E-02	2.19E+00	1.65E-02
D1407120	9.5	1.4	n.a.	0.0	2.81E-01	1.24E-02	3.13E+00	2.63E-03
D1507130	8.6	2.3	0.7	b.d.	5.23E-01	4.88E-03	3.54E+00	1.35E-03
D1507137	6.9	1.7	n.a.	0.0	3.06E-01	3.90E-03	2.54E+00	2.19E-03
D1507150	9.3	2.6	0.7	0.1	4.42E-01	4.88E-03	2.51E+00	3.44E-03
D1207006	9.7	4.2	n.a.	0.1	1.02E-01	8.68E-03	2.89E+00	7.45E-03
D1207033	9.5	3.6	0.2	b.d.	3.31E-01	8.73E-03	2.81E+00	2.88E-03
D1207050	8.6	3.7	1.1	b.d.	2.10E-01	8.38E-03	2.13E+00	5.58E-03
D1207056	4.9	3.8	0.5	b.d.	8.60E+00	9.29E-03	1.55E+00	1.08E-04
D1307060	6.3	3.9	0.2	b.d.	4.83E-01	1.09E-02	1.82E+00	2.36E-03
D1307083	6.5	4.0	0.4	b.d.	4.29E-02	9.26E-03	1.49E+00	1.78E-02
D1307093	9.9	3.9	0.3	0.0	7.91E-02	9.35E-03	2.61E+00	1.07E-02
D1307098	11.8	4.0	0.5	b.d.	1.38E-01	9.55E-03	4.59E+00	5.01E-03
D1407108	9.1	3.8	0.1	b.d.	n.a.	9.00E-03	2.74E+00	n.a.
D1407113	10.2	3.8	0.4	0.0	2.15E-01	1.19E-02	3.01E+00	5.92E-03
D1407121	10.1	4.2	0.4	b.d.	6.96E-01	1.15E-02	3.06E+00	1.46E-03
D1407124	10.3	3.8	0.8	b.d.	7.68E-01	9.83E-03	3.10E+00	1.44E-03
D1507127	11.2	4.1	0.6	b.d.	1.03E-01	1.05E-02	4.19E+00	6.65E-03
D1507139	9.8	3.7	n.a.	b.d.	2.17E-01	1.18E-02	3.25E+00	4.04E-03
D1507151	10.0	2.9	0.6	b.d.	5.11E-02	1.00E-02	3.66E+00	1.06E-02

Table 1. Water Quality of Agua Remora Site, Zuni Mountains, New Mexico (continued)

Sample ID	Sample Location	Sample Date	North* DMS	West* DMS	Elevation m	Type
D1207005	AR Upper Fish Pool	5/17/2012	35°19'36.43"	108°29'57.69"	2345	stream
D1207035	AR Upper Fish Pool	7/4/2012	35°19'36.43"	108°29'57.69"	2345	stream
D1207051	AR Upper Fish Pool	9/1/2012	35°19'36.43"	108°29'57.69"	2345	stream
D1207054	AR Upper Fish Pool	12/2/2012	35°19'36.43"	108°29'57.69"	2345	stream
D1307062	AR Upper Fish Pool	5/27/2013	35°19'36.43"	108°29'57.69"	2345	stream
D1307084	AR Upper Fish Pool	7/22/2013	35°19'36.43"	108°29'57.69"	2345	stream
D1307090	AR Upper Fish Pool	9/7/2013	35°19'36.43"	108°29'57.69"	2345	stream
D1207004	AR Upper Fishless Pool	5/17/2012	35°19'34.99"	108°29'56.105"	2344	stream
D1207053	AR Upper Fishless Pool	12/2/2012	35°19'34.99"	108°29'56.105"	2344	stream
D1307065	AR Upper Fishless Pool	5/27/2013	35°19'34.99"	108°29'56.105"	2344	stream
D1307086	AR Upper Fishless Pool	7/22/2013	35°19'34.99"	108°29'56.105"	2344	stream
D1307091	AR Upper Fishless Pool	9/7/2013	35°19'34.99"	108°29'56.105"	2344	stream
D1307099	AR Upper Fishless Pool	12/19/2013	35°19'34.99"	108°29'56.105"	2344	stream
D1407110	AR Upper Fishless Pool	5/23/2014	35°19'34.99"	108°29'56.105"	2344	stream
D1407115	AR Upper Fishless Pool	7/9/2014	35°19'34.99"	108°29'56.105"	2344	stream
D1407119	AR Upper Fishless Pool	10/12/2014	35°19'34.99"	108°29'56.105"	2344	stream
D1507128	AR Upper Fishless Pool	2/21/2015	35°19'34.99"	108°29'56.105"	2344	stream
D1507138	AR Upper Fishless Pool	4/3/2015	35°19'34.99"	108°29'56.105"	2344	stream
D1507148	AR Upper Fishless Pool	5/31/2015	35°19'34.99"	108°29'56.105"	2344	stream
D1407112	Zuni Mountain Hail	5/23/2014	35°19'34.84"	108°309'00.08"	2343	precip
D1407122	Zuni Mountain Hail	10/19/2014	35°13'02.32"	108°20'19.02"	2487	precip
D1407123	Zuni Mountain Rain	10/19/2014	35°13'02.32"	108°20'19.02"	2487	precip
D1507129	Zuni Mountain Snow	2/21/2015	35°19'34.84"	108°309'00.08"	2343	precip
D1507152	McGaffey Rain	6/5/2015	35°21'56.10"	108°31'20.79"	2371	precip
D1507155	Snow Aspen Campground	5/9/2015	35°24'25.68"	108°32'24.16"	2315	precip
D1507156	Snow CottonGulch	5/9/2015	35°18'50.06"	108°12'01.17"	2286	precip

* The North American Datum (NAD83) is used as the horizontal control datum.

Table 1. Water Quality of Agua Remora Site, Zuni Mountains, New Mexico (continued)

Sample ID	pH	Water Temperature °C	Dissolved Oxygen mg/l	Specific Conductivity µS/cm	Dissolved solids mg/l	δ^{18}O ‰ SMOW	δD ‰ SMOW	d-excess
D1207005	6.69	14.8	n.a.	406	284.0	-11.47	-85.26	6.51
D1207035	7.43	17.1	n.a.	559	362.9	-12.21	-90.26	7.39
D1207051	7.61	19.3	7.9	608	381.0	-12.53	-92.43	7.83
D1207054	7.33	1.1	n.a.	684	411.9	-12.83	-94.32	8.29
D1307062	7.26	11.9	2.3	339	287.5	-12.26	-87.68	10.37
D1307084	6.25	19.5	n.a.	532	373.9	-12.53	-91.67	8.60
D1307090	7.43	18.0	8.2	520	372.2	-11.45	-85.15	6.49
D1207004	6.28	12.9	n.a.	322	250.7	-10.44	-79.74	3.78
D1207053	8.77	1.2	n.a.	686	444.0	-12.42	-92.13	7.25
D1307065	6.83	11.9	1.7	341	267.2	-11.16	-85.15	4.09
D1307086	6.87	19.0	n.a.	485	335.6	-10.16	-79.63	1.61
D1307091	6.88	15.5	0.7	474	347.5	-9.82	-76.07	2.48
D1307099	7.07	0.8	4.7	307	213.5	-11.58	-82.01	10.64
D1407110	6.42	12.7	3.0	399	285.2	-10.04	-80.58	-0.25
D1407115	6.93	17.5	2.7	510	404.5	-10.76	-85.10	1.02
D1407119	7.45	8.5	4.5	500	372.9	-11.88	-87.53	7.54
D1507128	7.68	3.9	10.0	268	194.1	-12.83	-90.71	11.92
D1507138	7.47	6.5	2.5	281	190.9	-11.77	-85.93	8.25
D1507148	6.88	11.2	3.1	323	231.1	-12.28	-84.23	13.98
D1407112	n.a.	n.a.	n.a.	n.a.	n.a.	-12.08	-77.89	18.79
D1407122	n.a.	n.a.	n.a.	n.a.	n.a.	-9.14	-55.23	17.90
D1407123	n.a.	n.a.	n.a.	n.a.	n.a.	-9.25	-48.27	25.74
D1507129	n.a.	n.a.	n.a.	n.a.	n.a.	-11.84	-85.07	9.64
D1507152	n.a.	n.a.	n.a.	n.a.	n.a.	-11.42	-89.06	2.30
D1507155	n.a.	n.a.	n.a.	n.a.	n.a.	-10.30	-66.12	16.30
D1507156	n.a.	n.a.	n.a.	n.a.	n.a.	-11.00	-69.56	18.44

Table 1. Water Quality of Agua Remora Site, Zuni Mountains, New Mexico (continued)

Sample ID	Ca^{++} mg/l	Mg^{++} mg/l	Na^{+} mg/l	K^{+} mg/l	HCO$_3^{-}$ mg/l	SO$_4^{--}$ mg/l	Cl^{-} mg/l	Mass Balance** %
D1207005	28.0	7.1	44.4	1.8	131.2	60.6	10.2	3.41
D1207035	28.1	7.7	66.5	1.6	103.7	123.7	20.5	1.18
D1207051	26.9	6.6	78.2	1.7	101.3	131.4	21.3	3.24
D1207054	31.0	8.2	74.2	2.0	105.2	158.3	26.4	-2.33
D1307062	28.1	8.2	35.5	1.3	137.9	63.4	8.9	-2.32
D1307084	30.2	7.7	75.5	1.9	111.4	128.0	25.7	2.39
D1307090	32.6	8.5	59.5	1.2	161.2	83.1	13.5	1.98
D1207004	32.6	10.8	15.3	2.5	185.5	16.7	6.4	-4.77
D1207053	32.9	10.6	88.8	2.8	114.1	158.1	26.8	4.22
D1307065	33.7	11.6	21.0	2.3	171.5	26.9	5.4	1.17
D1307086	31.5	9.9	50.2	2.7	146.4	79.9	16.1	1.26
D1307091	36.9	11.5	36.6	2.2	207.5	40.0	10.0	-0.88
D1307099	28.1	9.7	10.6	2.1	147.7	10.8	4.0	-0.81
D1407110	35.8	10.9	26.0	2.7	185.6	32.3	7.1	-0.43
D1407115	37.2	13.4	64.1	3.0	148.3	117.0	17.4	4.15
D1407119	28.8	9.6	70.2	2.7	98.7	128.4	23.0	3.97
D1507128	26.6	9.5	11.2	2.0	114.7	19.6	3.8	5.04
D1507138	25.5	8.2	9.2	1.9	119.0	18.2	3.3	-0.57
D1507148	29.9	10.0	13.8	2.2	155.1	16.7	3.9	-0.42
D1407112	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
D1407122	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
D1407123	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
D1507129	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
D1507152	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
D1507155	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
D1507156	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

** Mass Balance Equation:

100*((2*Ca++(mg/l)/40.08)+(2*Mg++(mg/l)/24.305)+(Na+(mg/l)/22.99)+(K+(mg/l)/39.0983)-(HCO3-(mg/l)/61)-(Cl-(mg/l)/35.453)-(2*SO4-(mg/l)/96.06)) / ((2*Ca++(mg/l)/40.08)+(2*Mg++(mg/l)/24.305)+(Na+(mg/l)/22.99)+(K+(mg/l)/39.0983)-(HCO3-(mg/l)/61)-(Cl-(mg/l)/35.453)-(2*SO4-(mg/l)/96.06))

Table 1. Water Quality of Agua Remora Site, Zuni Mountains, New Mexico (continued)

Sample ID	SiO_2(aq) mg/l	F^- mg/l	Br^- mg/l	Fe^{++} mg/l	SI Calcite log Q/K	SI Gypsum log Q/K	SI Quartz log Q/K	CO_2(g) fugacity
D1207005	9.3	3.4	0.3	0.1	4.17E-02	5.72E-03	2.38E+00	1.50E-02
D1207035	9.0	4.2	0.3	b.d.	2.45E-01	1.02E-02	2.08E+00	3.05E-03
D1207051	9.2	4.8	1.1	0.0	3.78E-01	1.01E-02	1.94E+00	2.09E-03
D1207054	4.8	4.9	0.7	b.d.	1.15E-01	1.49E-02	2.31E+00	3.01E-03
D1307062	6.0	3.0	n.a.	b.d.	1.93E-01	5.97E-03	1.74E+00	5.39E-03
D1307084	6.5	4.2	0.3	0.1	9.56E-03	1.12E-02	1.36E+00	2.42E-02
D1307090	12.1	3.8	0.3	0.0	4.70E-01	8.11E-03	2.69E+00	4.81E-03
D1207004	9.0	1.6	n.a.	0.1	1.73E-02	1.99E-03	2.50E+00	3.42E-02
D1207053	5.0	4.5	0.5	0.0	3.94E+00	1.50E-02	2.28E+00	1.31E-04
D1307065	6.6	1.6	n.a.	b.d.	9.27E-02	3.14E-03	1.91E+00	1.49E-02
D1307086	5.5	2.9	0.3	0.1	9.93E-02	7.72E-03	1.18E+00	1.33E-02
D1307091	13.9	2.6	0.3	0.2	1.55E-01	4.69E-03	3.45E+00	1.75E-02
D1307099	7.8	1.0	0.6	0.0	9.12E-02	1.24E-03	3.81E+00	7.08E-03
D1407110	8.3	2.0	0.2	0.0	2.97E-02	3.97E-03	2.32E+00	2.93E-02
D1407115	9.0	3.6	0.4	0.2	1.25E-01	1.21E-02	2.05E+00	1.17E-02
D1407119	8.6	4.8	0.5	0.1	1.84E-01	1.10E-02	2.90E+00	2.45E-03
D1507128	7.3	1.3	n.a.	b.d.	3.60E-01	2.06E-03	3.05E+00	1.68E-03
D1507138	7.5	0.9	n.a.	0.1	2.36E-01	1.84E-03	2.78E+00	2.83E-03
D1507148	9.4	1.3	n.a.	0.1	8.68E-02	1.84E-03	2.81E+00	1.23E-02
D1407112	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
D1407122	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
D1407123	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
D1507129	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
D1507152	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
D1507155	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
D1507156	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

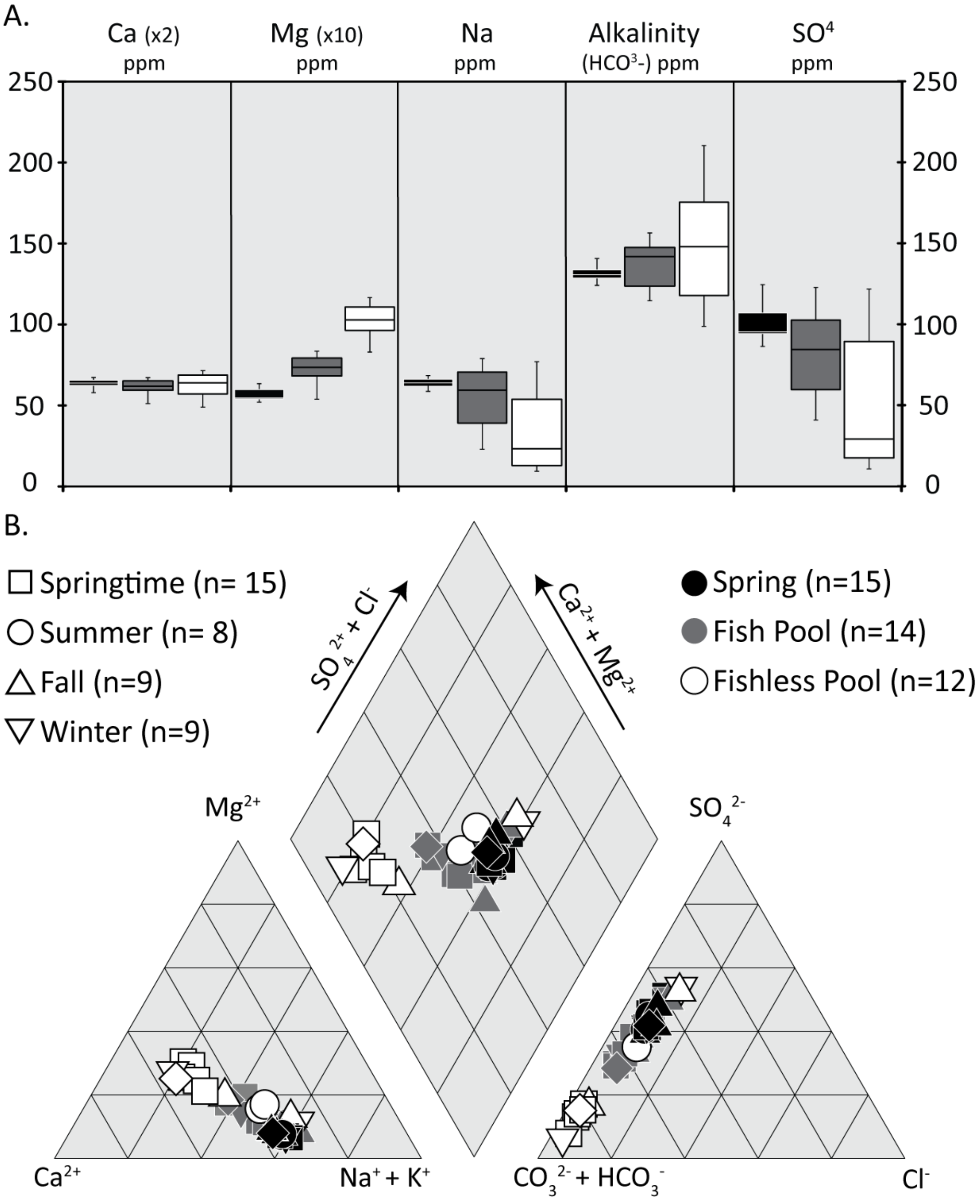


Figure 6. A) Whisker-plot diagram of major ions where the whiskers represent the minimum and maximum values, the box represents the 1st and 3rd quartile and the line is the median of the data. B) Piper diagram showing relative proportions of major ion concentrations for Agua Remora spring waters (black), fishless pool (white) and fish pool (gray).

Isotopes (δD and $\delta^{18}O$) can be useful in understanding recharge and atmospheric mechanisms for a system (Glynn and Plummer, 2005; Sharp, 2006). The Global Meteoric Water Line (GMWL) represents a linear relationship (slope of 8) for surface waters across the globe (Craig, 1961). Movement away from the GMWL represents alteration of precipitation due to evaporation, geothermal water-rock interaction or gaseous exchange (Craig, 1961). The weighted mean values of precipitation, surface waters and spring waters isotopologues are reported (Table 1)**.** Precipitation events show large variability (Figure 7). The springtime (May 2014 and Feb 2015; hail and snow, respectively) are relatively depleted (maximum value; -12.08‰ for $\delta^{18}O$; -77.89‰ for δD) compared to the October 2014 hail and rain events (maximum value; -9.14‰ for $\delta^{18}O$; -55.23‰ for δD). Of note is the δD values of precipitation events are always more enriched (less negative) in heavy isotopes as compared to the surface or spring waters. While the $\delta^{18}O$ values for precipitation are relatively high (less negative) for all samples as compared to the spring waters, the values are relatively low (more negative) for the springtime values when compared to the surface water samples. An investigation of the seasonal differences within the fishless site as well as the precipitation samples offers insight into the timing of recharge events where winter samples (diamonds) are lower (more negative) relative to summer samples (triangles). When accounting for these variations, a boundary for winter and summer (monsoon) recharge begins to take shape (Figure 7).

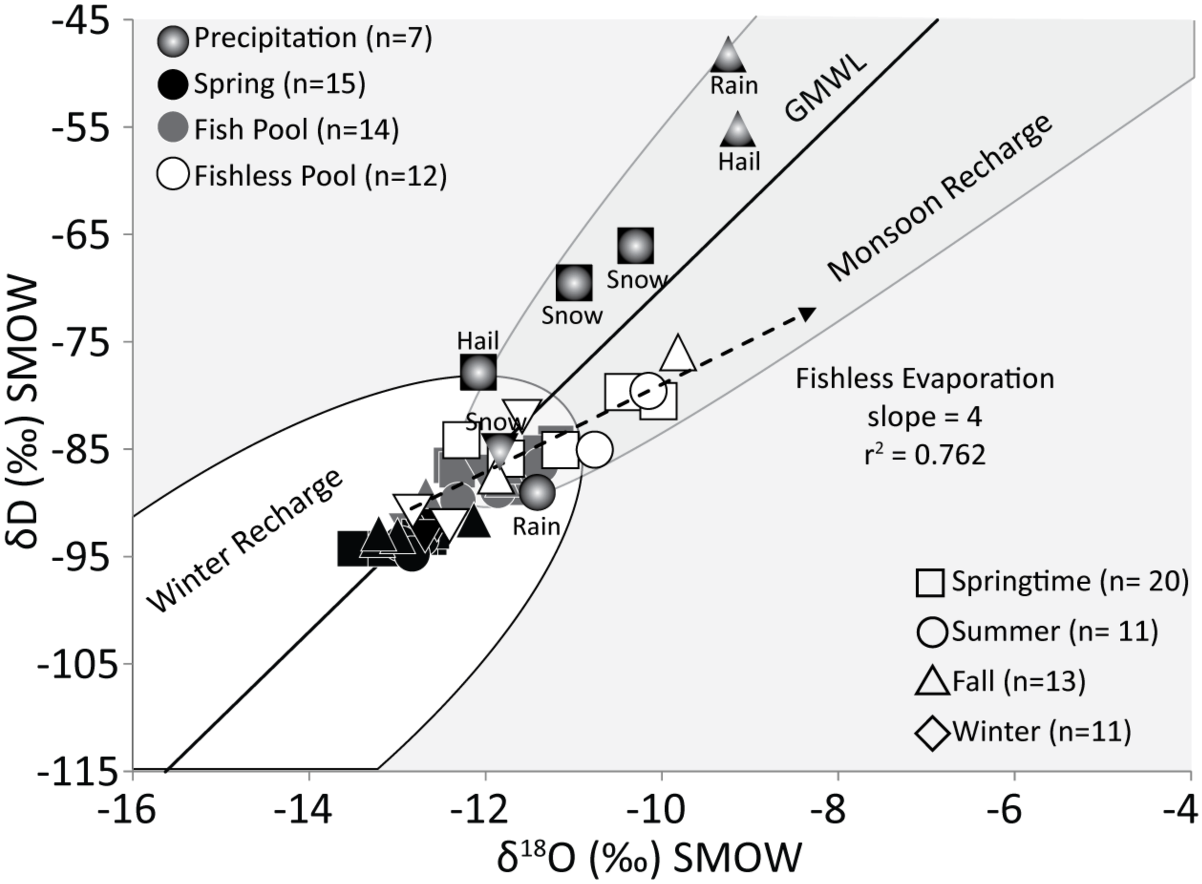


Figure 7. XY-plot of stable isotopes (δD and δ18O) of the Agua Remora site waters (n=46) as well as local precipitation events (n=7) are plotted relative to the global meteoric water line (GMWL, Craig 1961). A trend line (r^2=0.762) is plotted for the fishless waters as they move away from the GMWL. Combining the fishless seasonal variability with the precipitation seasonality a picture of hydrologic recharge takes shape with the winter and monsoonal recharge zones slightly overlapping (seasonal zones modified from Sharp, 2006).

Using these boundaries, mechanisms of recharge are interpreted. The isotopologues of the spring waters vary little across the seasons studied and are the lowest (more negative) from the site. Analysis of the isotopologues of AR waters indicates that the spring water is recharged from winter precipitation (snowmelt). The fishless pool has larger variations in the weighted mean values of both the δ^{18}O (16‰) and δD (3‰), but only winter values are as negative as the spring waters. Inspection of the fishless samples shows that winter samples (white diamonds) lie near the GMWL while the other seasons are variable in their position to the GMWL. This variability is due to the seasonal differences of precipitation as well as the timing of recharge where the fishless pool is recharged with both monsoonal rain and winter snowmelt.

Along with the seasonality of recharge and the variability of precipitation to the fishless pool, the samples also plot away from the GMWL. A linear regression (r^2=0.762, slope=4) on the fishless waters throughout seasons is within the range of those observed for evaporation trends (Sharp, 2006). Therefore we interpret the fishless pool undergoes evaporation during the warmer months.

Discussion of spring water influence on ZBS habitat

Analyzing hydrochemistry across annual timeframes illuminates the seasonal impacts the spring is having on ZBS habitat. Stable isotope (δD), water temperature and Mg^{2+} concentrations for each field visit to the AR site, along with precipitation, discharge and air temperatures for the region, are graphed over time to identify seasonal variations (Figure 8). In addition, physico-chemical parameters (pH and specific conductance) were collected with each field visit to help determine the springs influence on the ZBS habitat (Table 1).

The air temperatures for the AR site are typical for the region with daily mean temperatures (bold) having a minimum of -5°C for winter and a maximum of 24°C for the summer. The δD variations over time for the spring water samples are small with a range of 3.17‰. In contrast, the fishless pool shows larger variations throughout the seasons with a δD range of 16.06‰ where enriched values are in warmer seasons and more deplete values are in winter. Close inspection of water temperatures (Figure 8) for the spring waters do show a slight seasonal variability with an average temperature of 11.2°C ±3.3. Water temperature for the fishless pool reflected more of the seasonal air temperature changes with maximum temperature of 19.5 °C in the summer and a minimum temperature of 0.8°C in the winter. This yields an average temperature of 10.4°C, close to that of the spring waters, but with double the standard deviation at ±6.6. Water temperatures for the sites had a maximum of 19.5 °C and a minimum temperature of 0.8°C. Results from Table 1 show that all locations maintain acid neutrality with pH averages between 7.12-7.42 ±0.6. Specific conductance of all sites stayed below 700 µS/cm with the Fishless site having the largest variability (268-686 µS/cm; average 429 µS/cm ±126.4) and the spring having the least amount of variability (439-569 µS/cm; average 513 µS/cm ±37.2). The physico-chemical parameters of the site at Agua Remora provide additional evidence that the spring and fishless pool waters have different source waters and flow paths. The spring waters have a deeper flow path which buffers the waters from evaporation and freezing temperatures and are recharged primarily through snowmelt. The fishless pool waters are from the shallow alluvium that allows for exchange with the atmosphere thereby undergoing evaporation. The lower fish pool is then a mixture of these two different water sources.

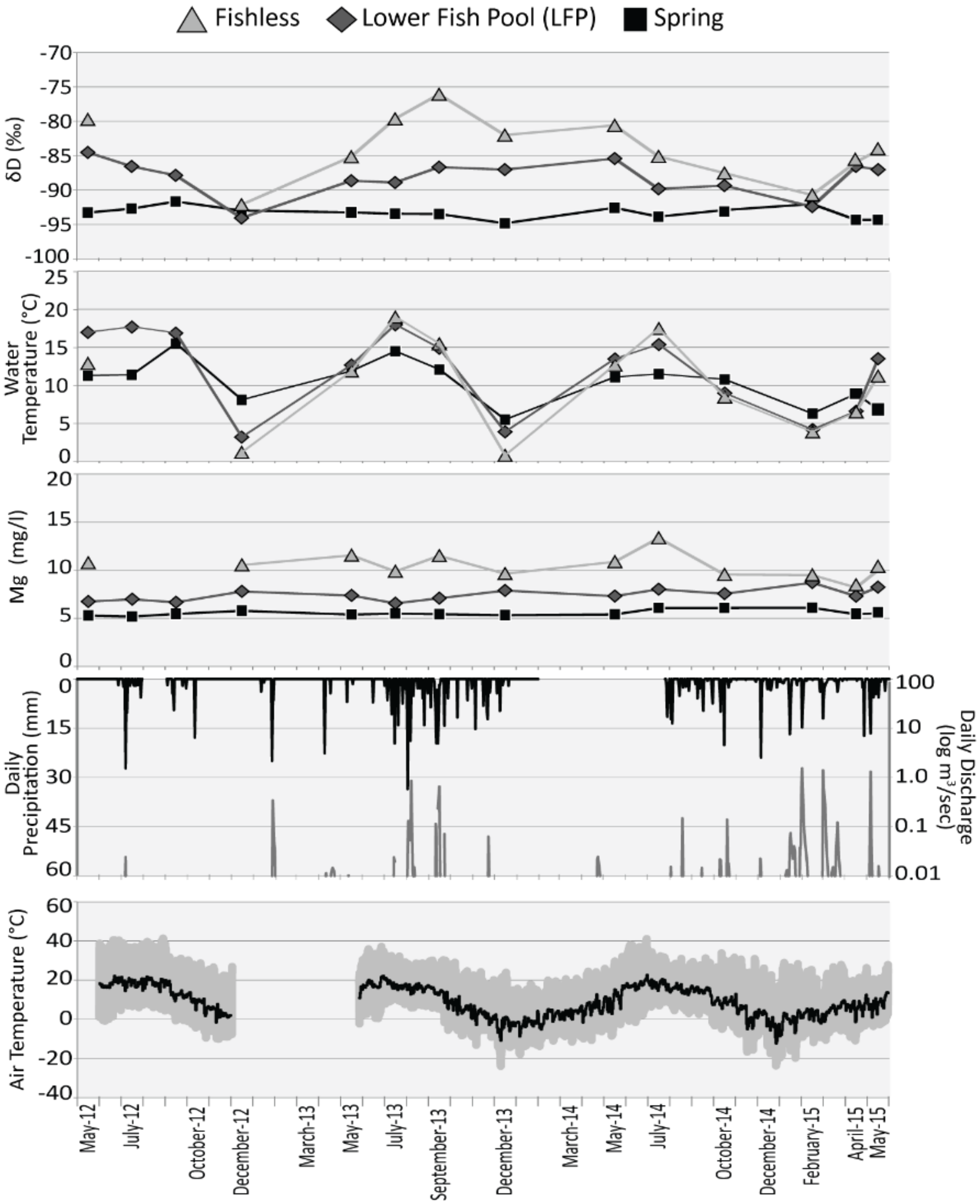
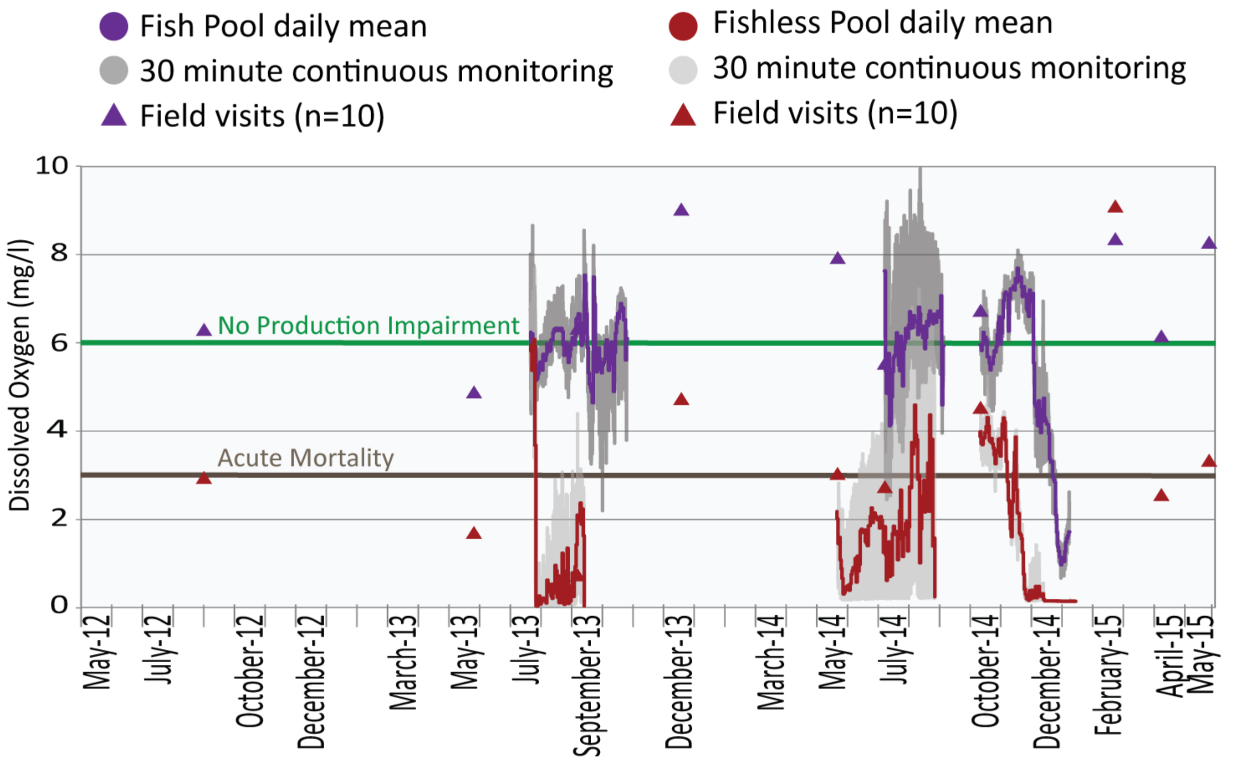


Figure 8. Physico-chemical parameters for sampling sites at Agua Remora are plotted over time including; δD (‰ SMOW), water temperature, Mg concentrations (mg/l), daily precipitation (mm) and daily discharge (m3/sec), and air temperature for the Agua Remora site.

The Environmental Protection Agency (EPA) has established federal water quality standards for the protection of aquatic life. Dissolved oxygen concentrations that maintain populations of cold water fish have been set with 6 mg/l established as the no production impairment limit and 3 mg/l being the limit to avoid acute mortality during different life stages (USEPA, 2014). Continuous monitoring data of dissolved oxygen concentrations (DO mg/l) were acquired to help understand the impact the spring waters have on the fish habitat (Figure 9). The daily mean DO concentrations at the LFP site (bold purple) have an average DO concentration of ~6 mg/l. In contrast, within 7 days of the first deployment (July 2013) there was a large rain event that corresponded with a drop in the DO concentration levels of the fishless pool (bold red) below 3 mg/l and the pool did not recover again through September 2013. While this rain event is also associated with lowered DO levels of the LFP, recovery to pre-event levels took less than 15 days, and DO concentrations never went below the acute mortality line established by the EPA.

The low values of the DO concentrations at both of the sites is interpreted to be the result of the delivery of labile organic carbon (both dissolved and particulate) by the rain event. The organic carbon stimulated metabolism that lowered DO concentrations (Dahm, 1981; Dahm et al., 2015; Grimm et al., 1997). With the delivery of oxygenated spring water to the lower fish pool, the pool recovers faster and DO concentration levels are maintained. In contrast the fishless pool waters are essentially stagnant, with limited reaeration, making recovery slow. In the fishless pool diffusion processes are overwhelmed by organic decomposition (Dahm, 1981; Dahm et al., 2015). This makes the fishless pool anoxic during low flow times, and suitable habitat for the fish species is not available upstream from the spring discharge location.



Impairment and mortality lines EPA Gold Book, 440/5-86-001

Figure 9. Plot of continuous monitoring and field measured Dissolved Oxygen concentrations (mg/l) for fishless (red) and fish pool (purple). Data is plotted against EPA water quality standards of DO concentrations for nonsalmonid cool water fish.

Additional declines of DO concentrations for both sites were found at the beginning of winter 2014. The fishless pool started to decline 07 November 2014 and bottomed out at 0.5 DO mg/l while the LFP began declining 05 December 2014 and fell below 2 DO mg/l. Through the remaining deployment (January 2015) neither of the pools recovered from this wintertime sag. This sag is interpreted as a direct effect of the ice covering the pools. Ice greatly reduces reaeration and DO sags are commonplace under the ice (Baehr and

Degrandpre, 2002). Metabolism does not stop under the ice, but re-oxygenation does (Bertilsson et al., 2013).

To determine the influence that the spring waters have on the LFP a mass solution mixing scenario was performed using Geochemists Workbench (Bethke, 2008). The percent of water that the spring provides for each season was determined using the mass chemistry of major ions from the spring and fishless pool waters (Figure 10). Results indicate that during high flow times (spring and winter) the spring and fishless pools are equally contributing to the LFP habitat. During base flow (summer and fall) the spring is providing as much as 99% of the water that is found in the LFP. This supports the idea that the spring waters are providing re-aerated waters to the LFP, while the fishless pools are stagnant and unable to maintain DO concentrations due to the lack of spring water discharge into the pool.

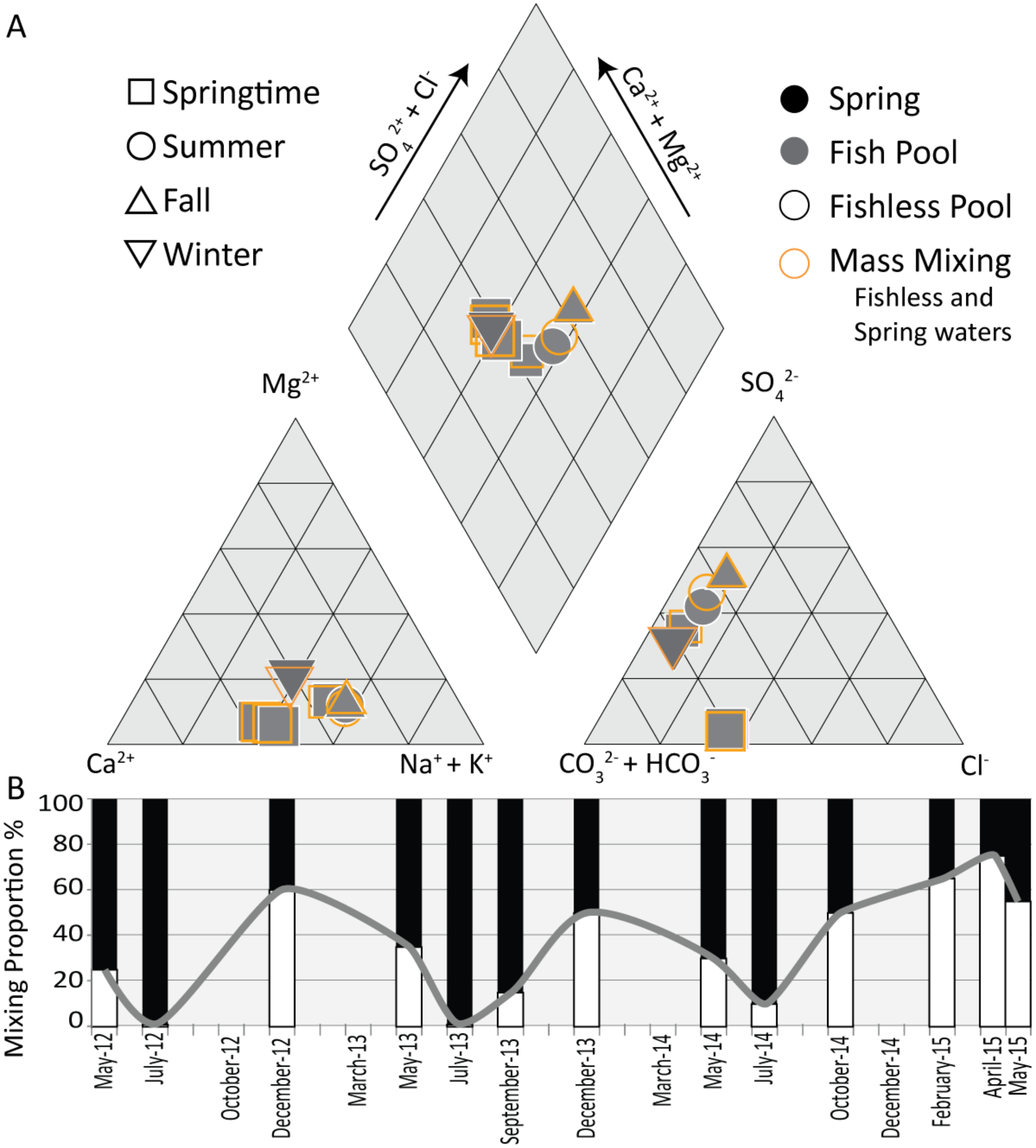


Figure 10. Mass solution mixing model used to determine seasonal mixing scenarios for lower fish pool. A) Piper diagram representing relative proportions of major ions for May 2014-May 2015 Fish Pool (gray) samples and mass mixing (yellow) for same time periods. B) Mixing of spring waters and fishless waters over time.

Regional hydrogeochemistry for spring water

To place the hydrologic flow paths sourcing the springs in a broader context, major ion chemistry was compared to regional ground water chemistry data (Figure 11, full data set available in Appendix IV). Hydrochemical mixing models were performed on known aquifer waters from aquifer units exposed at the site and in the region. To determine flow path and mixing scenarios, the spring water chemistry from October 2014 (Figure 12, black circle) was compared to regional aquifers. Using Geochemist WorkBench (Bethke, 2008) a mass solution mixing model of major ion chemistry as well as saturation indices (comparable to the spring waters) identified two end-members. Throughout the seasons, the spring waters have TDS<400 ppm and therefore regional waters from the Triassic Chinle (TRc) with TDS below 600 ppm (green circles; n=22) were averaged (solid green circle) and mixed with a regional water from the Permian Abo (Pa) that had a TDS<1200 ppm (solid blue circle) and plotted on a Piper diagram (Figure 12). Note the Pa is hydrologically poor quality and reported Pa waters from New Mexico (Figure 11, n=6) had TDS>2000 ppm and were eliminated from the mixing model. The results of the mass solution mixing model (yellow circle) were compared to an AR sample from October 2014. Mixing results indicate that the spring at the Agua Remora site is 80% TRc and 20% Pa.

To determine the amount of young waters recharging the spring, tritium (^3H) sampling was performed on 18 October 2014. ^3H has a half-life of 12.32 years and is found naturally in the Earth's atmosphere due to cosmic rays interacting with nitrogen-14 nuclei. Tritium can be used as an anthropogenic marker due to the influx of ^3H during the testing of nuclear weapons in the 1950's and 60's, with peak amount-weighted mean atmospheric

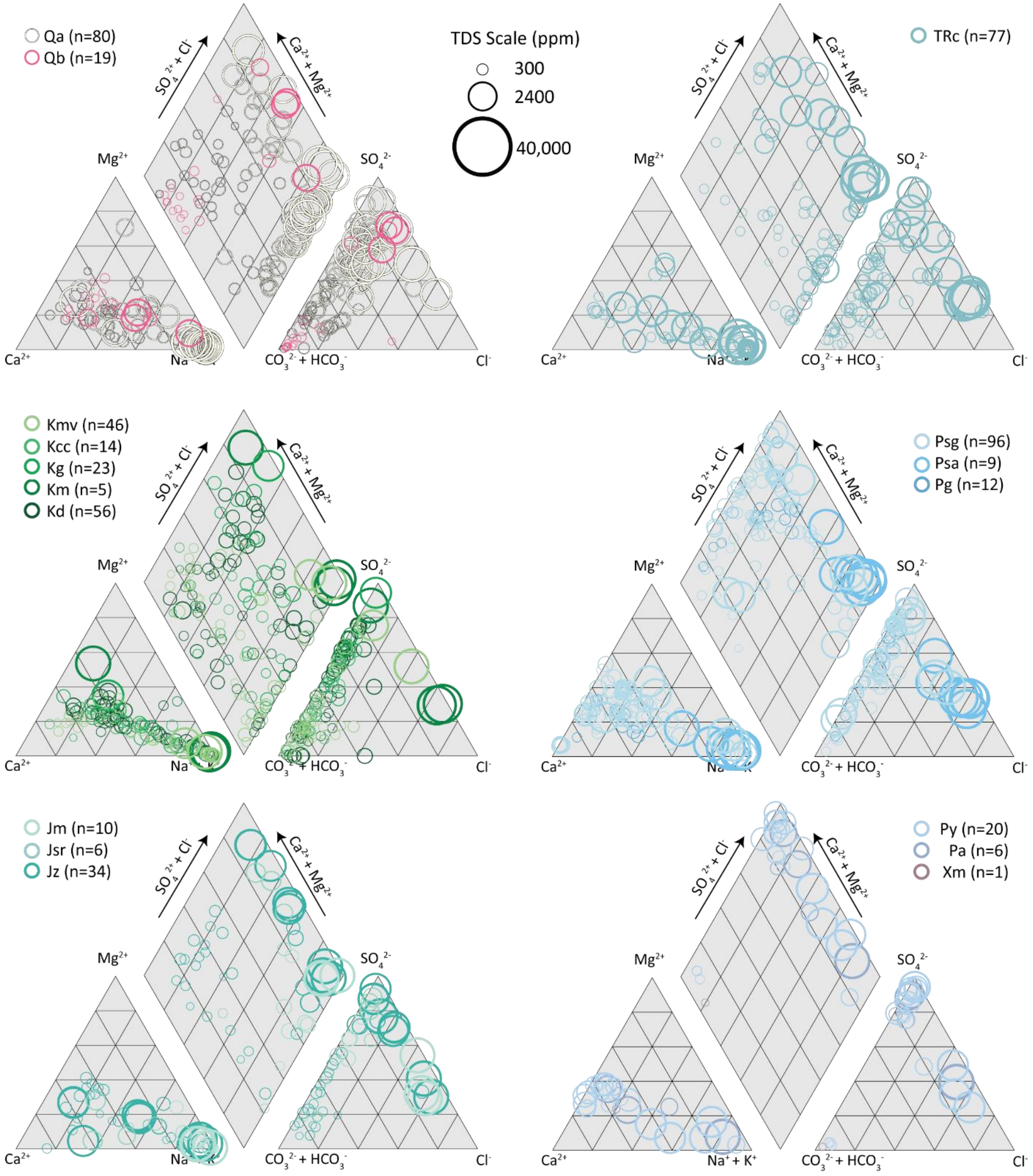


Figure 11. Piper diagrams for regional aquifers from ground water wells and springs. Refer to stratigraphic column (figure 3) for rock units.

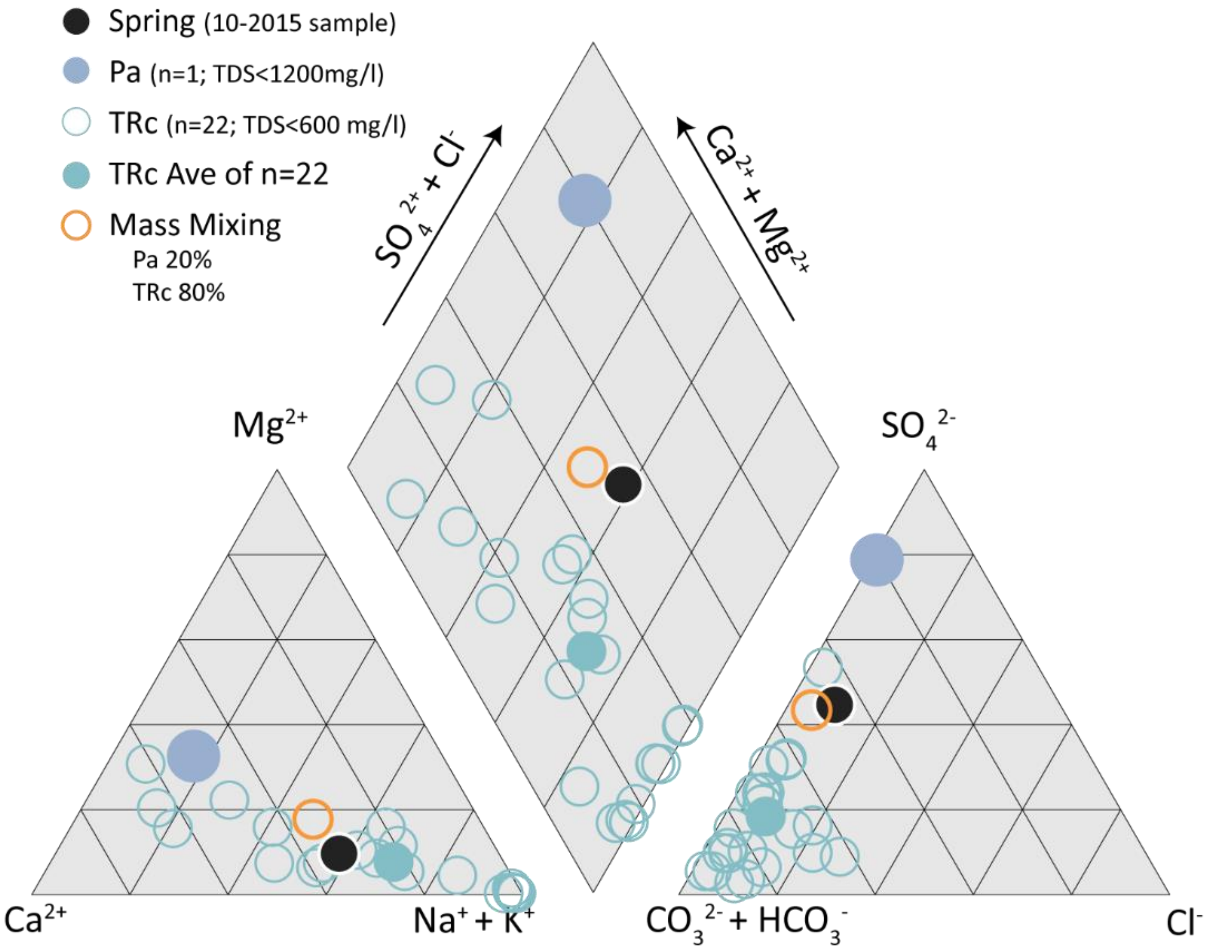


Figure 12. Piper diagram of regional ground waters. Hollow teal circles are Chinle Formation (TRc) waters with TDS<600 mg/l (n=22). Solid teal circle represents an average of TRc waters with TDS <600mg/l. Solid lavender circles are Abo Formation (Pa) waters with TDS<1200mg/l (n=1). Solid black circle is AR spring water from 10/2014. In addition, the orange circle represents a mass solution mixing result of TRc average and Pa with an 80/20 proportion respectively.

concentration (>1000 TU) in 1963 and 1964 (Glynn and Plummer, 2005; Plummer et al., 2004). Nuclear weapons-generated tritium concentrations rained out of the atmosphere in the 1970s and 1980s with precipitation collected from Albuquerque having amount-weighted mean concentrations at 200 TU and 23 TU, respectively (Plummer et al., 2004). Since 1992, seasonal mean tritium concentrations in precipitation is reported to be 9.1 ±3.7

TU for Albuquerque, New Mexico (Eastoe et al., 2012; Plummer et al., 2004). Although measurements of tritium concentration before the 1950's is lacking, natural atmospheric ^{3}H concentrations are estimated to be close to that of post-1992 values. Because of the short half-life, ^{3}H is used to determine the amount of young (post-1950) waters that are stored in aquifers and can help with understanding mixing scenarios (Glynn and Plummer, 2005). Accordingly, water with ^{3}H < 0.5 – 1.1 TU is interpreted to have principally/entirely been recharged before 1952; ^{3}H < 1.5 TU predominately recharged before 1952; ^{3}H = 1.5 TU to > 4 TU is a mix of pre-1952 and modern recharge (5-10 year old recharge); 4 to 10 TU has primarily modern recharge; ^{3}H > 10 TU indicates some nuclear weapons testing precipitation present (1950-1960's recharge) (Drakos et al., 2013; Eastoe et al., 2012). Amount-weighted mean concentrations of tritium for the AR spring waters was found to be 1.5 ± 0.30 TU and is interpreted as being recharged by predominantly older (>70 years) water sources.

Hydrogeochemical data (stable isotopes (δD and δ^{18}O), mass mixing and tritium analysis) are combined with geologic data (geologic mapping, cross-section and stratigraphy) to understand the flow path and residence time of the AR spring waters. More than 70 years ago, snow melt is infiltrated into the TRc in the northeast portions of the Zuni Mountains, outside of the Rio Nutria watershed. This water then flows horizontally toward the west, remaining in the TRc. Near the northern boundary of Oso Ridge, the water intersects a fault and flows vertically down into the Precambrian basement rock. The ground water then flows south and vertically up to mix with the Pa waters and emerges to the surface at the Agua Remora site.

Additional evidence for this flow path along the inferred basement faults are also supported by the specific conductance of the two water sources (Figure 8). While both the spring and fishless waters have a relatively low ion concentrations, the flow path for the spring waters is much longer. The explanation for the longer flow path associated with low conductivity is linked to minimal interaction with the Precambrian quartz monzonite (Xm). While geothermal waters are able to interact with basement rock and undergo significant chemical modification, cooler waters have very little ion exchange with these rocks over shorter timescales (Drever, 1982). We interpret that the AR spring waters carried the initial ion concentration from the TRc interaction upon infiltration and then flowed through the Xm fault and emerged at the Pa/Xm contact where waters mixed, without significant chemical modification.

Conclusions

Using spatial and temporal analyses of major ions, stable isotopes (δD, $\delta^{18}O$) and physico-chemical parameters of spring waters and channel pool-waters above and below the spring discharge, two sources of waters were identified at the AR site. The spring waters are found to have very little variability in the proportions of major ion concentrations and to be primarily recharged from snowmelt that has very limited interaction with the atmosphere. The second water source (fishless) has highly variable major ion concentrations throughout the seasons, is recharged with both rain and snow events and undergoes evaporation. The fishless pool is interpreted to be that of the shallow alluvium that flows in the stream channel from the surrounding area. The LFP is then a mixture of these two water sources. Depending on the season, the spring waters provide between 35-

99% of the LFP waters where in summer and fall the spring is contributing the majority of the waters to the ZBS habitat.

Continuous monitoring data reveals that the fishless pool is a stagnant pool which becomes hypoxic and anoxic due to the lack of movement of water through the system. The LFP is recharged by the spring waters, which provide re-aerated waters that keep the DO levels near the no production impairment limit.

Hydrochemical mixing models indicate that the spring is a mixture of Triassic Chinle Formation (TRc) and Permian (Pa) Abo Formation waters with an 80/20 ratio respectively. Analyzing tritium data on the spring waters indicate that the waters would have recharged more than 70 years ago. Therefore, before 1945, melting snow infiltrated the TRc (located on the eastern and northern flanks of the mountain range), flowed southwest along an unmapped fault through the Xm. The discharge of the spring is at the contact of the Xm and the Pa where small amounts of Pa waters mixed with the TRc waters before emerging to the surface.

It is clear from this work that snowmelt and ground water supplies are imperative for the survival of the ZBS. The DO data are a clear indication of the impacts that the spring waters are having on the ZBS and how essential the perennial spring flows during low flow times are for maintaining the ZBS habitat at the Agua Remora site. Future plans should include priorities for maintaining groundwater levels and managing snowpack where possible with thinning practices.

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References

Anderson, O.J., Maxwell, C.H., Lucas, S.G., 2003. Geology of Fort Wingate quadrangle , McKinley County , New Mexico, Open-file Report 473. Soccoro.

Anderson, O.J., Maxwell, C.H., Lucas, S.G., 1998. Geologic map of Fort Wingate quadrangle. McKinley County, New Mexico. Scale 1:24,000, in: Anderson, O.J., Maxwell, C.H., Lucas, S.G. (Eds.), Geology of Fort Wingate Quadrangle, McKinley County, New Mexico. New Mexico Bureau of Geology and Mienral Resources Open-File Report 47. New Mexico Bureau of Geology and Mineral Resources, Soccoro, p. 16.

Apaydin, A., 2010. Relation of tectonic structure to groundwater flow in the Beypazari region, NW Anatolia, Turkey. Hydrogeol. J. 18, 1343–1356. doi:10.1007/s10040-010-0605-1

APHA, 1999. Standard methods for the examination of water and wastewater, 21st ed. American Public Health Association, American Water Works Association, and Water Pollution Control Federation, Washington, DC.

Armstrong, A.K., Stamm, R.G., Kottlowski, F.E., Mamet, B.L., Dutro, T.J., Weary, D.J., 1994. Facies and age of the Oso Ridge Member (new), Abo Formation, Zuni Mountains, New Mexico. New Mex. Geol. May, 25–30.

Baars, D.L., 1974. Permian rocks of north-central New Mexico, New Mexico Geological Society Guidebook 25th Field Conference. Soccoro.

Baehr, M.M., Degrandpre, M.D., 2002. Under-ice CO2 and O2 variability in a freshwater lake. Biogeochemistry 61, 95–114. doi:10.1023/a:1020265315833

Baldwin, J.A., Anderholm, S.K., 1992. Hydrogeology and ground-water chemistry of the San Andres-Glorieta aquifer in the Acoma embayment and eastern Zuni uplift, west-central New Mexico, Water - Resources Investigations Report 91-4033. Albuquerque.

Baldwin, J.A., Rankin, D.R., 1995. Hydrogeology of Cibola County, New Mexico, Water-Resources Investigations 94-4178. Albuquerque.

Banerjee, A., Person, M., Hofstra, A., Sweetkind, D., Cohen, D., Sabin, A., Unruh, J., Zyvoloski, G., Gable, C.W., Crossey, L.J., Karlstrom, K.E., 2011. Deep permeable fault-controlled helium transport and limited mantle flux in two extensional geothermal systems in the Great Basin, United States. Geology 39, 195–198. doi:10.1130/G31557.1

Barnes, C., 1988. Tracing of water movement in the unsaturated zone using stable isotopes of hydrogen and oxygen. J. Hydrol. 100, 143–176. doi:10.1016/0022-1694(88)90184-9

Bertilsson, S., Burgin, A., Carey, C.C., Fey, S.B., Grossart, H.-P., Grubisic, L.M., Jones, I.D., Kirillin, G., Lennon, J.T., Shade, A., Smyth, R.L., 2013. The under-ice microbiome of seasonally frozen lakes. Limnol. Oceanogr. 58, 1998–2012. doi:10.4319/lo.2013.58.6.1998

Bethke, C.M., 2008. Geochemical and biogeochemical reaction modeling, 2nd ed. University Press, Cambridge.

Blanchard, P.J., 2004. Precipitation; groundwater age; groundwater nitrate concentrations, 1995-2002; and groundwater levels, 2002-03 in Eastern Bernalillo County, New Mexico, U.S. Geological Survey Scientific Investigations Report 2004-5189.

Canada, S., 2012. User guide Levelogger series software version 4. User Guid.

Carman, S.M., 2004. Zuni Bluehead sucker (Catostomus discobolus yarrowi) recovery plan. Santa Fe,.

Colpitts, R.M.J., 1969. Permian reference section for southeastern Zuni Mountains, Cibola County, New Mexico. New Mexcio Geol. Soc. Guid. 10th F. Conf. 8.

Connell, S.D., 2011. Preliminary study of the geologic framework of the Colorado Plateau – Middle Rio Grande Basin Transition, New Mexico, Open-file Report 539. Soccoro.

Cooley, M.E., Harshbarger, J.W., Akers, J.P., Hardt, W.F., 1969. Regional hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah. Professional Paper 521-A. Washington, DC.

Craig, H., 1961. Isotopic variations in meteoric waters. Science 133, 1702–1703. doi:10.1126/science.133.3465.1702

Crossey, L.J., Fischer, T.P., Patchett, P.J., Karlstrom, K.E., Hilton, D.R., Newell, D.L., Huntoon, P., Reynolds, A.C., de Leeuw, G. a M., 2006. Dissected hydrologic system at the Grand Canyon: Interaction between deeply derived fluids and plateau aquifer waters in modern springs and travertine. Geology 34, 25–28. doi:10.1130/G22057.1

Crossey, L.J., Karlstrom, K.E., Springer, A.E., Newell, D., Hilton, D.R., Fischer, T.P., 2009. Degassing of mantle-derived CO2 and He from springs in the southern Colorado Plateau region - Neotectonic connections and implications for groundwater systems. Bull. Geol. Soc. Am. 121, 1034–1053. doi:10.1130/B26394.1

Dahm, C.N., 1981. Pathways and mechanisms for removal of dissolved organic carbon from leaf leachate in streams. Can. J. Fish. Aquat. Sci. 38, 68–76. doi:10.1139/f81-009

Dahm, C.N., Candelaria-Ley, R.I., Reale, C.S., Reale, J.K., Van Horn, D.J., 2015. Extreme water quality degradation following a catastrophic forest fire. Freshw. Biol. 16. doi:10.1111/fwb.12548

Daly, C., Weisburg, J., 1997. Average annual precipitation New Mexico [WWW Document]. URL http://www.wrcc.dri.edu/pcpn/nm.gif (accessed 6.10.15).

Darton, N.H., 1928. “Red Beds” and associated formation in New Mexico, Bulletin 794. Washington, DC.

Drakos, P.G., Riesterer, J.W., Bemis, K., 2013. Recharge sources and characteristics of springs on the Zuni Reservation, New Mexico, in: Zeigler, K., Timmons, M., Timmons, S., Semken, S. (Eds.), New Mexico Geological Society Guidebook, 64th Field Conference, Geology of Route 66 Region: Flagstaff to Grants, 2013. New Mexico Geologic Society, Soccoro, pp. 205–213.

Drever, J.I., 1982. The Geochemistry of Natural Waters, 1st ed. Prenctice-Hall, Englewood Cliffs.

Eastoe, C.J., Watts, C.J., Ploughe, M., Wright, W.E., 2012. Future use of tritium in mapping pre-bomb groundwater volumes. Ground Water 50, 87–93. doi:10.1111/j.1745-6584.2011.00806.x

Erslev, E.A., 1991. Trishear fault-propagation folding. Geology 19, 617–620.

Giannini, A., Chiang, J.C.H., Cane, M.A., Kushnir, Y., Seager, R., 2001. The ENSO teleconnection to the Tropical Atlantic Ocean: Contributions of the remote and local SSTs to rainfall variability in the Tropical Americas. J. Clim. 14, 4530–4544. doi:10.1175/1520-0442(2001)014<4530:TETTTT>2.0.CO;2

Gido, K.B., Propst, D.L., 1999. Habitat use and association of native and nonnative fishes in the San Juan River, New Mexico and Utah. Copeia 1999, 321–332. doi:10.2307/1447478

Gilbert, E.I., Carman, S.M., 2013. Zuni Bluehead Sucker monitoring and conservation efforts 2011 and 2012. Santa Fe.

Glynn, P.D., Plummer, L.N., 2005. Geochemistry and the understanding of ground-water systems. Hydrogeol. J. 13, 263–287. doi:10.1007/s10040-004-0429-y

Goddard, E.N., 1966. Geologic map and sections of Zuni Mountains fluorspar district. Valencia County, New Mexico. Scale 1:31,680.

Grimm, N.B., Chacon, A., Dahm, C.N., Hostetler, S.W., Lind, O.T., Starkweather, P.L., Wurtsbaugh, W.W., 1997. Sensitivity of aquatic ecosystems to climatic and anthropogenic changes: the Basin and Range, American Southwest and Mexico. Hydrol. Process. 11, 1023–1041. doi:10.1002/(SICI)1099-1085(19970630)11:8<1023::AID-HYP516>3.0.CO;2-A

Gudmundsson, A., 2000. Active fault zones and groundwater flow. Geophys. Res. Lett. 27, 2993–2996. doi:10.1029/1999GL011266

Gupta, P., Noone, D., Galewsky, J., Sweeney, C., Vaughn, B.H., 2009. Demonstration of high-precision continuous measurements of water vapor isotopologues in laboratory and remote field deployments using wavelength-scanned cavity ring-down spectroscopy (WS-CRDS) technology. Rapid Commun. Mass Spectrom. 23, 2534–2542.

Harrington, G.A., Cook, P.G., Herczeg, Andrew, L., 2002. Spatial and temporal variability of ground water recharge in Central Australia: A tracer approach. Ground Water 40, 518–528.

Hautman, D.P., Munch, D.J., 1997. Determination of inorganic anions in drinking water by ion chromatography. Method 300.1. Matrix 40.

Heckert, A.B., 1999. Upper Triassic Tetrapods from the Lucero Uplift, central New Mexico, New Mexico Geological Society Guidebook, 50th Field Conference. Soccoro.

Heckert, A.B., Lucas, S.G., 2003. Triassic stratigraphy in the Zuni Mountains, west-central New Mexico, New Mexcio Geological Society Guidbook, 54th Field Conference. Soccoro.

Hoerling, M., Eischeid, J., Kumar, A., Leung, R., Mariotti, A., Mo, K., Schubert, S., Seager, R., 2014. Causes and predictability of the 2012 great plains drought. Bull. Am. Meteorol. Soc. 95, 269–282. doi:10.1175/BAMS-D-13-00055.1

Hoerling, M., Kumar, A., 2003. The perfect ocean for drought. Science 299, 691–694. doi:10.1126/science.1079053

Hood, J., Kister, L., 1962. Saline-water resources of New Mexico, Geological Survey Water-Supply Paper 1601. Washington, DC.

Hubbs, C., 1995. Springs and Spring Runs as Unique Aquatic Systems. Copeia 989–991.

Hunter-Lynn, C.I., 2013. Personal communications.

Hynes, H.B.., 1983. Groundwater and stream ecology. Hydrobiologia 100, 93–99.

Jacobs, K.L., Holway, J.M., 2004. Managing for sustainability in an arid climate: Lessons learned from 20 years of groundwater management in Arizona, USA. Hydrogeol. J. 12, 52–65. doi:10.1007/s10040-003-0308-y

Karlstrom, K.E., Dallmeyer, R.D., Grambling, J.A., 1997. Ar evidence for 1.4 Ga regional metamorphism in New Mexico: Implications for thermal evolution of lithosphere in the southwestern USA. J. Geol. 105, 205–224. doi:10.1086/515912

Kelley, V.C., 1967. Tectonics of the Zuni-Defiance region, New Mexico and Arizona, Guidebook of the Defiance - Zuni - Mt. Taylor Region Arizona and New Mexico. 18th Field Conference. New Mexico Geologic Society, Soccoro.

Krainer, K., Lucas, S.G., Kues, B.S., 2003. Upper Pennsylvanian strata in the Zuni Mountains, west-central New Mexico, New Mexico Geological Society Guidebook, 54th Field Conference. Soccoro.

Langman, J.B., Sprague, J.E., Durall, R.A., 2012. Geologic framework, regional aquifer properties (1940s-2009), and spring, creek and seep properties (2009-10) of the Upper San Mateo Creek Basin near Mount Taylor, New Mexico, U.S. Geological Survey Scientific Investigations Report 2012-5019. Reston, Virginia.

MacDonald, G.M., 2010. Climate change and water in Southwestern North America special feature: water, climate change, and sustainability in the southwest. Proc. Natl. Acad. Sci. U. S. A. 107, 21256–62. doi:10.1073/pnas.0909651107

Manga, M., 1999. On the timescales characterizing groundwater discharge at springs. J. Hydrol. 219, 56–69. doi:10.1016/S0022-1694(99)00044-X

Manga, M., 1996. Hydrology of spring-dominated streams in the Oregon Cascades. Water Resour. Res. 32, 2435–2439. doi:10.1029/96WR01238

Martin, T.D., Brockhoff, C.A., Creed, J.T., 1994. Determination of metals and trace elements in water and wastes by Inductively Coupled Plasma-Atomic Emissions Spectrometry. Method 200.7. Usepa 4.4, 1–58.

Minckley, W.L., Deacon, J.E., 1991. Battle against extinction. Native fish management in the American southwest. University of Arizona Press, Tucson.

Minckley, W.L., Douglas, M.E., 1991. Discovery and extinction of western fishes: A blink of the eye in geologic time. Chapter 1, in: Minckley, W.L., Deacon, J.E. (Eds.), Battle Against Extinction: Native Fish Management in the American Southwest. University of Arizona Press, Tucson, pp. 1–7.

Newell, D.L., Crossey, L.J., Karlstrom, K.E., Fischer, T.P., Hilton, D.R., 2005. Continental-scale links between the mantle and groundwater systems of the western United States: Evidence from travertine springs and regional He isotope data. GSA Today 15, 4–10. doi:10.1130/1052-5173(2005)015[4:CSLBTM]2.0.CO;2

Newton, B.T., Rawling, G.C., Timmons, S.S., Land, L., Johnson, P.S., Kludt, T.J., Timmons, J.M., 2012. Sacramento Mountains hydrogeology study, Final Technical Report

Prepared for Otero Soil and Water Conservation District. Open-File Report 543. Soccoro.

Oakton, 2000. Portable Waterproof pH/Con 300 Meter, R1 ed. U.S.A.

Orr, B.R., 1987. Water resources of the Zuni tribal lands , McKinely and Cibola Counties, New Mexico, Water-Supply Paper 2227. Washington, DC.

Overpeck, J., Udall, B., 2010. Dry times ahead. Science 328, 1642–1644.

Paul, D., Mitra, S., 2012. Control of basement faults on the geometry and evolution of compressional basement-involved structures. Am. Assoc. Pet. Geol. Bull. 96, 1899–1930. doi:10.1306/02271211140

Perla, B.S., Stevens, L.E., 2008. Biodiversity and productivity at an undisturbed spring in comparison with adjacent grazed riparian and upland habitats, in: Stevens, L.E., Meretsky, V.J. (Eds.), Aridland Springs in North America Ecology and Conservation. The University of Arizona Press and The Arizona-Sonora Desert Museum, Tucson, pp. 230–243.

Phillips, F.M., Walvoord, M.A., Small, E.E., 2013. Effects of environmental change on groundwater recharge in the desert southwest, in: Groundwater Recharge in a Desert Environment: The Southwestern United States. pp. 273–294. doi:10.1029/009WSA15

Piper, A.M., 1944. A graphical procedure in the geochemical interpretation of water analyses. Geophys. Union Trans. 25, 914–923.

Plummer, L.N., Bexfield, L.M., Anderholm, S.K., Sanford, W.E., Busenberg, E., 2004. Geochemical characterization of ground-water flow in the Santa Fe Group aquifer system, Middle Rio Grande Basin, New Mexico, U.S. Geological Survey Water-Resources Investigation Report 03-4131.

Pool, T.K., Olden, J.D., 2015. Assessing long-term fish responses and short-term solutions to flow regulation in a dryland river basin. Ecol. Freshw. Fish 24, 56–66. doi:10.1111/eff.12125

Propst, D.L., 1999. Threatened and endangered fishes of New Mexico, Technical Report No. 1. Santa Fe,.

Propst, D.L., Gido, K.B., Stefferud, J.A., 2008. Natural flow regimes, nonnative fishes, and native fish persistence in arid-land river systems. Ecol. Appl. 18, 1236–1252. doi:10.1890/07-1489.1

Propst, D.L., Hobbes, A.L., Stroh, T.L., 2001. Distribution and notes on the biology of Zuni Bluehead Sucker, Catostomus discobolus yarrowi, in New Mexico. Southwest. Nat. 46, 158–170.

Repenning, C.A., Cooley, M.E., Akers, J.P., 1969. Stratigraphy of the Chinle and Moenkopi Formations, Navajo and Hopi Indian reservations, Arizona, New Mexico, and Utah, United States Geological Survey Professional Paper 521-B. Arlington.

Robertson, A.J., Henry, D.W., Langman, J.B., 2013. Geochemical evidence of groundwater flow paths and the fate and transport of constituents of concern in the alluvial aquifer at Fort Wingate Depot Activity , New Mexico, 2009, U.S. Geological Survey Scientific Investigations Report 2013 – 5098. Reston.

Romanini, D., Kachanov, A.A., Stoeckel, F., 1997. Diode laser cavity ring down spectroscopy. Chem. Phys. Lett. 270, 8.

Ruhí, A., Holmes, E.E., Rinne, J.N., Sabo, J.L., 2014. Anomalous droughts, not invasion, decrease persistence of native fishes in a desert river. Glob. Chang. Biol. 21, 1482–1496. doi:10.1111/gcb.12780

Seager, R., Kushnir, Y., Herweijer, C., Naik, N., Velez, J., 2005. Modeling of tropical forcing of persistent droughts and pluvials over western North America: 1856-2000. J. Clim. 18, 4065–4088. doi:10.1175/JCLI3522.1

Sharp, Z., 2006. Priniciples of Stable Isotope Geochemistry, 1st ed. Pearson Prentice Hall, Upper Saddle River, New Jersey.

Shoemaker, J.W., 1971. Water resources of Fort Wingate Army Depot and adjacent areas, McKinley County, New Mexico. U.S. Geol. Surv. Water-Resources Investig. Rep. 230.

Springer, A.E., Stevens, L.E., 2009. Spheres of discharge of springs. Hydrogeol. J. 17, 83–93. doi:10.1007/s10040-008-0341-y

Stevens, L.E., Meretsky, V.J., 2008a. Aridland springs in North America ecology and conservation. University of Arizona Press and The Arizona-Sonora Desert Museum, Tucson.

Strickland, D., Heizler, M.T., Selverstone, J., Karlstrom, K.E., 2003. Proterozoic evolution of the Zuni Mountains, western New Mexico: Relationship to the Jemez Lineament and implications for a complex cooling history, New Mexico Geological Society Guidebook, 54th Field Conference. Soccoro.

Turner, T.F., Wilson, W.D., 2009. Conservation genetics of Zuni Bluehead Sucker (Catostomus discobolus yarrowi) in New Mexico, Final Report Contract # 09-516-0000-00017. Albuquerque.

Unmack, P.J., Minckley, W.L., 2008. The demise of desert springs, in: Stevens, L.E., Meretsky, V.J. (Eds.), Aridland Springs in North America Ecology and Conservation. The University of Arizona Press and The Arizona-Sonora Desert Museum, Tucson, pp. 11–34.

USEPA, 2014. Water quality standards handbook (40 CFR 131 - Subpart C). Washington, DC.

USEPA, 2002. Standard operating procedure for calibration and field measurement procedures for the YSI Model 6-series Sondes (including: temperature, pH, specific conductance, turbidity, and dissolved oxygen). North Chelmsford.

USFWS, 2014. DOI Federal Register: Endangered and threatened wildlife and plants; endangered species status for the Zuni Bluehead sucker; Final Rule. 50 CFR Part 17., Federal Register.

USFWS, 2013. Endangered and threatened wildlife and plants; proposed endangered status for the Zuni Bluehead Sucker, Federal Register.

Wagner, R.J., Boulger, Jr., R.W., Oblinger, C.J., Smith, B.A., 2006. Guidelines and standard procedures for continuous water-quality monitors: station operation, record computation, and data reporting. USGS Tech. Methods 1-D3, 96.

Williams, A.J., Crossey, L.J., Karlstrom, K.E., Newell, D., Person, M., Woolsey, E., 2013. Hydrogeochemistry of the Middle Rio Grande aquifer system — Fluid mixing and salinization of the Rio Grande due to fault inputs. Chem. Geol. 351, 281–298. doi:http://dx.doi.org/10.1016/j.chemgeo.2013.05.029

Wilson, M.J., 2004. Weathering of the primary rock-forming minerals: processes, products and rates. Clay Miner. 39, 233–266. doi:10.1180/0009855043930133

YSI Incorporated, 2009. Multiparameter water quality Sondes user manual 6-series. YSI Incorporated.

Zektser, S., Loáiciga, H.A., Wolf, J.T., 2005. Environmental impacts of groundwater overdraft: Selected case studies in the southwestern United States. Environ. Geol. 47, 396–404. doi:10.1007/s00254-004-1164-3

Appendices

The following appendices have been submitted separately from this dissertation as supplemental material.

Appendix I. Dissolved Oxygen Concentrations for Surface Waters at Agua Remora, Zuni Mountains, New Mexico

Appendix II. Daily Mean Dissolved Oxygen Concentrations for Surface Waters at Agua Remora, Zuni Mountains, New Mexico

Appendix III. Ground Water Quality of Zuni Mountains, New Mexico

Chapter 2: Multidisciplinary Approach to Link Water Quality to Aquatic Biological Communities in Desert Springs

Authors: Rebecca J. Frus, Rebecca J. Bixby, Ayesha S. Burdett, Laura J. Crossey, Louis Scuderi

Abstract

Perennial waters and associated aquatic habitats, in the desert Southwestern United States, are dependent on ground water discharge at spring sites. Arid land spring waters provide surface waters for aquatic habitats of endemic and endangered species and are areas of rich biodiversity. Over use of ground water for anthropogenic purposes coupled with drought and climate change has reduced water quality and quantity. Seasonal sampling of hydrochemistry and several years of continuous monitoring of physico-chemical parameters of specific conductance (SC), water temperature and dissolved oxygen were used to propose a water quality stability classification (WQSC). For this research we examined five sites within the Zuni Mountains, west-central New Mexico to quantify the WQSC and examined associated biological communities. Results indicate that in these arid land streams, three pools located downstream from springs discharge have high WQSC. High WQSC has low variability in hydrochemistry and measurements of specific conductance (SC) that deviate below baseline conditions due to large rain events (>10mm) or cumulative days of rain (6 days with >10 mm). High WQSC pools maintain non-impairment levels of dissolved oxygen to support desert fish and diverse biological communities. One pool, located upstream from spring discharge, was identified to have medium WQSC where perennial, stagnant waters have high variability in hydrochemistry

and specific conductance measurements that respond to rain similarly to high WQSC. In contrast, medium WQSC pools are also impacted by the lack of rain where evaporation increases SC above baseline conditions. Additionally, medium WQSC have stagnant waters that became anoxic such that desert fish are not able to survive and biological communities were markedly different from high WQSC pools. One pool, lacking spring waters, have low WQSC such that the stream area dries. The low WQSC is effected by rain events and the lack of rain. Stream areas that dry also showed a notable difference in the biological community that was present when the area was wet. These findings utilize variability in hydrochemistry and continuous monitoring of physico-chemical parameters to propose a WQSC where preliminary results indicate that aquatic biological communities are different based on the WQSC. Due to unknown impacts of climate change, this work underscores the importance of continued monitoring of physico-chemical parameters in sensitive habitats to identify the influence of perennial spring discharge, changes to water quality and differences in biological communities.

Introduction

Spring waters create habitats that support a considerable proportion of the freshwater biodiversity found in the desert southwestern United States (Sada et al., 2005). Continuous discharge of ground water at spring sites may provide the only perennially-wet sections of entire stream systems (Kreamer and Springer, 2008; Springer and Stevens, 2009). Year-round ground water discharge has been linked to increased biodiversity within arid land spring ecosystems (Bogan and Lytle, 2007). Spring-fed ecosystems in arid environments have a high concentration of endemism (Kodric-Brown and Brown, 2007;

Springer and Stevens, 2009; Stevens and Springer, 2005) and have been identified as isolated islands that provide stable habitats for endemic species (Cantonati et al., 2012; Stevens and Meretsky, 2008). Biodiversity within spring habitats can be completely different from other (even adjacent) wetland habitats (Bogan and Lytle, 2007; Cantonati et al., 2012).

Water quality stability for aquatic habitats is maintained through long-term (decades to centuries) presence of surface water. Species diversity can be significantly affected by the loss of water (Boulton and Lake, 1992). In addition, seasonal changes in water temperature and conductivity can be significant drivers to dramatically shift biological assemblages (Cantonati et al., 2012; Grimm et al., 1997; van der Kamp, 1995). Connectivity of perennially wet and intermittently wet sections of desert streams has been shown to drive biological diversity in aquatic communities (Bogan et al., 2013). For example, in high elevation headwater streams of the Sonoran desert, significant aquatic insect community differences were found between areas with perennially wet sections and areas that dried (Bogan and Lytle, 2007). When surface water velocity is eliminated and pools become stagnant, oxygen concentrations are reduced and species richness can be sharply reduced (Boulton and Lake, 1992). Loss of surface flow leads to a rise in water temperature, an increase in conductivity and a decrease in dissolved oxygen concentrations, which can also lead to changes in the biological abundance and diversity (Bogan et al., 2014; Boulton and Lake, 1992; Grimm et al., 1997; van der Kamp, 1995). Diversity can decline gradually in drying stream reaches, and can be linked to the frequency and extent of drying in the habitat (Bogan et al., 2014).

Finally the effects of total water loss and complete drying of aquatic habitats can lead to catastrophic, long term loss of biodiversity (Bogan and Lytle, 2011; Bogan et al., 2014).

Across the arid Southwest of the United States, ground water springs are drying, and historically productive aquatic habitats have seen significant losses of biodiversity (Sada et al., 2005) and spatial areal extent (Bogan and Lytle, 2011; Grimm et al., 1997). Much of these losses are due to overuse of ground water resources (Merritt and Bateman, 2012; Zektser et al., 2005), drought (Hoerling and Kumar, 2003; Ruhí et al., 2014) and climate change (Loáiciga, 2003; Phillips et al., 2013; Taylor et al., 2013). The loss of area for aquatic ecosystems, due to the lack of water, is predicted to increase as the planet continues to warm (Carpenter et al., 2011; Klove et al., 2011).

Spring ecosystems in arid regions have had very little comprehensive, multidisciplinary research performed. Controversial demands on spring waters has led to understanding some of the hydrologic, geomorphologic and biological characteristics, but little effort has been made to understand the ecosystem as a whole (Cantonati et al., 2012; Newman et al., 2006; Stevens and Meretsky, 2008b). In this research, we hypothesize that variability in water quality stability (hydrochemistry and physico-chemical parameters) influences the biodiversity of desert aquatic ecosystems.

To further understand the influence of desert springs we used variability in major ion concentrations, stable isotopes, specific conductance, dissolved oxygen and water temperature to develop a water quality stability classification (WQSC). We then present preliminary data that identified differences within biological communities based on different WQSC's. This multidisciplinary approach describes aquatic habitats upstream from springs (low and medium WQSC) and downstream from springs (high WQSC). Understanding how differences in WQSC can impact biodiversity of desert springs habitats provides knowledge about how spring waters and aquatic habitats can be affected by drought, overuse of ground waters and potential impacts of climate change (Grimm et al., 1997; Overpeck and Udall, 2010). This knowledge can be used to help inform resource managers on the preservation of desert aquatic systems.

Regional Setting

The Zuni Mountains of west-central New Mexico are located in the southeast portion of the Colorado Plateau (Figure 1). The precipitation patterns for the Zuni Mountains are bi-modal with snowfall from January through March and monsoonal rain from July through August. The average annual precipitation for the region from 1961-1990 is approximately 350 mm per year (Daly and Weisburg, 1997). Since 2000 the region has experienced abnormal to extreme drought conditions with SNOTEL data for April 01, 2012 reporting 0% of normal snow water equivalent (National Weather Service, 2012). However, the Zuni Mountain region received more than 100% of its normal precipitation in the 2015 water year (National Weather Service, 2015).

The Zuni Mountains are an uplifted 1655 Ma quartz monzonite (Xm) block that is highly fractured due to repeated deformation since the early Proterozoic (Karlstrom et al., 1997; Strickland et al., 2003) (Figure 2). In unconformable contact with the Xm is Paleozoic and Mesozoic sedimentary strata that show evidence of being thinned, thickened and fractured (Baldwin and Anderholm, 1992; Baldwin and Rankin, 1995; Connell, 2011; Robertson et al., 2013). Due to geologically historic compressional and tensional forces the subsurface of the Zuni Mountains is a complex pattern of folds and faults (Karlstrom et al., 1997; Strickland et al., 2003). These geologic structures provide pathways for vertical flow of water and have a concentration of springs along the faults zones (Drakos et al., 2013; Williams et al., 2013).

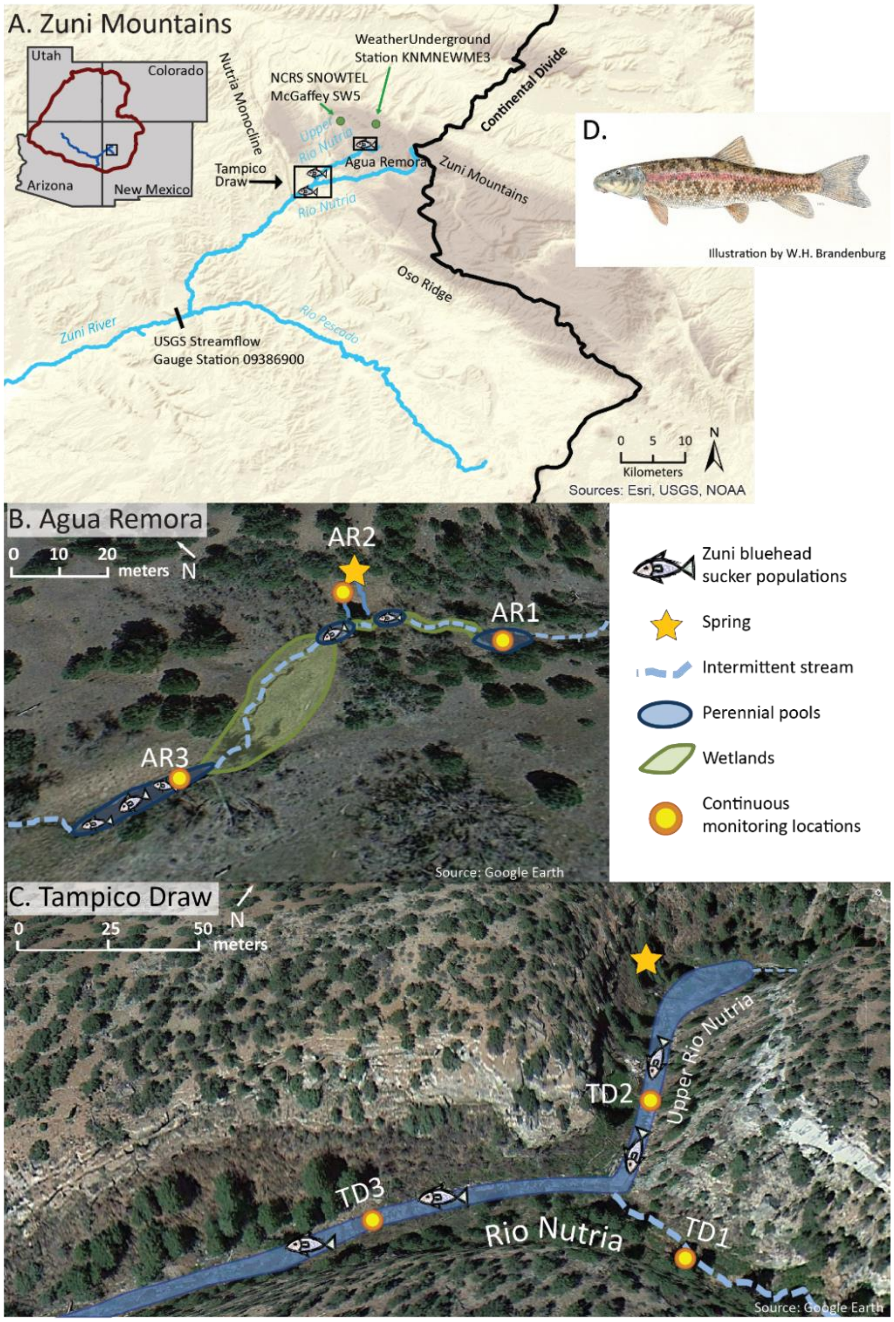
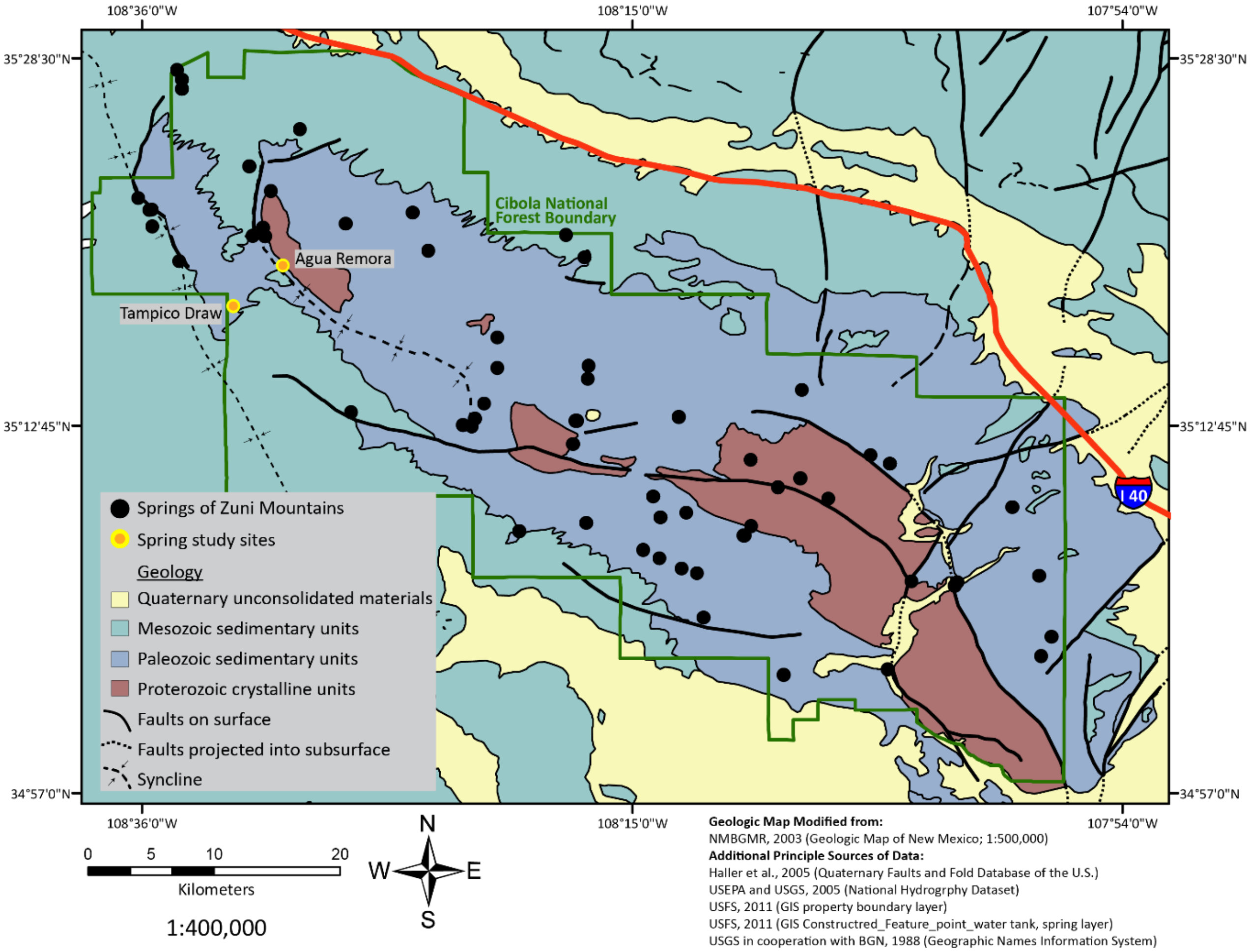


Figure 1. Spring site locations. A) Digital elevation map of Zuni Mountains and Rio Nutria and Zuni River (blue) with current ZBS populations (fish), weather stations (green dots), USGS gauge station (black dash) and Continental Divide. (Inset: 4 Corners area with Colorado Plateau and Little Colorado River. B) Google Earth image of ZBS habitat at Agua Remora with spring (star) and ZBS fish populations (fish) and monitoring stations (yellow circles). C) Google Earth image of ZBS habitat at Tampico Draw on the Rio Nutria with spring (star) and ZBS fish populations (fish) and monitoring stations (yellow circles). D) Illustration of Zuni Bluehead Sucker (*Catostomus discobolus yarrowi*).



Geologic Map Modified from:
NMBGMR, 2003 (Geologic Map of New Mexico; 1:500,000)
Additional Principle Sources of Data:
Haller et al., 2005 (Quaternary Faults and Fold Database of the U.S.)
USEPA and USGS, 2005 (National Hydrogrphy Dataset)
USFS, 2011 (GIS property boundary layer)
USFS, 2011 (GIS Constructred_Feature_point_water tank, spring layer)
USGS in cooperation with BGN, 1988 (Geographic Names Information System)

Figure 2. Geologic map of Zuni Mountains showing rock units exposed along with large mapped faults and spring locations within the Cibola National Forest.

The geologic units of the Zuni Mountains have variable hydrologic capabilities (Robertson et al., 2013). The region's primary water supplies are stored in the hydrologically connected Permian Glorieta Sandstone and San Andres Limestone (Psg) confined aquifer. The Psg has the highest water quality and productivity in the region (Baldwin and Anderholm, 1992; Baldwin and Rankin, 1995; Robertson et al., 2013). Additional aquifers in the Zuni Mountains store water locally, including confined layers within the Triassic Chinle (TRc) and unconfined units in the Quaternary Alluvium (Qa).

Mechanisms for recharging confined aquifers rely on snowpack as the principal source for infiltration over recharge areas for the confined aquifer, while unconfined desert alluvium can be recharged through both snow and rain events (Shanafield and Cook, 2014). Understanding the hydrogeology and recharge mechanisms of spring sites can greatly inform how climate change, drought and land use practices will alter aquatic spring ecosystems along the reach where the WQSC was measured.

Site Description

Two spring sites within the western Zuni Mountains were examined (Figure 1), Agua Remora (AR) and Tampico Draw (TD). Both AR and TD are located within the Rio Nutria drainage basin, where the springs discharge out of the stream channel and flow into the stream channel. The Rio Nutria is an intermittent headwater stream that flows west from the continental divide and has a confluence with the Zuni River on the Zuni Pueblo (Figure 1). Perennially wet sections of the Rio Nutria are mostly found downstream from spring discharge locations making springs of the Zuni Mountains critical for wetland and aquatic habitats. AR and TD springs are approximately eight kilometers apart and discharge from different confined aquifers. The AR and TD sites are hydrologically separated where the stream goes dry between the sites except in extreme flow events.

Since the 1970's, Zuni Mountain spring and stream ecosystems have been highly altered by water resource development (Poff and Richter, 2012), poisoning of endemic fish (USFWS, 2014), introduction of non-native fish (Pool and Olden, 2015), and overgrazing and drought (Drakos et al., 2013; Robertson et al., 2013). In general, Zuni Mountain springs have been drying due to drought and ground water withdrawal (Drakos et al., 2013).

The Zuni Bluehead Sucker (ZBS) (*Catostomus discobolus yarrowi*) (Figure 1) is the only remaining endemic fish species still found in Zuni River drainage (Propst, 1999; Propst et al., 2008, 2001). The aquatic habitat for the ZBS has seen a 90% reduction since the 1970's (Gido and Propst, 1999; USFWS, 2014). In 2014 the ZBS was federally listed as endangered (USFWS, 2014) and its habitat was recognized to be critical as it is limited to isolated patches in the Rio Nutria where perennial spring water provides refugia (Carman, 2004; Gilbert and Carman, 2013; Turner and Wilson, 2009). For the purposes of this research, the ZBS habitats are ideal indicators of high water quality and stability, and aquatic biodiversity because they represent desert aquatic ecosystems that have perennial spring waters (Magurran, 2009).

Five sites within TD and AR were selected to measure water quality stability (WQS). Three sites (2 at TD, 1 at AR) are downstream from springs discharge, have provided refugia for the endangered ZBS since the 1970's and are considered to have high WQS. Upstream from the spring discharge at AR is a perennial pool (AR1) that becomes stagnant and anoxic during dry seasons (Frus et al., in review), has historically not been able to maintain ZBS populations (Carman, 2004), and is considered medium WQS. Upstream from the spring discharge at TD is an ephemeral pool (TD1) that has not been able to maintain ZBS populations since 1992 because it dries during summer months (Carman, 2004) and is considered to have low WQS.

Agua Remora (AR) includes a low-flow hillslope spring (< 80 cm^3/sec) that provides perennials waters to ZBS habitat (Figure 1B). The spring and ZBS habitat are located on public lands managed by Cibola National Forest (USFS). The AR stream bed is primarily made up of cobbles and pebbles of grus with some large (2 m) granite boulders strewn down the length of the site. The spring (AR2) discharges into the middle two perennial pools and flows downstream to the lowest of the ZBS habitats (AR3). The fourth perennial pool (AR1), upstream from the spring discharge, is a stagnant pool that has not been able to maintain ZBS populations (Figure 1B).

Downstream from Agua Remora at the confluence of the Upper Rio Nutria and the Rio Nutria, are two additional populations of ZBS (Figure 1c). The confluence of the intermittent rivers is found within Tampico Draw (TD). The TD area is on land owned and maintained by The Nature Conservancy. TD is a narrow box canyon comprised of cross bedded sandstone, 80 m deep and 20 m wide. The length of the northwest canyon wall has small travertine deposits (star) from ground waters seeping along cross bedding contacts within limey-sandstone. The north wall is covered with moss and vines during warm months and is identified as a hanging garden spring that seeps perennial waters to ZBS habitats (Figure 1c). At the confluence, the canyon widens, has less relief and makes a sharp left turn to flow more westward. The stream bed is wider and pools in the sandstone bedrock are somewhat deeper. The creek has aggregated sections of pools with loose pebbles and cobbles. These perennial pools are the habitat for ZBS populations at the TD site.

At TD, one ZBS population is located above the confluence, within the Upper Rio Nutria (TD2). The second population is in the Rio Nutria below the confluence (TD3), located 0.5 km downstream (Figure 1c). The Rio Nutria above the confluence (TD1) has been ephemerally dry since 1993 and has no known spring source (Carman, 2004; Gilbert and Carman, 2013). After snowmelt and large rain events, a pool is formed at TD1, but becomes dry in summer months.

Hydrogeochemical work indicates two distinct flow paths to both ZBS habitats. The first, and most consistent, is the water supplied by the springs. Both springs are from confined aquifers that are recharged through snowmelt that was infiltrated more than 50 years ago (Drakos et al., 2013, Frus et al., in review). The second flow path is from the shallow alluvium found within the creek beds upstream from the spring discharge (AR1) or above the confluence within the Rio Nutria (TD1). These shallow alluvium are recharged through both snow and large rain events and is highly impacted by evaporation. During dry seasons, AR1 is a no-flow stagnant pool which becomes anoxic and TD1 dries completely. Previous work on seasonal samples indicates that the spring (AR2) provides up to 99% of waters for ZBS habitats (AR3) during dry months (Frus et al, in review).

Methods

To develop a water quality stability classification (WQSC) for the aquatic habitats in the Zuni Mountains, biotic and abiotic data were gathered. Spring and surface water samples were collected for hydrochemical analysis of major ion concentrations and stable isotopes for both the AR and TD sites (Figure 1B and C). Water samples were collected at the AR site starting in May 2012, including upstream from spring discharge, AR1 (n = 13), the spring, AR2 (n = 16) and downstream from the spring discharge within the ZBS habitat, AR3 (n = 15). Starting in May 2013, spring and summer samples were collected from surface waters within Tampico Draw, including; in the Rio Nutria, above the confluence, TD1

($n_{wet} = 3$), at the spring seep area in the Upper Rio Nutria, TD2 (n=8), downstream from the spring and below the confluence, TD3 (n = 6).

For each visit, water was collected in two 125 ml polypropylene bottle using USGS field collection standards (Myers, 2006). The first sample bottle was used for analysis of alkalinity and anion concentrations and was filled without treating the water but gathered with no head space. The endpoint titration method using a weak acid was used to determine alkalinity (APHA, 1999). Anion concentrations were determined by Ion Chromatography (IC) conducted in the Department of Earth and Planetary Sciences at the University of New Mexico, Albuquerque, New Mexico using USGS sampling standards (Martin et al., 1994). The second sample bottle had water filtered through a 0.45 µm hydrophilic polyethersulfone filter in the field and immediately treated with ~1 mm of concentrated nitric acid (69.5% HNO_3). Cation concentrations were analyzed using Inductively Coupled Plasma/Optical Emission Spectroscopy (ICP/OES) (Martin et al., 1994). Isotopologues of liquid water (δD and $\delta^{18}O$) were analyzed using untreated surface waters, spring waters and precipitation event waters. Laser ring-down cavity spectrometry (Gupta et al., 2009; Romanini et al., 1997) was performed at the Center for Isotopic Studies at the University of New Mexico where the weighted mean values are reported.

In May 2012, a shallow (1 m) well was installed at the Agua Remora (AR) spring site for continuous monitoring of spring waters (Figure 1; yellow circles). On 1 June 2012, two Solinst leveloggers (Canada, 2012) were deployed at the AR site, including AR2 (the shallow well at the spring), AR3 (the fish habitat) (Figure 1). The leveloggers recorded physico-chemical parameters (conductivity, temperature and water pressure) at 15 minute intervals through 2 December 2012. From 27 May 2013 through 9 October 2015, the leveloggers were re-deployed with an additional levelogger placed at AR1 (fishless). A Solinist barologger was also deployed during these times for onsite measurement of atmospheric pressure and air temperature. Furthermore, from 27 May 2013 to 2 February 2015, two YSI sondes 6-series (YSI Incorporated, 2009) were deployed in the surface waters (AR1 and AR3) at Agua Remora recording at 30 minute intervals. The sondes measured additional physico-chemical conditions including dissolved oxygen concentrations, pH and turbidity.

To further understand the physico-chemical conditions related to water quality stability additional continuous monitors were deployed at Tampico Draw (TD1, TD2 and TD3). The Forest Guild installed three Solinst leveloggers and one Solinst barologger on The Nature Conservancy land on 28 August 2013. The Forest Guild removed the Leveloggers during the winter season but collected late spring, summer and fall data through 3 October 2015.

Before deployment into the field, all *in situ* measurement devices, were calibrated in the lab using manufactures guidelines with the highest quality standards available (Canada, 2012; USEPA, 2002; Wagner et al., 2006). Specific conductance (levelogger), pH and turbidity (YSI sonde) were calibrated using three point calibration standards. Seasonal field visits to each of the sites allowed for additional calibration of *in situ* instruments and field verification of parameters using Oakton 300 and/or Yellow Springs Instruments Professional Plus hand held meters. Prior to seasonal field work, hand held meters were calibrated in the lab, and DO meters were recalibrated in the field using the local barometric pressure in 100% water-saturated air.

Solinist continuous monitoring data were uploaded and calibrated in the field using a high speed optical reader. YSI sonde continuous monitoring measurements were calibrated and uploaded using an external Yellow Springs Instruments 650 multi-parameter display system (YSI Incorporated, 2009). Continuous monitoring data were then analyzed using the Aquarius software (Wagner et al., 2006). *In situ* measurements were verified based on calibration data and field parameter measurements made during calibrations. At different times, the YSI sondes had equipment failure due to low battery voltage or equipment out of the water. The data during these periods have been removed from analysis.

Weather stations of the western Zuni Mountains have long term data sets but the area that the data covers is large and remote. Precipitation for the western Zuni Mountains has been recorded daily from the 1950's to January 2014 by a National Weather Service (NWS) volunteer (Figure 1 green circle, NWS Station MCGAFFEY 5 SE). In August 2014, hourly and daily precipitation values began to be recorded by a weather station run by the Forest Guild (Figure 1 green circle, Weather Underground Station ID is KNMNEWME3). The locations of these weather stations are relatively close to the Agua Remora site (~1 km) but are more than 8 km away from the Tampico Draw site. The USGS streamflow gauge station at Ramah (Figure 1 USGS Ramah 09386900) is located below the confluence of the Rio Pescado and data has been gathered since 1969. The USGS Ramah station is more than 40 km away from the weather stations. A regression analysis was run to determine the correlation between precipitation and discharge measurements. As expected for arid land stream systems, the results (r^2=0.067, $p<0.0001$) indicate a significant but inconsequential correlation between precipitation in the Upper Rio Nutria area and discharge on the Lower Rio Nutria at Ramah.

At both sites (AR and TD), a one-way ANOVA analysis was run to determine the interaction and effect of total precipitation on measured physico-chemical parameters. In addition, a post hoc comparison using the Fisher PLSD test was run with an individual error rate of 0.05. Each site and parameter was analyzed independently, to reveal any significance between lower or higher measurements and total precipitation.

To determine biological community assemblages, biological samples were collected in May and June 2015. At Agua Remora, samples were collected from habitats above the spring input (AR1) and below the spring input (AR3). At Tampico Draw, collections were from each site (TD1-3). Diatom samples were collected using a corer modified from a 60 mL syringe and preserved in 10% formalin. Invertebrate samples were collected along a standardized surface area using a kick net and preserved in 95% ethanol. Opportunistic spot sampling also occurred at these sites.

To determine diatom richness (number of taxa) and species abundance (cells/mm^2), 3 mL aliquots from each sample were boiled in 30% hydrogen peroxide to oxidize organic material. These samples were then rinsed six times with distilled water to remove oxidation by-products. Processed samples were evaporated onto coverslips and mounted to microscope slides with Z-rax mounting medium, making permanent slides. Specimens along transects were examined under oil immersion at 1000× magnification using brightfield optics. 400 valves were enumerated, identified at the genus level, and converted to relative abundance. All diatom samples were accessioned into the collection at the Museum of Southwestern Biology, University of New Mexico.

Invertebrate samples were examined using a dissecting microscope and all invertebrate organisms were removed from the sample and preserved in ethanol (70%). Specimens were identified to the lowest practical level using a dissecting microscope (75x). Non-insect taxa were identified at least to order (Smith, 2001) while insect taxa were sorted to family or genus (Merritt et al. 2008). The number of individuals of each taxa was recorded and then invertebrate data were converted to relative abundance to be comparable to diatom relative abundance. All invertebrate specimens were accessioned into the collection at the New Mexico Museum of Natural History and Science.

For biological community ordination analysis, diatom and macroinvertebrate relative abundance datasets were combined. The data were analyzed using a non-metric multidimensional scaling ordination (PRIMER v.6 for Windows, Primer-E) to visualize similarities among samples. In total, 38 diatom taxa and 29 invertebrate taxa were included. Because of this high diversity relative to the number of samples (n=8), no further statistical analyses were conducted.

Results

Continuous monitoring: Agua Remora

To determine a water quality stability classification (WQSC) at the AR site, continuous monitoring of physico-chemical parameters (water temperature, specific conductance, and depth) were measured (2012-2015). Appendix I provides 15 minute interval measurements, Appendix II provides mean daily values and Appendix III provides seasonal and monthly descriptive statistics. Mean daily water temperature (°C) for the spring waters (AR2, dark blue) and surface waters (AR1, pink; AR3, light blue) are compared to hourly measurements of air temperature for the site (Figure 3). Surface water temperatures (AR1 and AR3) are significantly correlated to the air temperature ($r^2 = 0.8$, $p = 0.0001$) (Table 1). Seasonal temperature changes in surface water temperatures range from -1 to 22°C throughout the sampling period, with water and air temperature peaking mid-July (Table 1). The mean daily water temperature for the spring (AR2) is also correlated with air temperature ($r^2 = 0.67$, $p = 0.001$). The spring (AR2) does have a seasonal temperature trend but when compared to the surface waters (AR1 and AR3) the range is reduced (5-14°C) and peaks two months later in mid-September.

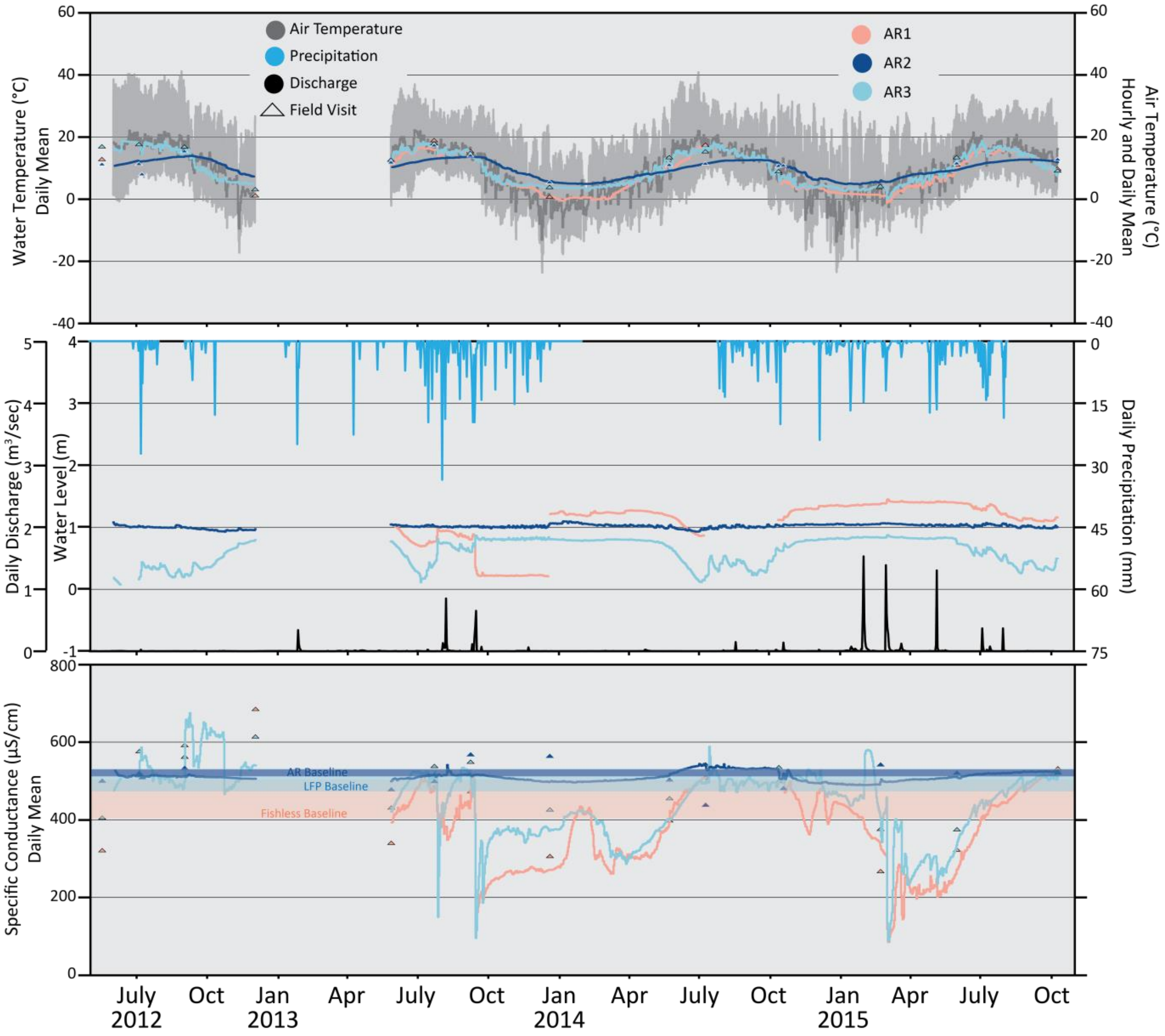
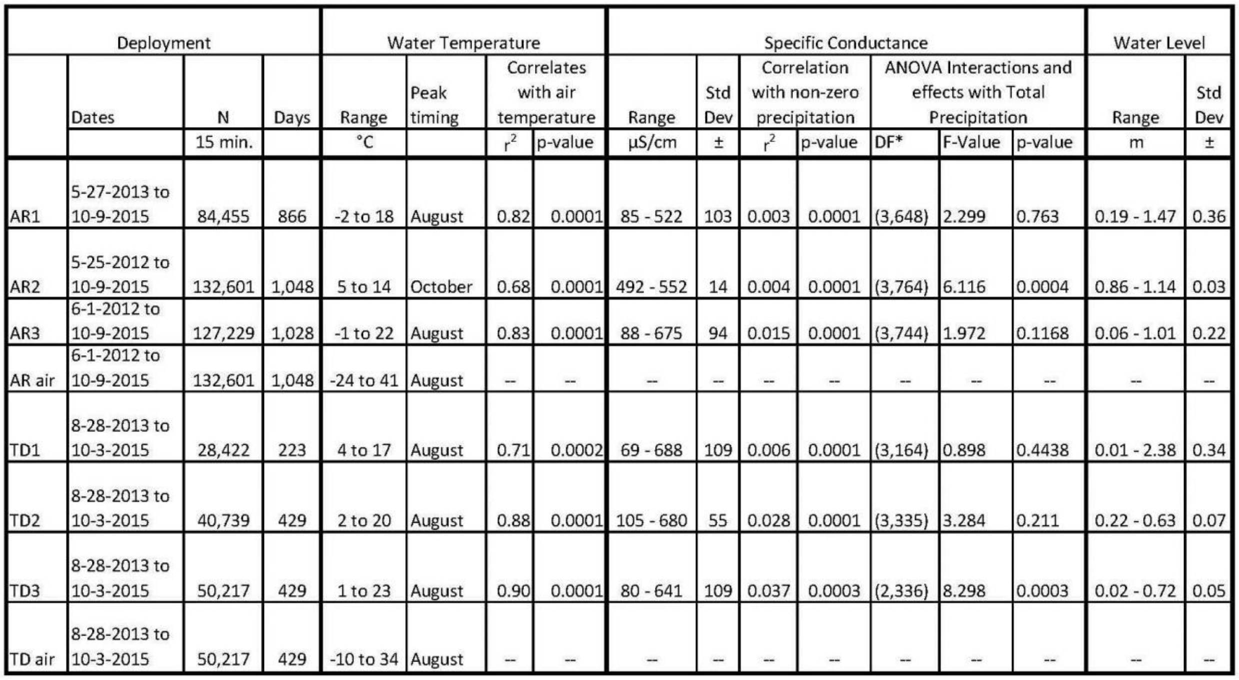


Figure 3. X-Y graph of continuous monitoring of physico-chemical parameters (water temperature, air temperature, specific conductance, water level, precipitation and discharge) at the Agua Remora site.

Table 1. Descriptive statistics for continuous monitoring of water temperature, specific conductance and water level for Agua Remora (AR) and Tampico Draw (TD).

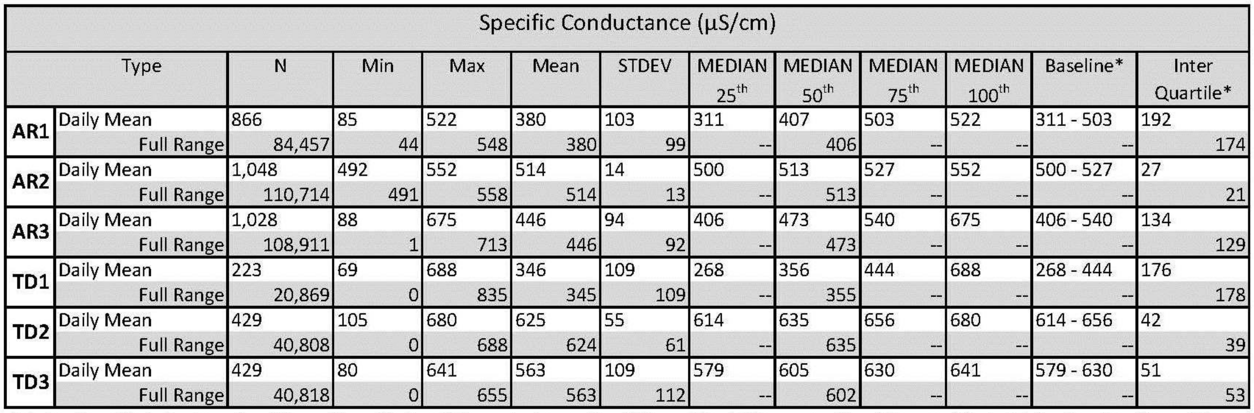


Deployment				Water Temperature				Specific Conductance							Water Level	
	Dates	N	Days	Range	Peak timing	Correlates with air temperature		Range	Std Dev	Correlation with non-zero precipitation		ANOVA Interactions and effects with Total Precipitation			Range	Std Dev
		15 min.		°C		r^2	p-value	µS/cm	±	r^2	p-value	DF*	F-Value	p-value	m	±
AR1	5-27-2013 to 10-9-2015	84,455	866	-2 to 18	August	0.82	0.0001	85 - 522	103	0.003	0.0001	(3,648)	2.299	0.763	0.19 - 1.47	0.36
AR2	5-25-2012 to 10-9-2015	132,601	1,048	5 to 14	October	0.68	0.0001	492 - 552	14	0.004	0.0001	(3,764)	6.116	0.0004	0.86 - 1.14	0.03
AR3	6-1-2012 to 10-9-2015	127,229	1,028	-1 to 22	August	0.83	0.0001	88 - 675	94	0.015	0.0001	(3,744)	1.972	0.1168	0.06 - 1.01	0.22
AR air	6-1-2012 to 10-9-2015	132,601	1,048	-24 to 41	August	--	--	--	--	--	--	--	--	--	--	--
TD1	8-28-2013 to 10-3-2015	28,422	223	4 to 17	August	0.71	0.0002	69 - 688	109	0.006	0.0001	(3,164)	0.898	0.4438	0.01 - 2.38	0.34
TD2	8-28-2013 to 10-3-2015	40,739	429	2 to 20	August	0.88	0.0001	105 - 680	55	0.028	0.0001	(3,335)	3.284	0.211	0.22 - 0.63	0.07
TD3	8-28-2013 to 10-3-2015	50,217	429	1 to 23	August	0.90	0.0001	80 - 641	109	0.037	0.0003	(2,336)	8.298	0.0003	0.02 - 0.72	0.05
TD air	8-28-2013 to 10-3-2015	50,217	429	-10 to 34	August	--	--	--	--	--	--	--	--	--	--	--

* DF is Degrees of Freedom where 1st number listed is DF and 2nd number is residual DF

Mean daily specific conductance (SC) was calculated from 15 minute interval measurements from the three sites at AR (Table 2). Using the second and third median interquartile (median 50 to median 75), a baseline, or typical SC range, is established for each of the three sites at AR (Figure 3, shaded regions). This baseline includes the values with a significantly higher frequency of measurements when compared to the other quartiles. The SC for the spring (AR2) shows very little variation with a baseline between 513 to 527 µS/cm and a standard deviation ± 13.2. SC for the surface waters show more variation with a larger range of the baseline (AR1: 407-503 µS/cm, AR3: 473-540 µS/cm) and a significantly larger standard deviation (AR1: ± 99.1, AR3: ± 92.1). The surface waters can also have dramatic variability with a change of more than 400 µS/cm in one day. Table 2 presents SC descriptions for all sites.

Table 2. Baseline configuration of specific conductance for sites at Agua Remora (AR) and Tampico Draw (TD).



Specific Conductance (µS/cm)												
Type		N	Min	Max	Mean	STDEV	MEDIAN 25th	MEDIAN 50th	MEDIAN 75th	MEDIAN 100th	Baseline*	Inter Quartile*
AR1	Daily Mean	866	85	522	380	103	311	407	503	522	311 - 503	192
	Full Range	84,457	44	548	380	99	--	406	--	--	--	174
AR2	Daily Mean	1,048	492	552	514	14	500	513	527	552	500 - 527	27
	Full Range	110,714	491	558	514	13	--	513	--	--	--	21
AR3	Daily Mean	1,028	88	675	446	94	406	473	540	675	406 - 540	134
	Full Range	108,911	1	713	446	92	--	473	--	--	--	129
TD1	Daily Mean	223	69	688	346	109	268	356	444	688	268 - 444	176
	Full Range	20,869	0	835	345	109	--	355	--	--	--	178
TD2	Daily Mean	429	105	680	625	55	614	635	656	680	614 - 656	42
	Full Range	40,808	0	688	624	61	--	635	--	--	--	39
TD3	Daily Mean	429	80	641	563	109	579	605	630	641	579 - 630	51
	Full Range	40,818	0	655	563	112	--	602	--	--	--	53

* Inter Quartile is the baseline (Figure 3) and is the distance between the 25th and the 75th percentile of the empirical distribution function of the data within the bin.

For all three AR sites, SC has no significant correlation relative to non-zero precipitation events ($r^2 < 0.015$) (Table 1). One-way ANOVA was performed on data from each site to understand the effect and interaction of total precipitation events on deviation away from each site's SC baseline (Table 2). For AR1, deviation above or below the SC baseline total precipitation is verging on significance $F_{(3,648)} = 2.30$, p = 0.08. A post hoc comparison of AR1, using the Fisher PLSD test, reveals significance between the SC median 100 when compared to the median 25 (p = 0.03) and median 50 (p = 0.03). For AR2 the deviation above or below the SC baseline reveals total precipitation is significant $F_{(3,764)} =$ 6.1, p = 0.0004. At the AR3 site, total precipitation effect and interaction on the deviation above or below the SC baseline has no significance $F_{(3,744)} = 1.972$, p = 0.12. Using the Fisher

LSP test on the different SC median quartiles at AR3 reveals significance between the median 25 and median 50 ($p = 0.02$).

Water levels for the surface waters (AR1 and AR3) vary by season with the summer months having the shallowest depths. Winter and monsoonal seasons have deeper pools. Appendix III provides means, standard deviations and ranges for depths of all sites. In general, AR1 is the deepest pool (maximum = 1.47 m) and while it becomes shallower in dry seasons (minimum = 0.67 m) its depth is still greater than AR3. AR3 water level ranges between 0.06 and 1.01 m with the lowest levels being in the dry season. The water level of the AR2, within the spring well, is constant year round at 1 m.

Additional parameters of pH, turbidity and dissolved oxygen concentrations were measured at AR. Appendix IV provides 15 minute interval measurements, Appendix V provides mean daily values. The pH of AR1 has a daily median of 7.19 pH units and daily maximum turbidity measurements range from 0.0 to 179 NTU (Table 3). The daily median pH for AR3 is 7.3 pH units and daily maximum turbidity measurements range from -0.3 to 1054 NTU. Of note is the lack of data for AR1 during the highest turbidity measurements for AR3 in July 2013. The data gap is due to the 6 series YSI Sonde at AR1 not being equipped with a turbidity meter on the first deployment in 2013. Analysis of variance reveals total precipitation has no significant interaction or effect on turbidity over time at AR1, $F_{(4,125)} = 0.072$, $p < 0.99$, or at AR3, $F_{(6,220)} = 0.563$, $p = 0.76$.

Mean daily dissolved oxygen concentrations for AR3 are 5.76 mg/l, with only 17 non-consecutive days below 3 mg/l (Table 3). In contrast, the mean daily dissolved oxygen concentrations for AR1 are 1.49 mg/l, with 195 (83%) days below 3 mg/l. There was no significant difference in the concentration of dissolved oxygen over time for either site (ANOVA: AR1, $F_{(2,170)} = 1.7$, $p = 0.19$ and AR3, $F_{(2,224)} = 1.36$, $p = 0.26$).

Table 3. Descriptive statistics for continuous monitoring of turbidity, dissolved oxygen concentrations and pH for Agua Remora sites, AR1 and AR3.

Deployment		Turbidity (NTU)						Dissolved Oxygen (mg/l)								pH			
	Dates	Days	Daily Max Range	Std Dev	ANOVA Interactions and effects with Total Precipitation			Days	Range	Mean Daily	Std Dev	Days below 3 mg/l	ANOVA Interactions and effects with Total Precipitation			Days	Range	Daily Mean	Std Dev
		n	NTU	±	DF**	F-Value	p-value	n	mg/l	mg/l	±	n	DF*	F-Value	p-value	n	pH units		±
AR1	7-22-2013 to 2 21-2015	192*	-0.6 to 179	14	(4,125)	0.07	0.99	235	0.01 to 7.22	1.49	1.6	195	(2,170)	1.7	0.19	235	6.91 to 7.58	7.19	0.12
AR3	7-22-2013 to 2 21-2015	241	-0.3 to 1054	98	(6,220)	0.56	0.76	241	0.95 to 7.67	5.76	1.4	17	(2,224)	1.36	0.26	241	6.84 to 7.63	7.28	0.19

* Turbidity was not measured for AR1 until 7-12-2014

** DF is Degrees of Freedom where 1st number listed is DF and 2nd number is residual DF

Continuous monitoring: Tampico Draw

In situ measurements of water temperature, specific conductance (SC) and water level began 1 June 2012 at Tampico Draw (TD). Appendix VI provides 15 minute interval measurements, Appendix VII provides mean daily values and Appendix III provides seasonal and monthly descriptive statistics. Mean daily water temperature for ZBS habitat above the confluence on the Upper Rio Nutria (TD2, red), below the confluence (TD3, orange), and above the confluence on the Rio Nutria (TD1, yellow) is plotted with hourly measurements of air temperature (gray) (Figure 4). All three locations have seasonal variations that follow the same sinusoidal trend as air temperature with peaks happening at the same time (refer to Table 1 for statistical descriptions). Both the TD2 and TD3 water temperatures strongly correlate to air temperatures ($r^2=0.9$, $p = 0.0001$). The TD1 dries out for 206 days of the 429 days of measurements. The correlation of TD1 with air temperature is lower (r^2=0.7, p = 0.0002) but still highly significant.

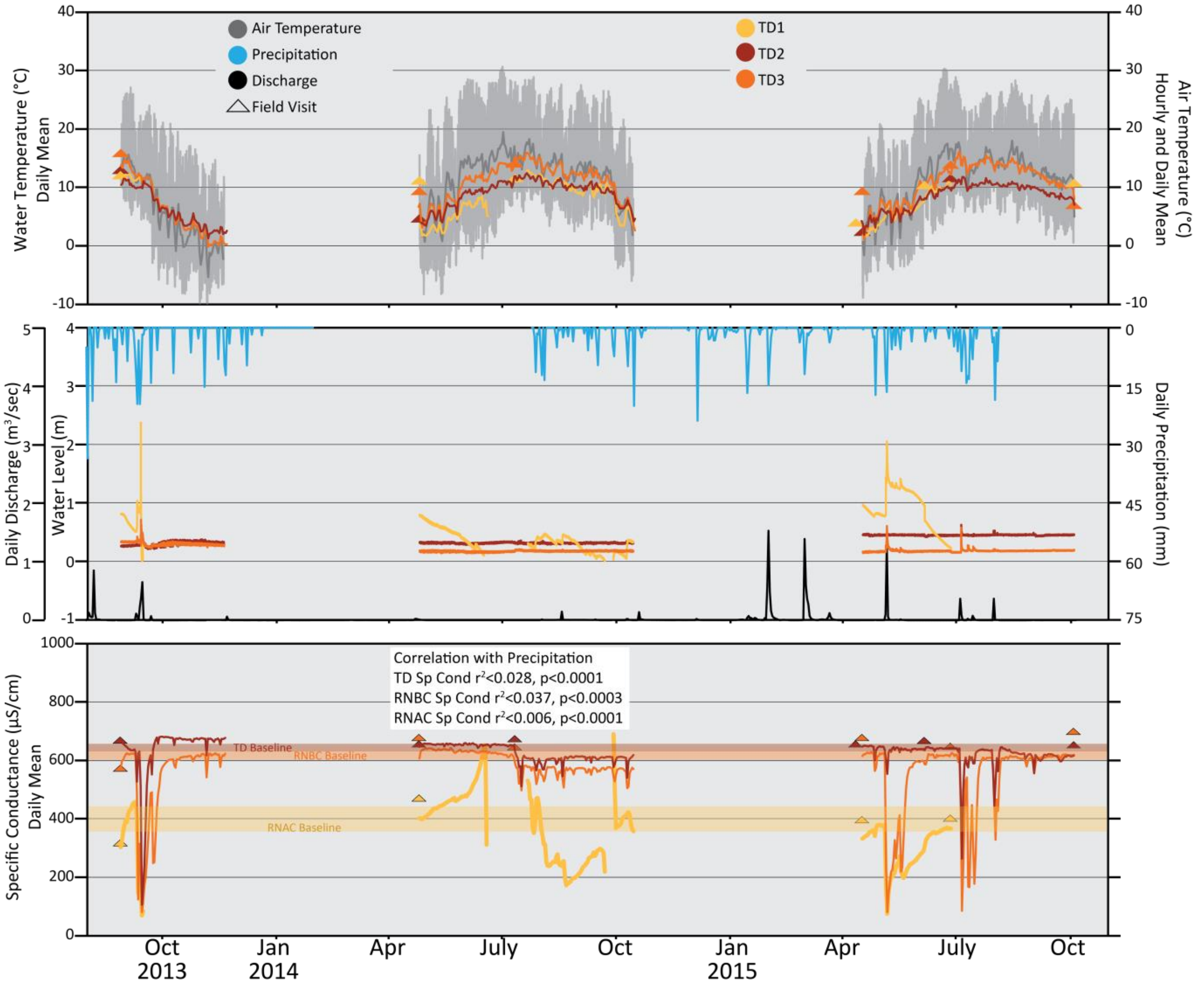


Figure 4. X-Y graph of continuous monitoring of physico-chemical parameters (water temperature, air temperature, specific conductance, water level, precipitation and discharge) for the Rio Nutria at Tampico Draw site.

Specific conductance (SC) for the Tampico Draw habitats is similar at the TD2 and TD3 sites, while the TD1 has a lower SC (Figure 4), refer to Table 2 for statistical descriptions. Overall, precipitation and SC for the sites are not strongly correlated (r^2<0.04, p = 0.003). At TD2 precipitation and movement away from the SC baseline are not significant $F_{(3,335)} = 3.287$, $p = 0.02$. Applying a post hoc Fisher PLSD with 5% significance level, at TD2 only SC below 614 µS/cm (25 median) is significantly different to baseline ($p = 0.002$), but all SC values above 614 µS/cm have no significance relative to precipitation. At TD3, below the confluence, an ANOVA analysis reveals precipitation and SC have a difference of mean values that are significantly different ($F_{(2,336)} = 8.298$, $p = 0.0003$). The Fisher PLSD test identifies that SC values at TD3, below 579 µS/cm (median 25) are significantly different from those of the median 50 ($p = 0.002$) and of the median 75 ($p = 0.0005$). TD2 and TD3 were again analyzed using ANOVA with a one day lag of SC compared to the timing of precipitation events, with both sites having no significant changes to relationships when the one day lag is applied.

The Tampico Draw site includes TD1 which is a site that seasonally dries and has not supported ZBS since 1993. Analysis of variance for continuous monitoring of SC at TD1 is not significant with total precipitation ($F_{(3,164)} = 0.898$, $p = 0.444$) (Table 1). The post hoc Fisher PLSD test also reveals no significance for deviations away from the SC baseline due to total precipitation. In contrast, when applying a one day lag time on the ANOVA of SC versus precipitation for TD1, the relationship becomes more significant ($F_{(3,165)} = 2.475$, $p = 0.634$). The post hoc Fisher PLSD test reveals that with a one day lag median 100 is significantly related to median 50 ($p = 0.023$) and median 25 ($p = 0.023$).

Water level for the Rio Nutria at Tampico Draw sites are constant at the TD2 and TD3 sites throughout the year (Appendix III). TD2 water levels have a mean of 0.37 m and in general has a higher water level than TD3 (mean = 0.21 m). The variation of water level for both TD2 and TD3 is minimal with very little change from season to season. TD1 has the highest mean water level (0.56 m) but also fluctuates (0.01 – 2.38 m) seasonally. During warm season, TD1 becomes dry and rain events fill the basin but then without additional rain, the pool dries again.

Alkalinity and nutrients

Water quality measurements of alkalinity concentrations for Agua Remora (AR) and Tampico Draw (TD) are reported in Appendix VIII. Both sites have alkalinity concentrations that are below 350 mg/l with the TD site higher in all cases. Seasonal variability of alkalinity at the AR site is lowest for the spring, AR2, and the spring-fed habitat (AR3) with averages and standard deviations of (131.9 ±5.6 and 137.2 ±15.8 mg/l) (Table 4). In contrast AR1, which receives no spring discharge, has an average alkalinity which is similar to AR2 and AR3 but with two times the standard deviation (146.9 ±33.5 mg/l). Similarly the spring-fed sections of the TD site, TD2 and TD3, change very little over the sampling seasons with averages and standard deviations of 328.2 ±8.1 and 323.2 ±11.1 mg/l, respectively. While the TD1 site, which has no spring input, had lower averages but a standard deviation that is six times more (246.4 ±62.2 mg/l).

Nutrient concentrations for the different habitat sites follow a similar pattern to alkalinity concentrations (Appendix VI), with statistical descriptions provided in (Table 4). For AR, the spring (AR2) has the highest average nitrate concentration with the lowest standard deviation while both AR1 and AR3 have lower nitrate concentrations with standard deviations that are the same as the concentration values. Correspondingly, TD2 (closest to spring) also has the highest average nitrate concentrations but with slightly higher variability. The TD1 and TD3 sites have the lowest nitrate concentrations for all sites.

Of note are the differences represented in the standard deviations for all sites. The standard deviations correlate to concentrations that are significantly higher (rather than lower) from the averages (Table 4). Phosphate concentrations for both habitat sites are below detection limits with only AR1 having any measureable concentration (0.2 mg/l, ±0.5).

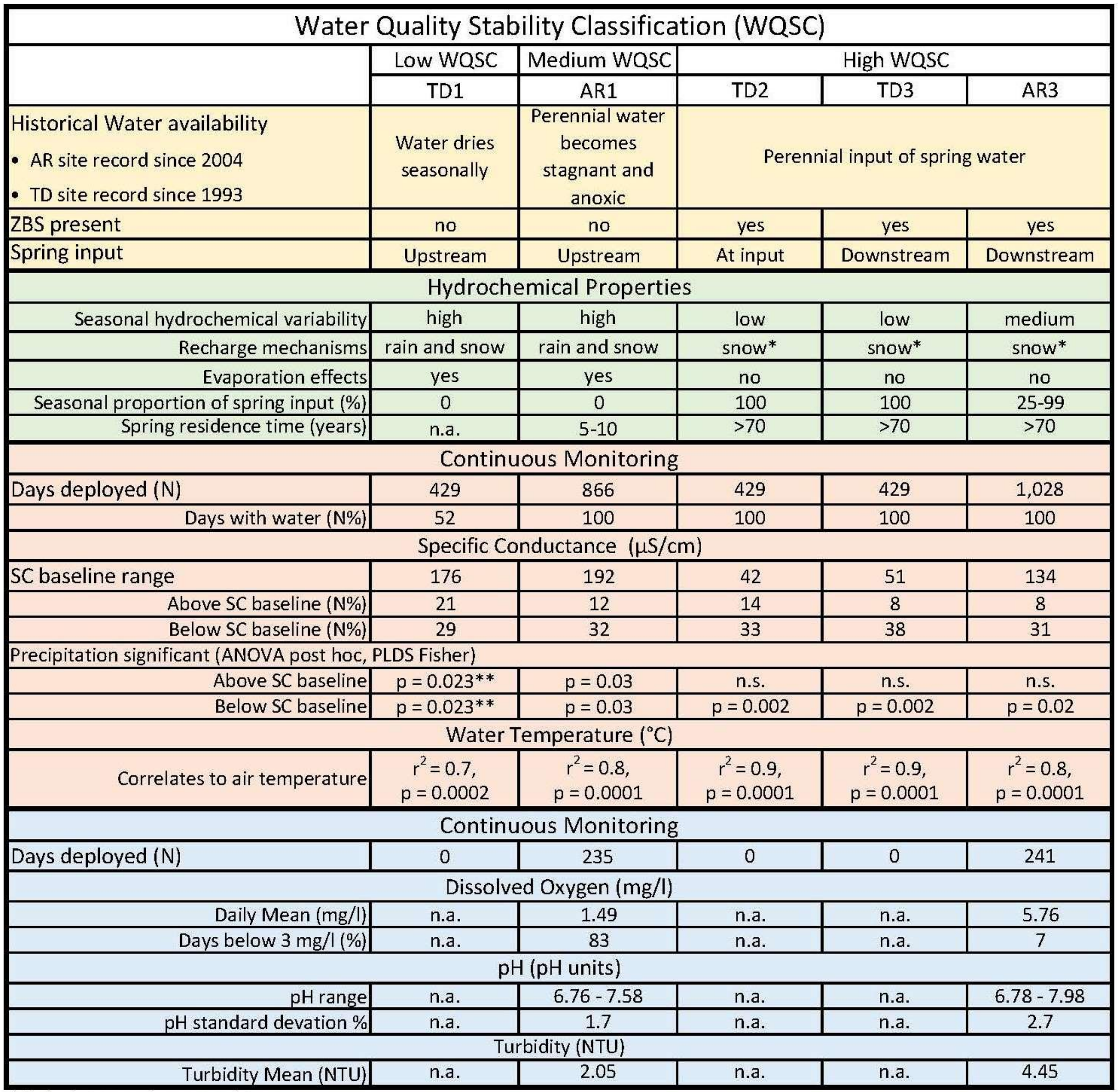
Table 4. Descriptive statistics for alkalinity and nutrient concentrations at Agua Remora (AR) and Tampico Draw (TD).

	n	Alkalinity (HCO_3^-) average	Nitrate (NO_3^-) average	Phosphate (PO_4^{3-}) average	Alkalinity (HCO_3^-) std dev	Nitrate (NO_3^-) std dev	Phosphate (PO_4^{3-}) std dev
AR1	13	147	0.79	0.21	33.53	0.82	0.46
AR2	16	132	0.95	0.00	5.97	0.43	0.00
AR3	15	137	0.68	0.04	15.77	0.67	0.15
TD1	3	246	0.44	0.00	62.22	0.32	0.00
TD2	7	328	0.92	0.00	8.07	0.64	0.00
TD3	6	323	0.35	0.00	11.12	0.35	0.00

Water Quality Stability Classification

To determine a water quality stability classification (WQSC) for the AR and TD sites, variability in hydrochemistry and physico-chemical parameters were quantified (Table 5). The high WQSC is downstream from springs discharge and has low seasonal hydrochemical variability with the primary recharge mechanism being snowmelt to confined aquifers, no effects from evaporation and a residence time greater than 70 years. In contrast the medium and low WQSC is upstream from springs discharge, has high seasonal hydrochemical variability and is recharged through both snowmelt and monsoonal rains. These sites are effected by evaporation with water residence time < 10 years.

Table 5. Water quality stability classification for at Agua Remora (AR) and Tampico Draw (TD).



Water Quality Stability Classification (WQSC)					
	Low WQSC	Medium WQSC	High WQSC		
	TD1	AR1	TD2	TD3	AR3
Historical Water availability • AR site record since 2004 • TD site record since 1993	Water dries seasonally	Perennial water becomes stagnant and anoxic	Perennial input of spring water		
ZBS present	no	no	yes	yes	yes
Spring input	Upstream	Upstream	At input	Downstream	Downstream
Hydrochemical Properties					
Seasonal hydrochemical variability	high	high	low	low	medium
Recharge mechanisms	rain and snow	rain and snow	snow*	snow*	snow*
Evaporation effects	yes	yes	no	no	no
Seasonal proportion of spring input (%)	0	0	100	100	25-99
Spring residence time (years)	n.a.	5-10	>70	>70	>70
Continuous Monitoring					
Days deployed (N)	429	866	429	429	1,028
Days with water (N%)	52	100	100	100	100
Specific Conductance (µS/cm)					
SC baseline range	176	192	42	51	134
Above SC baseline (N%)	21	12	14	8	8
Below SC baseline (N%)	29	32	33	38	31
Precipitation significant (ANOVA post hoc, PLDS Fisher)					
Above SC baseline	p = 0.023**	p = 0.03	n.s.	n.s.	n.s.
Below SC baseline	p = 0.023**	p = 0.03	p = 0.002	p = 0.002	p = 0.02
Water Temperature (°C)					
Correlates to air temperature	$r^2 = 0.7$, $p = 0.0002$	$r^2 = 0.8$, $p = 0.0001$	$r^2 = 0.9$, $p = 0.0001$	$r^2 = 0.9$, $p = 0.0001$	$r^2 = 0.8$, $p = 0.0001$
Continuous Monitoring					
Days deployed (N)	0	235	0	0	241
Dissolved Oxygen (mg/l)					
Daily Mean (mg/l)	n.a.	1.49	n.a.	n.a.	5.76
Days below 3 mg/l (%)	n.a.	83	n.a.	n.a.	7
pH (pH units)					
pH range	n.a.	6.76 - 7.58	n.a.	n.a.	6.78 - 7.98
pH standard devation %	n.a.	1.7	n.a.	n.a.	2.7
Turbidity (NTU)					
Turbidity Mean (NTU)	n.a.	2.05	n.a.	n.a.	4.45

* Relative to spring water input

** TD1 movement away from the SC baseline as an effect or interaction with precipitation is lagged by one day

Continuous monitoring for the different sites indicates that high WQSC deviates below SC baseline only during large rain events, while medium and low WQSC deviates both below and above SC baseline due to large rain events and lack of rain (evaporation), respectively. Addition continuous monitoring of DO at the AR site shows that high WQSC is able to maintain non-impairment concentrations levels (appropriate for desert fish), while the medium WQSC is unable to maintain levels above the acute mortality limit.

Biological community

Overall taxonomic richness of diatoms and macroinvertebrates have a mean value of 29.2 ± 6.2. Thirty-eight diatom genera were identified from collections with a diverse assemblage of common taxa and two genera reported from only one sample. The site with the greatest taxa richness was AR1 with 32 genera, reflecting a diverse benthic diatom community. In comparison, AR3 had a lower taxa richness (28 genera), with a community dominated by two planktonic, chain-forming diatom taxa (*Staurosira*, *Staurosirella*).

Twenty-nine different taxa were identified from the invertebrate samples, but almost half of these (n=14) only occurred once. Two taxa (Chironominae, Baetidae) occurred in six of the eight samples. Another chironomid subfamily (Tanypodinae) occurred in half of the samples, as did two microcrustaceans (Ostracoda, Cladocera). The sample with the greatest taxonomic richness was collected at TD1 (11 taxa), and the sample with the least taxonomic richness was collected at AR3 (3 taxa).

Non-metric multidimensional scaling indicates some differences in the biological community among sites along a WQSC transcet (Figure 5). At TD1, the diatom genus *Sellaphora* was very abundant and this was the only site where larvae of the mosquito *Culex* was found. Microcrustacean Cladocera was also abundant at TD1; it was only found at one other site (AR1: medium WQSC).

At high WQSC sites (AR3, TD3) the diatom *Staurosira* was abundant (40-70%). Additionally, midge larvae *Chironominae* and diatom *Staurosirella* occurred in high numbers at these sites. Other diatom taxa at these sites occurred in low abundances (<5%) and several of the less common diatoms were missing from the high WQSC sites (*Craticula, Cymatopleura, Hanzschia, Luticola, Neidium, Surirella*, all associated with sediment or temporary aquatic habitats).

TD2 also had a high WQSC but had a different community composition, compared to the other high WSI sites. Collections from TD2 were characterized by a relatively high abundance of planktonic diatoms, *Staurosirella* (55%), *Stagnicola* snails (30%), baetid mayflies and ostracods (20% each). The number of invertebrates found at this site was very low (n=10). Other taxa were opportunistically collected from this site, including *Psychoronia* caddisflies and *Euparyphus* soldier fly larvae (Stratiomyidae).

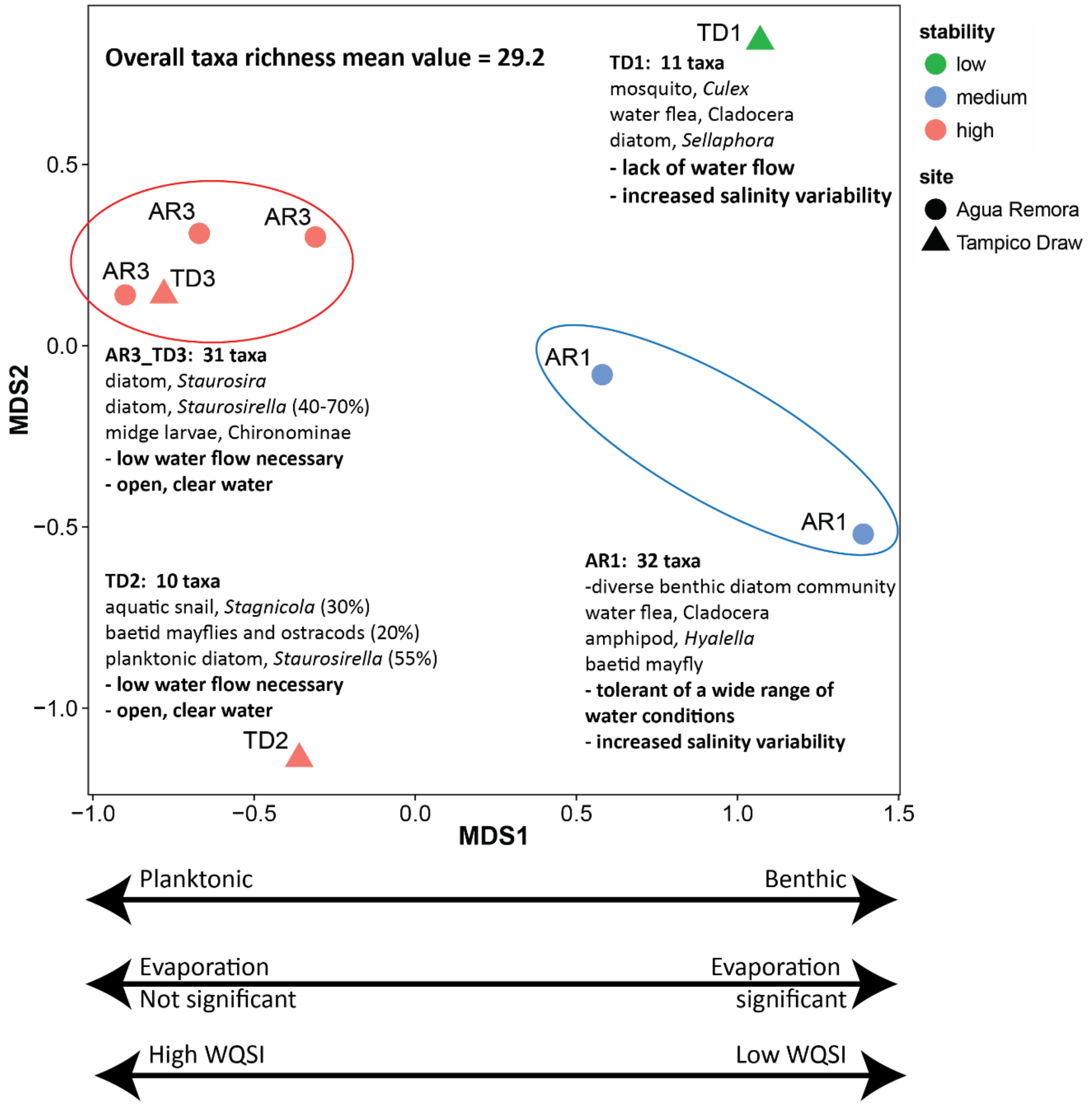


Figure 5. Results from non-metric multidimensional scaling (MDS) of biological communities at the study sites. No fish are found at the low WSI site (TD1) or the medium WSI site (AR1). Stress = 0.04

Discussion

To determine a water quality stability classification (WQSC) of resources for the western Zuni Mountains, two spring systems were monitored for physico-chemical parameters, nutrient and alkalinity concentrations and biodiversity of aquatic organisms. The two sites were selected because they had perennial springs that provide refugium to endangered desert fish. These sites were also selected because upstream from the spring discharge there were two scenarios typical of desert stream channels: one that dries during the summer, and one that is perennially wet but stagnant. Looking at the current habitats below and above the spring discharge of two different sites can help us to understand the influence of desert spring waters on aquatic habitats as well as how the lack of spring water affects these habitats.

Air temperature influences surface water temperatures in the desert, but can be less of an influence on spring water temperatures. The water temperature for the spring at Agua Remora (AR2) has an annual temperature cycle that is dampened and lags behind the air temperature by 60 days. This lag time and temperature dampening has been reported to be related to the infiltrating waters interacting with an unsaturated vadose zone and then flowing in the saturated zone that is no more than 10 m deep where heat is diffused or exchanged (Plummer et al., 2004; van der Kamp, 1995). The longer the lag time, the more dampened the temperature range. The temperature range is also dampened when water is infiltrated deeper into the aquifer (van der Kamp, 1995). AR2 maintains the seasonal signal and therefore may be related to a slow, shallow flow which correlates to the residence time of more than 70 years (Frus et al., in review). While the spring (AR2) discharges only into AR3, both AR1 and AR3 are closely tied to the atmosphere. The surface waters (AR1 and AR3) are shallow (< 1.5 m), the spring is low flow and is ~100 m away from AR3; therefore it is expected that the surface waters would be closely effected by air temperatures (Rutherford et al., 2004).

At Tampico Draw, the hanging garden spring is a seep area along the contact between sandstone cross beds and continuous monitors are within the stream channels at all three TD sites, not in the spring itself. Therefore, understanding the exact temperature of the seep water as it emerges from the ground is unclear. Even so, TD2, adjacent to the seep, has water temperatures that are cooler than the average daily air temperature as well as TD3 daily mean water temperatures. The temperature difference is a reflection of the spring waters which are expected to be cooler (Glynn and Plummer, 2005) in combination with the cover from the walls of the box canyon. As the spring waters run downstream from TD2 to TD3, they are exposed longer on the surface and have more direct sunlight where the water warms and becomes more closely tied to the atmosphere (Rutherford et al., 2004). TD1 water temperature is cooler because it is a small pool that is shaded by a large outcrop of sandstone in the channel that shades the pool for most of the day. Also, during the warmest and driest parts of the year, TD1 is dry due to the lack of spring discharge in the channel.

A baseline for specific conductance (SC) was determined for each site as a proxy to understanding typical total ionic concentrations that are present in arid land waters of the Zuni Mountains. Comparing SC baseline ranges of spring waters (AR2, TD2) to surface waters that 1) receive spring waters (AR3, TD3) or 2) do not get any input from spring waters (AR1, TD1), can help to determine the influence that spring waters have on aquatic habitats. The smallest baseline range for SC is that of the spring waters (AR2, TD2) which have a range of 14 and 21 µS/cm, respectively. This range indicates that the spring waters have a hydrologically constant and geochemically consistent source of fresh waters (Pilgrim et al., 1979). The baseline SC for waters downstream from springs (AR3, TD3) have a range of 67 and 26 µS/cm, respectively. AR3 and TD3 have a larger baseline range, when compared to the spring's baseline range. The widening of the baseline range for AR3 and TD3 is attributed to the other in-stream seasonal contributions from upstream sources (AR1, TD1), as well as possibly related to evaporation effects (Langmuir, 1997). The largest range of SC baseline is found in the waters that do not receive spring input (AR1, TD1) with a range of 96 and 88 µS/cm, respectively. This large baseline is a reflection of the variability of pools that are stagnant (AR1) and that dry out (TD1). With atmospheric effects and lack of additional inputs, arid land systems similar to AR1 and TD1 can become highly erratic and unstable (Pilgrim et al., 1979), possibly making their aquatic habitats also unstable. Whereas the spring input to AR3 and TD3 stabilize SC making for healthier downstream aquatic habitats.

Establishing a baseline for specific conductance (SC) is appropriate for understanding how inputs of precipitation or outputs from evaporation can cause a deviation away from typical SC values (Pilgrim et al., 1979). At AR1, total precipitation was shown to have significance with deviations both above and below the SC baseline. At AR1, when the SC goes below 407 µS/cm, it is related to precipitation events that are inputting fresher water to the system and reducing the total SC (i.e. July 2013). When the SC goes above 503 µS/cm (i.e. August), this is due to the lack of precipitation and evaporation is increasing the SC at AR1. At AR3, significance is found between precipitation and deviations below the SC baseline. AR3 is another example of how precipitation is effecting the SC of aquatic habitats by reducing the SC with an input of fresher, rain water (i.e. July 2013). In contrast, the AR3 site precipitation does not have significance with rainless periods, which appears to be related to the amount of spring water (AR2) that is discharging into AR3. The constant and consistent SC source of AR2 maintains AR3's SC baseline and the lack of precipitation events do no significantly deviate AR3 SC baseline. These results are also reflected at the Tampico Draw site where the spring waters (TD2) and downstream (TD3) have a significant effect from precipitation when the SC values deviate below the established baselines. The difference for the TD site is that the differences of SC at TD3 is significant for all precipitation events. This is likely related to the location below the confluence of TD1 and TD2. Regardless of the magnitude of the rain event, TD3 has precipitation contributions from both TD1 and TD2, which produces a stronger relationship to precipitation at the TD3 site.

Additional parameters of physico-chemical conditions that are important for desert aquatic habitats include clear, pH-neutral waters that maintain appropriate dissolved oxygen concentrations. While the data from this report on turbidity and pH is useful for understanding the status quo conditions, there were too few large rain events to allow identification of a threshold where large precipitation amounts might decrease water quality by carrying sediments into the aquatic habitats. With the increase in sediment load the pH-neutrality and dissolved oxygen concentrations can be significantly altered due to processes of diffusion and adsorption on the surface of the sediments (Langmuir, 1997). These ionic interactions can create anoxic conditions (Dahm, 1981), and more acidic waters

(Drever, 1982). Large rain events can also deliver labile organic carbon (both dissolved and particulate) that can stimulate metabolism and lower dissolved oxygen concentrations (Dahm, 1981; Dahm et al., 2015; Grimm et al., 1997). In addition, increases in sediment load can alter photosynthesis by not allowing the sunlight to penetrate deeply, subsequently affecting aquatic biodiversity (Wetzel, 2001).

Water level data for the aquatic habitats are important for understanding that shallow surface waters can maintain high levels of biodiversity. Whether the surface waters are stagnant (AR1) or have spring input (AR3, TD3), the water is the most important factor for aquatic habitats. Perennial sources of clean, reaerated waters from the springs (AR2, TD2) provide year round surface water that maintains appropriate dissolved oxygen concentration levels, to the desert fish habitats. As droughts persist, ground water is removed and the effects of climate change continue, water quality stability of spring water resources could reduce (Carpenter et al., 2011; Klove et al., 2011) and likely impact desert spring ecosystems.

The biological communities differed among the sites that had different levels of WSI. The presence of *Culex* mosquitoes and the diatom *Sellaphora* indicate the lack of water flow at (TD1). *Sellaphora* is often associated with higher alkalinity and conductivity water (Potapova and Charles, 2003; Kociolek and Spaulding, 2003) and may be an indicator of low flow and higher ion concentrations related to drying and low WSI at TD1. *Culex* mosquitoes have been found in drying pools in both Europe (Verdonschot et al., 2014) and Australia (Boulton and Lake, 2008); they are mobile as adults, colonize drying pools and can be dominant in stagnating, lentic water such as that found at TD1.

AR1 was characterized by two invertebrate taxa: Cladocera and Hyalella. These organisms are tolerant of a wide range of conditions (e.g. high salinity, low dissolved oxygen) (Barbour et al., 1999), and could realistically be expected to be found at any of the sites included in this study. Their presence at AR1 may be attributed to other physical characteristics of the site such as appropriate habitat and refuge from predation. Interestingly, baetid mayflies were also found at AR1, despite the low levels of dissolved oxygen recorded there. Mayflies are generally associated with well-oxygenated water. The mayfly taxa found at AR1 are relatively tolerant of poor water conditions, (Barbour et al., 1999) but this does highlight some of the potential seasonal variability within the biological community and the ability of some taxa to use microhabitats within a larger system.

The high WQSC sites (AR3, TD3) were characterized by the two dominant diatom taxa: *Staurosira* and *Staurosirella*. Cells of these two general form chains in shallow lentic systems and are associated with slightly alkaline, oligotrophic conditions (Silver et al., 2005). The invertebrate community at these sites was not easy to characterize, other than the ubiquitous presence of chironomid larvae. The most unusual high WSI site (TD2) was driven by the dominance of *Staurosirella* and the low number of invertebrate individuals collected at the site. This outcome emphasizes that this data set is preliminary in its scope but does illustrate the biological differences among the sites. Further research on biological communities and the water quality stability classification (WQSC) is warranted.

Conclusion

Springs of desert lands provide stable water sources for aquatic habitats. In the Zuni Mountains, New Mexico, two spring sites were monitored to determine a water quality stability and to understand the importance of spring discharge on biodiversity of aquatic habitats. This research used hydrochemistry of major ions and stable isotopes as well as continuous monitoring of physico-chemical parameters of spring and surface waters, upstream and downstream of the spring sites to determine a water quality stability classification (WQSC).

Continued monitoring of physico-chemical and nutrient conditions for perennial spring-fed aquatic habitats is an important measure of understanding the water quality stability for the desert southwest. While larger precipitation events can produce more sediment load to surface waters, spring waters can reduce the effects of these sediment inputs. This research shows that spring waters supply downstream aquatic habitats with 1) generally clear and clean water, 2) consistent SC source which can help to maintain pH-neutrality, 3) increased interaction with the atmosphere for sustained reaeration, 4) provide nutrients for primary productivity through aquifer water rock interaction and 5) something about biodiversity.

Results indicate that the springs provide high WQSC with clean and clear water which maintains a high level of biodiversity downstream from spring inputs. This research also shows that stream sections upstream from the spring discharge have lower WQSC due to complete drying of waters or the inability to maintain aerobic conditions of the surface waters. Because confined aquifers are primarily recharged through snowmelt (Frus et al., in review), with continued drought and climate change, implications for changes to spring conditions to have a lower WQSC within the Zuni Mountains are not positive. Continued monitoring of physico-chemical parameters of spring and surface waters will be imperative.

The future data will provide ways to confirm the WQSC and how decreases in WQSC is changing in the region and how large rain events might decrease suitable aquatic habitat conditions.

References

APHA, 1999. Standard methods for the examination of water and wastewater, 21st ed. American Public Health Association, American Water Works Association, and Water Pollution Control Federation, Washington, DC.

Baldwin, J.A., Anderholm, S.K., 1992. Hydrogeology and ground-water chemistry of the San Andres-Glorieta aquifer in the Acoma embayment and eastern Zuni uplift, west-central New Mexico, Water - Resources Investigations Report 91-4033. Albuquerque.

Baldwin, J.A., Rankin, D.R., 1995. Hydrogeology of Cibola County, New Mexico, Water-Resources Investigations 94-4178. Albuquerque.

Bogan, M.T., Boersma, K.S., Lytle, D.A., 2014. Resistance and resilience of invertebrate communities to seasonal and supraseasonal drought in arid-land headwater streams. Freshw. Biol. 60, 2547–2558. doi:10.1111/fwb.12522

Bogan, M.T., Boersma, K.S., Lytle, D.A., 2013. Flow intermittency alters longitudinal patterns of invertebrate diverstiy and assemblage composition in an arid-land stream network. Freshw. Biol. 58, 1016–1028. doi:10.1111/fwb.12105

Bogan, M.T., Lytle, D.A., 2011. Severe drought drives novel community trajectories in desert stream pools. Freshw. Biol. 56, 2070–2081. doi:10.1111/j.1365-2427.2011.02638.x

Bogan, M.T., Lytle, D.A., 2007. Seasonal flow variation allows “time-sharing” by disparate aquatic insect communities in montane desert stream. Freshw. Biol. 52, 290–304.

Boulton, A.J., Lake, P.S., 1992. The ecology of two intermittent streams in Victoria, Australia. II. Comparisons of faunal compositions between habitats, rivers and years. Freshw. Biol. 27, 99–121. doi:10.1111/j.1365-2427.1992.tb00527.x

Canada, S., 2012. User guide Levelogger series software version 4. User Guid.

Cantonati, M., Fureder, L., Gerecke, R., Juttner, I., Cox, E.J., 2012. Crenic habitats, hotspots for freshwater biodiversity conservation: toward an understanding of their ecology. Freshw. Sci. 31, 463–480. doi:10.1899/11-111.1

Carman, S.M., 2004. Zuni Bluehead sucker (Catostomus discobolus yarrowi) recovery plan. Santa Fe,.

Carpenter, S.R., Stanley, E.H., Vander Zanden, M.J., 2011. State of the world's freshwater ecosystems: physical, chemical and biological changes. Annu. Rev. Environ. Resour. 36, 75–99. doi:10.1146/annurev-environ-021810-094524

Connell, S.D., 2011. Preliminary study of the geologic framework of the Colorado Plateau – Middle Rio Grande Basin Transition, New Mexico, Open-file Report 539. Soccoro.

Dahm, C.N., 1981. Pathways and mechanisms for removal of dissolved organic carbon from leaf leachate in streams. Can. J. Fish. Aquat. Sci. 38, 68–76. doi:10.1139/f81-009

Dahm, C.N., Candelaria-Ley, R.I., Reale, C.S., Reale, J.K., Van Horn, D.J., 2015. Extreme water quality degradation following a catastrophic forest fire. Freshw. Biol. 16. doi:10.1111/fwb.12548

Daly, C., Weisburg, J., 1997. Average annual precipitation New Mexico [WWW Document]. URL http://www.wrcc.dri.edu/pcpn/nm.gif (accessed 6.10.15).

Drakos, P.G., Riesterer, J.W., Bemis, K., 2013. Recharge sources and characteristics of springs on the Zuni Reservation, New Mexico, in: Zeigler, K., Timmons, M., Timmons, S., Semken, S. (Eds.), New Mexico Geological Society Guidebook, 64th Field Conference, Geology of Route 66 Region: Flagstaff to Grants, 2013. New Mexico Geologic Society, Soccoro, pp. 205–213.

Drever, J.I., 1982. The Geochemistry of Natural Waters, 1st ed. Prenctice-Hall, Englewood Cliffs.

Gido, K.B., Propst, D.L., 1999. Habitat use and association of native and nonnative fishes in the San Juan River, New Mexico and Utah. Copeia 1999, 321–332. doi:10.2307/1447478

Gilbert, E.I., Carman, S.M., 2013. Zuni Bluehead Sucker monitoring and conservation efforts 2011 and 2012. Santa Fe.

Glynn, P.D., Plummer, L.N., 2005. Geochemistry and the understanding of ground-water systems. Hydrogeol. J. 13, 263–287. doi:10.1007/s10040-004-0429-y

Grimm, N.B., Chacon, A., Dahm, C.N., Hostetler, S.W., Lind, O.T., Starkweather, P.L., Wurtsbaugh, W.W., 1997. Sensitivity of aquatic ecosystems to climatic and anthropogenic changes: the Basin and Range, American Southwest and Mexico. Hydrol. Process. 11, 1023–1041. doi:10.1002/(SICI)1099-1085(19970630)11:8<1023::AID-HYP516>3.0.CO;2-A

Gupta, P., Noone, D., Galewsky, J., Sweeney, C., Vaughn, B.H., 2009. Demonstration of high-precision continuous measurements of water vapor isotopologues in laboratory and remote field deployments using wavelength-scanned cavity ring-down spectroscopy (WS-CRDS) technology. Rapid Commun. Mass Spectrom. 23, 2534–2542.

Hoerling, M., Kumar, A., 2003. The perfect ocean for drought. Science 299, 691–694. doi:10.1126/science.1079053

Karlstrom, K.E., Dallmeyer, R.D., Grambling, J.A., 1997. Ar evidence for 1.4 Ga regional metamorphism in New Mexico: Implications for thermal evolution of lithosphere in the southwestern USA. J. Geol. 105, 205–224. doi:10.1086/515912

Klove, B., Allan, A., Bertrand, G., Druzynska, E., Erturk, A., Goldscheider, N., Henry, S., Karakaya, N., Karjalainen, T.P., Koundouri, P., Kupfersberger, H., Kvcerner, J., Lundberg, A., Muotka, T., Preda, E., Pulido-Velazquez, M., Schipper, P., 2011. Groundwater dependent ecosystems. Part II. Ecosystem services and management in Europe under risk of climate change and land use intensification. Environ. Sci. Policy 14, 782–793. doi:10.1016/j.envsci.2011.04.005

Kodric-Brown, A., Brown, J.H., 2007. Native fishes, exotic mammals, and the conservation of desert springs. Front. Ecol. Environ. 5, 549–553.

Kreamer, D.K., Springer, A.E., 2008. The hydrology of desert springs in North America, in: Stevens, L.E., Meretsky, V.J. (Eds.), Aridland Springs in North America Ecology and Conservation. University of Arizona Press and The Arizona-Sonora Desert Museum, Tucson, pp. 35–49.

Langmuir, D., 1997. Aqueous Environmental Geochemistry, 2nd ed. Prenctice-Hall, Upper Saddle River, New Jersey.

Loáiciga, H.A., 2003. Climate change and ground water. Ann. Assoc. Am. Geogr. 93, 30–41. doi:10.1111/1467-8306.93103

Magurran, A.E., 2009. Threats to freshwater fish. Ecology 325, 1215–1216. doi:10.1126/science.1177215

Martin, T.D., Brockhoff, C.A., Creed, J.T., 1994. Determination of metals and trace elements in water and wastes by Inductively Coupled Plasma-Atomic Emissions Spectrometry. Method 200.7. Usepa 4.4, 1–58.

Merritt, D.M., Bateman, H.L., 2012. Linking stream flow and groundwater to avian habitats in a desert riparian system. Ecol. Appl. 22, 1973–1988.

Myers, M.D., 2006. National field manual for the collection of water-quality data, in: Wilde, F.D. (Ed.), USGS Techniques of Water-Resources Investigations. Book 9 Handbooks for Water-Resources Investigations. U.S. Geological Survey, Reston, p. 231.

National Weather Service, 2015. Drought summary 2015 water year [WWW Document]. Natl. Weather Serv. Weather Forecast Off. URL http://www.srh.noaa.gov/abq/?n=drought (accessed 6.10.15).

Newman, B.D., Wilcox, B.P., Archer, S.R., Breshears, D.D., Dahm, C.N., Duffy, C.J., McDowell, N.G., Phillips, F.M., Scanlon, B.R., Vivoni, E.R., 2006. Ecohydrology of water-limited environments: A scientific vision. Water Resour. Res. 42, 15. doi:10.1029/2005WR004141

Overpeck, J., Udall, B., 2010. Dry times ahead. Science 328, 1642–1644.

Phillips, F.M., Walvoord, M.A., Small, E.E., 2013. Effects of environmental change on groundwater recharge in the desert southwest, in: Groundwater Recharge in a Desert Environment: The Southwestern United States. pp. 273–294. doi:10.1029/009WSA15

Pilgrim, D.H., Huff, D.D., Steele, T.D., 1979. Use of specific conductance and contact time relations for separating flow components in storm runoff. Water Resour. Res. 15, 329–339.

Plummer, L.N., Bexfield, L.M., Anderholm, S.K., Sanford, W.E., Busenberg, E., 2004. Geochemical characterization of ground-water flow in the Santa Fe Group aquifer system, Middle Rio Grande Basin, New Mexico, U.S. Geological Survey Water-Resources Investigation Report 03-4131.

Poff, N.L., Richter, B.D., 2012. Water resources and sustainable aquatic ecosystems: A vision for 2050, in: Toward a Sustainable Water Future: Visions for 2050. pp. 175–186.

Pool, T.K., Olden, J.D., 2015. Assessing long-term fish responses and short-term solutions to flow regulation in a dryland river basin. Ecol. Freshw. Fish 24, 56–66. doi:10.1111/eff.12125

Propst, D.L., 1999. Threatened and endangered fishes of New Mexico, Technical Report No. 1. Santa Fe,.

Propst, D.L., Gido, K.B., Stefferud, J.A., 2008. Natural flow regimes, nonnative fishes, and native fish persistence in arid-land river systems. Ecol. Appl. 18, 1236–1252. doi:10.1890/07-1489.1

Propst, D.L., Hobbes, A.L., Stroh, T.L., 2001. Distribution and notes on the biology of Zuni Bluehead Sucker, Catostomus discobolus yarrowi, in New Mexico. Southwest. Nat. 46, 158–170.

Robertson, A.J., Henry, D.W., Langman, J.B., 2013. Geochemical evidence of groundwater flow paths and the fate and transport of constituents of concern in the alluvial aquifer at Fort Wingate Depot Activity , New Mexico, 2009, U.S. Geological Survey Scientific Investigations Report 2013 – 5098. Reston.

Romanini, D., Kachanov, A.A., Stoeckel, F., 1997. Diode laser cavity ring down spectroscopy. Chem. Phys. Lett. 270, 8.

Ruhí, A., Holmes, E.E., Rinne, J.N., Sabo, J.L., 2014. Anomalous droughts, not invasion, decrease persistence of native fishes in a desert river. Glob. Chang. Biol. 21, 1482–1496. doi:10.1111/gcb.12780

Rutherford, J.C., Marsh, N.A., Davies, P.M., Bunn, S.E., 2004. Effects of patchy shade on stream water temperature: How quickly do small streams heat and cool? Mar. Freshw. Res. 55, 737–748. doi:10.1071/MF04120

Sada, D.W., Fleishman, E., Murphy, D.D., 2005. Associations among spring-dependent aquatic assemblages and environmental and land use gradients in a Mojave Desert mountain range. Divers. Distrib. doi:10.1111/j.1366-9516.2005.00131.x

Shanafield, M., Cook, P.G., 2014. Transmission losses, infiltration and groundwater recharge through ephemeral and intermittent streambeds: A review of applied methods. J. Hydrol. 511, 518–529. doi:10.1016/j.jhydrol.2014.01.068

Springer, A.E., Stevens, L.E., 2009. Spheres of discharge of springs. Hydrogeol. J. 17, 83–93. doi:10.1007/s10040-008-0341-y

Stevens, L.E., Meretsky, V.J., 2008a. Aridland springs in North America ecology and conservation. University of Arizona Press and The Arizona-Sonora Desert Museum, Tucson.

Stevens, L.E., Springer, A.E., 2005. A conceptual model of springs ecosystem ecology. Task 1B Final report. NPS Coop. Agreem. Number CA 1200-99-009 86011, 1–73.

Stevens, L.E., Springer, A.E., Ledbetter, J.D., 2008. SEAP: An integrated springs ecosystem assessment protocol [WWW Document]. URL http://springstewardship.org

Strickland, D., Heizler, M.T., Selverstone, J., Karlstrom, K.E., 2003. Proterozoic evolution of the Zuni Mountains, western New Mexico: Relationship to the Jemez Lineament and implications for a complex cooling history, New Mexico Geological Society Guidebook, 54th Field Conference. Soccoro.

Taylor, R.G., Scanlon, B., Doll, P., Rodell, M., van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J.S., Edmunds, M., Konikow, L., Green, T.R., Chen, J.Y., Taniguchi, M., Bierkens, M.F.P., MacDonald, A., Fan, Y., Maxwell, R.M., Yechieli, Y., Gurdak, J.J., Allen, D.M., Shamsudduha, M., Hiscock, K., Yeh, P.J.F., Holman, I., Treidel, H., 2013. Ground water and climate change. Nat. Clim. Chang. 3, 322–329. doi:10.1038/nclimate1744

Turner, T.F., Wilson, W.D., 2009. Conservation genetics of Zuni Bluehead Sucker (Catostomus discobolus yarrowi) in New Mexico, Final Report Contract # 09-516-0000-00017. Albuquerque.

USEPA, 2014. Water quality standards handbook (40 CFR 131 - Subpart C). Washington, DC.

USEPA, 2002. Standard operating procedure for calibration and field measurement procedures for the YSI Model 6-series Sondes (including: temperature, pH, specific conductance, turbidity, and dissolved oxygen). North Chelmsford.

USFWS, 2014. DOI Federal Register: Endangered and threatened wildlife and plants; endangered species status for the Zuni Bluehead sucker; Final Rule. 50 CFR Part 17., Federal Register.

USFWS, 2013. Endangered and threatened wildlife and plants; proposed endangered status for the Zuni Bluehead Sucker, Federal Register.

van der Kamp, G., 1995. The hydrogeology of springs in relation to the biodiversity of spring fauna : A review. J. Kansas Entomol. Soc. 68, 4–17.

Wagner, R.J., Boulger, Jr., R.W., Oblinger, C.J., Smith, B.A., 2006. Guidelines and standard procedures for continuous water-quality monitors: station operation, record computation, and data reporting. USGS Tech. Methods 1-D3, 96.

Wetzel, R.G., 2001. Limnology Lake and River Ecosystems, 3rd ed. Academic Press, San Diego.

Williams, A.J., Crossey, L.J., Karlstrom, K.E., Newell, D., Person, M., Woolsey, E., 2013. Hydrogeochemistry of the Middle Rio Grande aquifer system — Fluid mixing and salinization of the Rio Grande due to fault inputs. Chem. Geol. 351, 281–298. doi:http://dx.doi.org/10.1016/j.chemgeo.2013.05.029

YSI Incorporated, 2009. Multiparameter water quality Sondes user manual 6-series. YSI Incorporated.

Zektser, S., Loáiciga, H.A., Wolf, J.T., 2005. Environmental impacts of groundwater overdraft: Selected case studies in the southwestern United States. Environ. Geol. 47, 396–404. doi:10.1007/s00254-004-1164-3

Appendices

The following appendices have been submitted separately from this dissertation as supplemental material.

Appendix I.	15 minute intervals for continuous monitoring of physico-chemical parameters at Agua Remora (AR) with list of corrections
Appendix II.	Mean daily values for continuous monitoring of physico-chemical parameters at Agua Remora (AR)
Appendix III.	Seasonal and monthly summary of continuous monitoring of physico-chemical parameters at Agua Remora (AR) and Tampico Draw (TD)
Appendix IV.	15 minute intervals for continuous monitoring of additional parameters (Turbidity, pH and Dissolved Oxygen) at Agua Remora (AR) with list of corrections
Appendix V.	Mean daily values for continuous monitoring of additional parameters (Turbidity, pH and Dissolved Oxygen) at Agua Remora (AR)
Appendix VI.	15 minute intervals for continuous monitoring of physico-chemical parameters at Tampico Draw (TD) with list of corrections
Appendix VII.	Mean daily values for continuous monitoring of physico-chemical parameters at Tampico Draw (TD)
Appendix VIII.	Alkalinity and nutrient concentrations for Agua Remora (AR) and Tampico Draw (TD)

Chapter 3: Cibola National Forest Spring Inventory: Hydrogeochemical Analysis of Springs Waters of the Sandia, Mt. Taylor and Zuni Mountains, New Mexico

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Executive Summary

Springs and surface waters in the Zuni Mountains, Mount Taylor and Sandia Mountains, in New Mexico, were visited by students and faculty from the University of

New Mexico. Much of this work was funded through a cost share agreement with the Cibola National Forest (USFS). The purpose of the project was to collect basic information about springs including spring type, spring location, geologic and hydrologic setting, water and flow conditions, geochemistry and physico-chemical parameters. In the 2012-2015 field seasons, graduate and undergraduate students investigated 78 spring sites in the Sandia (n=23) and Mount Taylor (n=15) and Zuni (n=40) Mountains. Some spring sites were visited multiple times, while others were visited just once. Each spring site was assessed using part or all of the Spring Ecosystem Assessment Protocol (SEAP) (Stevens et al., 2008) and the USDA Ground water-Dependent Ecosystems: Level I, and II Inventory Field Guides (USDA Forest Service, 2012a, 2012b). The spring site assessments combined hydrological and ecological measures to determine driving mechanisms to the spring ecosystem.

The assessment of each spring included identification of the spring's location using a protocol developed for the survey and verified in the field by a GPS unit. In addition, the sub-basin and watershed hydrologic units and the geologic setting as well as an assessment of spring wetlands flora and fauna was conducted. When water was present, physico-chemical parameters and spring discharge was measured. Additionally, spring water samples were collected and taken to the laboratory for analysis of major cations and anions, stable isotopes (δ^2H and δ^{18}O) and in some cases tritium (^{3}H). Several spring areas, indicated by Cibola USFS as areas of interest, also had continuous monitoring of physico-chemical and hydrologic parameters.

A protocol for identifying locations of spring sites within Cibola land boundaries was established using digital data from USFS, National Hydrologic Data (NHD) and Geographic Names Information System (GNIS). A total of 308 springs were found within Cibola USFS Mountain Districts. This report covers spring sites found in 1) the Zuni Mountains 2) Mt Taylor Mountains 3) the Sandia Mountains.

Abstract

Ground waters in the semi-arid region of southwestern USA are important resources and have multiple uses for cities, businesses, ranchers, recreation and ecosystems. The current state of springs within Cibola National Forest will help to understand how spring waters are being affected by land use practices, drought and climate change. From 2012 to 2015 a total of 110 spring assessments were completed to take baseline data and characterize the springs in the Zuni Mountains, Mount Taylor and Sandia Mountains within the Cibola National Forest. Of the total spring visits, 51 (46%) were dry. Mount Taylor had the highest percentage (67%) of dry springs, followed by the Zuni Mountains with 63% dry springs and with the Sandia Mountains having 13% dry. Of the 59 spring visits that were wet, waters were collected for hydrochemical analyses to determine flow path, recharge mechanisms and for some the age of the ground waters. In addition, several creeks were sampled and monitored to determine water quality and availability for surface waters on the National Forest. Geochemical results indicate that the majority of the waters are from the confined aquifers of the mountain regions. Isotopologues of these waters, compared to regional precipitation events that were collected, indicate that a majority of the ground waters are recharged through

snowmelt. A small proportion of the spring waters are stored in unconfined shallow alluvium aquifers that can be recharged through both snow and rain events. These results can be used to inform resource managers about the hydrologic flow paths, residence time, recharge mechanisms and water quality for springs within the National Forest. Future work can help provide additional information to assist in monitoring changes to water quality and availability due to management activities, drought and climate change.

Introduction

Across the desert southwestern United States, water resources are stressed due to anthropogenic demands, severe drought and climate change (Loaiciga et al., 2003). Ground water has been over pumped in metropolitan areas within the southwest (Jacobs and Holway, 2004), and as the population continues to grow we will become more dependent on ground water resources (Zetsker et al., 2005). Springs are areas where ground water emerges to the surface (Hynes, 1983). In arid lands, springs can provide the only perennial source of surface waters during the dry season (Springer and Stevens, 2009). Due to water management practices, extreme temperatures and low precipitation (Overpeck and Udall, 2010), springs of the southwest are drying (Unmack and Minckley, 2008).

Springs in arid regions are hotspots of biological diversity (Springer and Stevens, 2009; Stevens and Meretsky, 2008a). Spring waters provide refugia for aquatic and wetland flora and fauna, creating isolated areas that concentrate endemism. Natural and anthropogenic changes to discharge and water quality can cause stress on ecosystems that rely on perennial flow and can have lasting effects on the spring ecosystem (Stevens & Springer, 2004). Through the application of geochemical analysis and continuous monitoring of spring waters, an understanding of sustainable hydrology policies can be developed to adapt to effects of climate and anthropogenic changes on springs and the ground water systems that support them.

Hydrogeochemical analysis of spring waters are ideal methods of monitoring surface water quality. During times of low or no precipitation in arid land stream systems, ground water is the primary contributor to baseflow. Baseflow accounts for most stream flow throughout the year (Hornberger et al., 1998; Hynes, 1983) where ground water can be more saline than surface waters. Water quality can be impacted by reduced surface flow. Constituents of deeply sourced ground water fluids will have higher proportions in surface waters, degrading water quality. With this understanding, it is imperative to identify changes to spring water quality as these parameters are tied directly to surface water quality in a changing climate.

Continuous monitoring of springs are excellent methods for monitoring surface water sustainability, especially during baseflow. Spring discharge rates can be variable with trends in timing and magnitude and exhibit change on a diurnal, seasonal and/or annual basis (Springer and Stevens, 2009). Discharge can also be affected by changes in the climate (Loáiciga, 2003; Phillips et al., 2013; Zektser et al., 2005) and land use practices (Grimm et al., 1997; Johnson and Campbell, 2002; Zektser et al., 2005). Monitoring springs offers insight as to how reduced snowpack will impact spring discharge and surface water baseflow.

This research was tasked with contributing to an inventory of spring sites within Cibola National Forest, including the Zuni Mountain, Mount Taylor and Sandia Mountain divisions. The inventory consisted of verifying locations, taking chemical and flow data according to established protocols. These mountain regions are part of the west central and central New Mexico public lands that are managed by the Department of Agriculture. A protocol was developed to verify spring locations within the Cibola National Forest boundaries (Appendix I). Appendix II gives the results of the protocol including spring names, locations, hydrologic units and geologic units for all Mountain Districts within Cibola National Forest. Districts and divisions that were not visited during this study are also included in Appendix II.

Development on springs of Cibola National Forest depends on the type of spring being utilized. Slope springs are developed using headboxes, dug into the source to collect water. Water table springs are developed by digging a hole for collection. Spring flow within channels can be collected in earthen dams which also captures surface flow. Cattle troughs and uncountable water hoses and pipes divert spring water away from spring sites.

Spring flow on the Cibola National Forest mountain districts have reduced possibly due to changes in climate and drought as well as land use (Carman, 2004; Drakos et al., 2013; Orr, 1987; Robertson et al., 2013). Because of the changes to spring resources the Cibola National Forest has identified a spring inventory as a priority since 2010. For this work, beginning in 2012, priorities for spring sites were established by the Forest Service.

This report includes local climate and precipitation, hydrogeologic, stratagraphic and aquifer hydrochemical data for each of the mountain regions. Included in the report are general trends of ground water resources related to spring areas. A SEAP worksheet and pictures are completed for each individual site visit. The goal is to report on the results of the inventory process which included location verification, and characterization of spring's flows in terms of chemistry and flow to inform management decisions.

Hydrogeochemical Spring Inventory

It is crucial to understand the hydrogeology and climate of each area in order to understand the hydrology and water chemistry of springs. The geology influences flow patterns and water-rock interaction. Geologic formations consist of different minerals that interact with ground water as it flows through aquifer materials. Geologic formation differences also impact storativity and transmissivity of ground waters. Geologic structures can act as barriers or conduits for ground water flow and allow for aquifer waters to mix vertically. Using hydrochemistry, ground water flow paths and mixing scenarios can be modeled. Climate provides information about the amount and timing of precipitation. Isotopologues of water ($\delta^{18}O$ and δD) determine the mechanisms of recharge, as well as atmospheric interactions. Tritium (^{3}H) concentrations help to determine how much young water is present in the ground waters. Continuous monitoring of physico-chemical parameters helps to determine water stability and ecosystem viability. The next sections describe the hydrogeology and climate of the study areas.

Zuni Mountains, West Central New Mexico

The Zuni Mountains in west-central New Mexico are located in the southeastern portion of the Colorado Plateau. The Zuni Mountains are considered a low-lying mountain with the lowest elevation of 1,920 m (6,300 ft) at Plumasano Wash. The Continental Divide straddles the Zuni Mountains with the western side (Lower Colorado River Basin, LCRB) having lower elevation than the eastern side (Rio Grande Basin) (Figure 1). The Rio Grande Basin is higher with a maximum elevation just over 2,730 m (8,900 ft) at Lookout Mountain. Within the LCRB boundaries, the highest peak is located on Oso Ridge at an elevation of just under 2,648 m (8,700 ft).

Climate and surface water hydrology

The annual precipitation is bimodal, occurring as snowfall from January through March and as monsoonal rainfall from July through August. Overall, the Zuni Mountains are reported to receive ~370 mm (14.6 in) of precipitation annually (Anderson et al., 2003), with a majority falling as monsoonal rains and the remaining primarily falling as wintertime snow. The sources of precipitation events for the Zuni Mountains can vary spatially and temporally with the El Niño/Southern Oscillation (ENSO) phenomenon being a driving factor for interannual variability (Giannini et al., 2001). During an El Niño year, the eastern tropical and subtropical ocean temperature is warmer and the Southwest typically gets higher volumes of precipitation from the Pacific. The effects of El Niño led to the very wet periods of the early 20th century and 1990s in the Southwest (Seager et al., 2005). In comparison, when the eastern tropic Pacific is cool (La Niña) there is less precipitation, producing only half to one-third the precipitation of an El Niño year (Hoerling and Kumar, 2003). The drought of 1998-2002, as well as the current drought conditions are in part a result of the cold phase of ENSO (La Niña) (Hoerling and Kumar, 2003; Hoerling et al., 2014). In addition to the Pacific Ocean, storms in the Gulf of Mexico can provide up to 30% of seasonal rainfall totals for New Mexico (Newton et al., 2012). The ocean temperature differences and sources affect the chemical signature of the storm systems and the water that recharges the regional aquifers. These differences in precipitation sources can be identified in water samples as the geochemical signature is unique to the location and temperature of each of the precipitation events.

The Zuni Mountains is separated by the Continental Divide where western Zuni Mountain streams flow west and eastern Zuni Mountain streams flow east. The major streams within the western Zuni Mountains are the Rio Nutria and Rio Pescado, and tributaries to the Zuni River. These streams are ephemeral and only flow in direct response to precipitation or snowmelt. The Rio San Jose and its tributary, Bluewater Creek, flow to the east (Figure 1) and are perennial streams. There are two USGS stream gauges outside of the Cibola National Forest boundary, which measure flows on streams that originate in the Zuni Mountains. Rio Nutria discharge (09386900 Rio Nutria near Ramah) is located above the Nutria Monocline and has operated from 1 October 1969 through 5 October 2015 (n=16,804 days). The average of the daily mean discharge for Rio Nutria is 0.14 m^3/sec (5.10 ft^3/sec), with a median of 0.003 m^3/sec (0.12 ft^3/sec) and maximum of 29.17 m^3/sec (1,030 ft^3/sec). Bluewater Creek also had a gauge upstream from Bluewater Creek Reservoir where discharge was measured from 1 October 1960 through 4 January 1973 (n=4,479 days) (08342000 Bluewater Creek) (Figure 1). The average of the daily mean discharge for Bluewater Creek was 0.14 m^3/sec (4.91 ft^3/sec), with a median of 0.05 m^3/sec (1.60 ft^3/sec) and a maximum of 1.02 m^3/sec (36 ft^3/sec). The streams can flood during high precipitation events (maximum), but discharge is higher and more consistent (median) on the creeks east of the Continental Divide.

Surface waters for the Zuni Mountains are mapped on (Figure 1), including the major creeks and all spring sites. Spring sites identified in the protocol (Appendix I and II) are plotted within the Hydrologic Unit Codes for basin level (08). Water at springs are at the interface of surface and ground water hydrology. This research recognizes that the subsurface hydrology, including flow paths and recharge areas are not necessarily reflected in the HUC boundaries for surface waters.

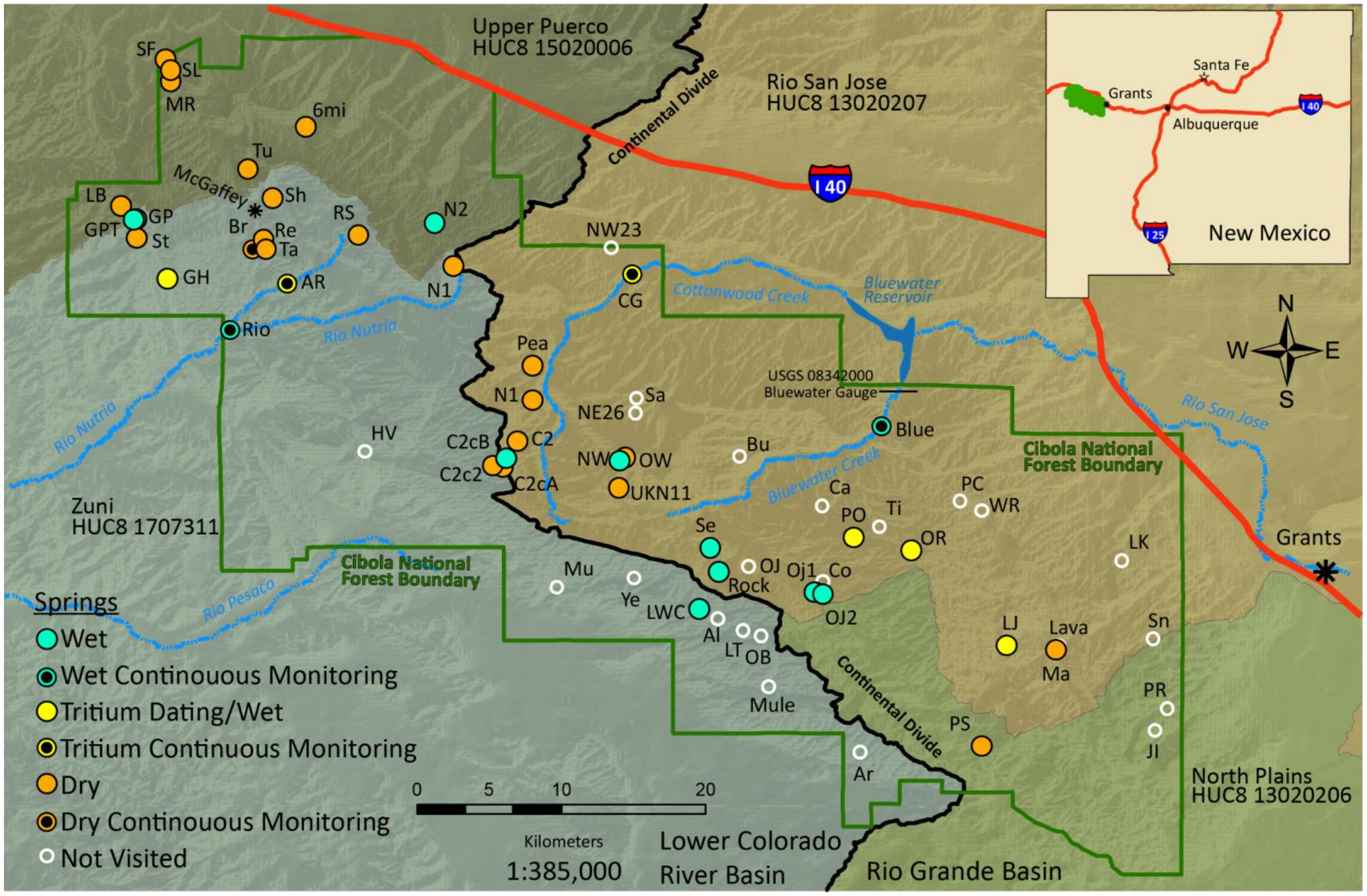


Figure 1. Map of Zuni Mountains, Cibola National Forest. Inset: Map of New Mexico with major Interstates and location of Cibola National Forest, Zuni Mountain Division boundaries. Hydrologic Unit (HUC08) boundaries, digital elevation model (DEM) showing topography and Cibola National Forest boundaries are mapped with surface water features including springs, streams and rivers. Spring locations are color coded based on type of visit (i.e., hollow white = not visited, blue = visited and wet, orange = visited and dry). A legend for complete spring name is found in Appendix II.

Geology

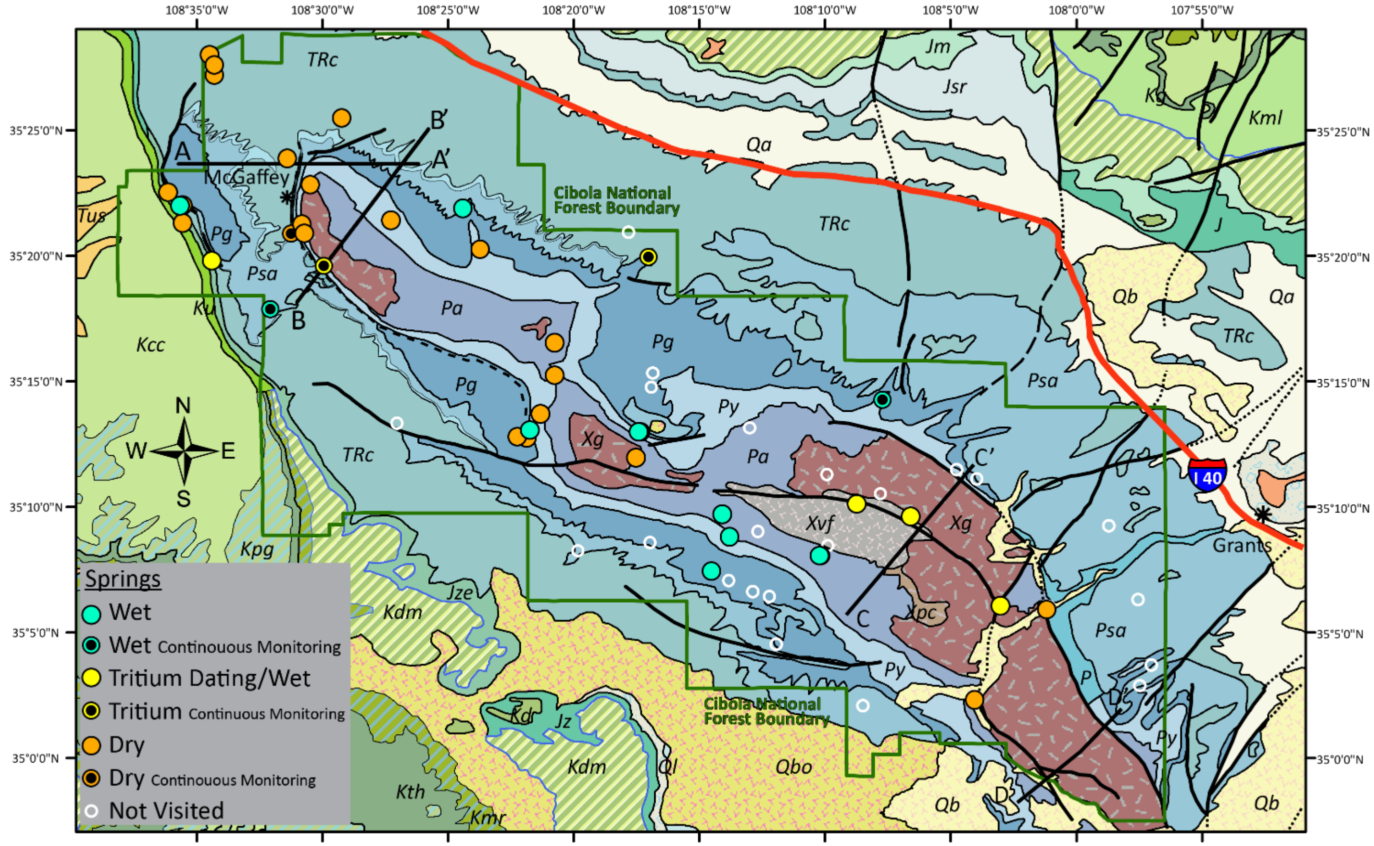
Geologic rock units and geologic structures can create or obstruct ground water flow paths. As well, different rock types interact with ground water by dissolving and absorbing different ions found in the rock material. Describing the subsurface geology and water-rock interactions allows for understanding where ground water is stored and how the water quality is impacted. Spring waters are especially important indicators of ground water hydrochemistry as springs can be concentrated along fault structures and can represent waters that are a mixture of different aquifer ground waters.

The Zuni Mountains are an uplifted basement block with the topographically highest peaks consisting of exposed 260 million year old granites and metavolcanics. These crystalline rocks represent continental building of island-arcs accreting to the craton (Karlstrom et al., 1997; Strickland et al., 2003). The Zuni Mountain Paleoproterozoic basements rocks are unconformably overlain with Paleozoic, Mesozoic and Cenozoic sedimentary rocks (Anderson et al., 2003; Baars, 1974; Colpitts, 1969; Darton, 1928; Goddard, 1966; Heckert and Lucas, 2003; Heckert, 1999; Mack, 2003). The unconformity between the Proterozoic and Paleozoic rocks represent a loss of more than 100 million years, a feature found throughout the Colorado Plateau and Rio Grande Rift Valley and referred to as The Great Unconformity (Connell, 2011; Crossey et al., 2009, 2006; Newell et al., 2005; Williams et al., 2013). In the Zuni Mountains, there is a concentration of springs along this unconformity. The springs, including ZBS habitat at Agua Remora, have water that has infiltrated fault structures in the Xm at higher altitudes (Figure 2).

The sedimentary rocks of the Zuni Mountains have been folded, faulted and eroded since deposition by several regional tectonic events, including Laramide uplift and compression and subsequently the spreading of the Basin and Range (Aldrich et al., 1986; Anderson et al., 2003; Karlstrom et al., 1997; Kelley, 1967; Paul and Mitra, 2012): these major events were in part controlled by pre-existing structural grains that date back to the Precambrian (Aldrich et al., 1986; Banerjee et al., 2011; Crossey et al., 2009; Karlstrom et al., 1997). The reactivation of these faults creates a complex surface and subsurface with geologic units juxtaposed at different angles and against units of significantly different geologic ages. In addition, these reactivated faults intersect all regional rock units, creating conduits for the vertical movement of ground water and mixing between aquifers.

A geologic map of the Zuni Mountain region (Figure 2) shows the contacts and structures and identifies that springs are concentrated along these structures. A cross section (Figure 3) provides insight into the subsurface structures and provides a hydrologic framework for the study. A geologic explanation (Figure 4) provides detailed descriptions of geologic units and symbols.

The Nutria monocline is a dominant topographic and structural feature in the Zuni Mountains. The monocline consists of two paralleling ridges 304 – 366 m (1,000-1,200 ft) that extend north-northwest along the western margin of the Zuni uplift (Anderson et al., 2003, 1998; Kelley, 1967). These monoclines are developed on Permian and Cretaceous sandstones which dips commonly exceed 60 degrees and as much as 80 degrees to the southwest (Anderson et al., 2003). A thrust fault, associated with the Laramide Orogeny, cuts the monocline belt, eliminating all Jurassic and Triassic strata (Heckert and Lucas, 2003) and brings Permian rocks in contact with upper Cretaceous rocks of the Dakota Sandstone (Anderson et al., 2003; Heckert and Lucas, 2003; Lucas et al., 1999). Oso Ridge is another monocline present in the western margin of the Zuni Mountains (Figure 3). Oso Ridge is formed of Permian rock (San Andres and Glorieta Formations) and dips as much as 75 degrees to the west (Anderson et al., 2003). The Nutria and Oso Ridge monoclines display similarities in form, geometry and trend and are considered to have developed in response to original primary vertical uplift and later by horizontal compression (Anderson et al., 2003). These geologic structures are important hydrogeologic features as they have associated faults where springs are concentrated.



Geologic Map Modified from:
NMBGMR, 2003 (Geologic Map of New Mexico; 1:500,000)
Anderson et al., 1998 (Geologic Map of Ft. Wingate Quadrangle; 1:24,000)
Stoeser et al., 2005 (Geologic Map Databases for the U.S. Central States)
-Note that the enlargement used here could cause misunderstanding in the detail of mapping and may result in erroneous interpretations.

Additional Principle Sources of Data:
Haller et al., 2005 (Quaternary Faults and Fold Database of the U.S.)
USEPA and USGS, 2005 (National Hydrogrphy Dataset)
USFS, 2011 (GIS property boundary layer)
USFS, 2011 (GIS Constructred_Feature_point_water tank, spring layer)
USGS in cooperation with BGN, 1988 (Geographic Names Information System)

Figure 2. Geologic map of Zuni Mountains, New Mexico. Geologic units exposed at the surface with faults (black) and cross section line (A-A', B-B', C-C', D-D'). Cibola National Forest Boundary (green) and springs within the National Forest boundary identified by protocol (Appendix II) are color coded to represent the work that has been completed. Geologic explanation is Figure 4 for unit descriptions.

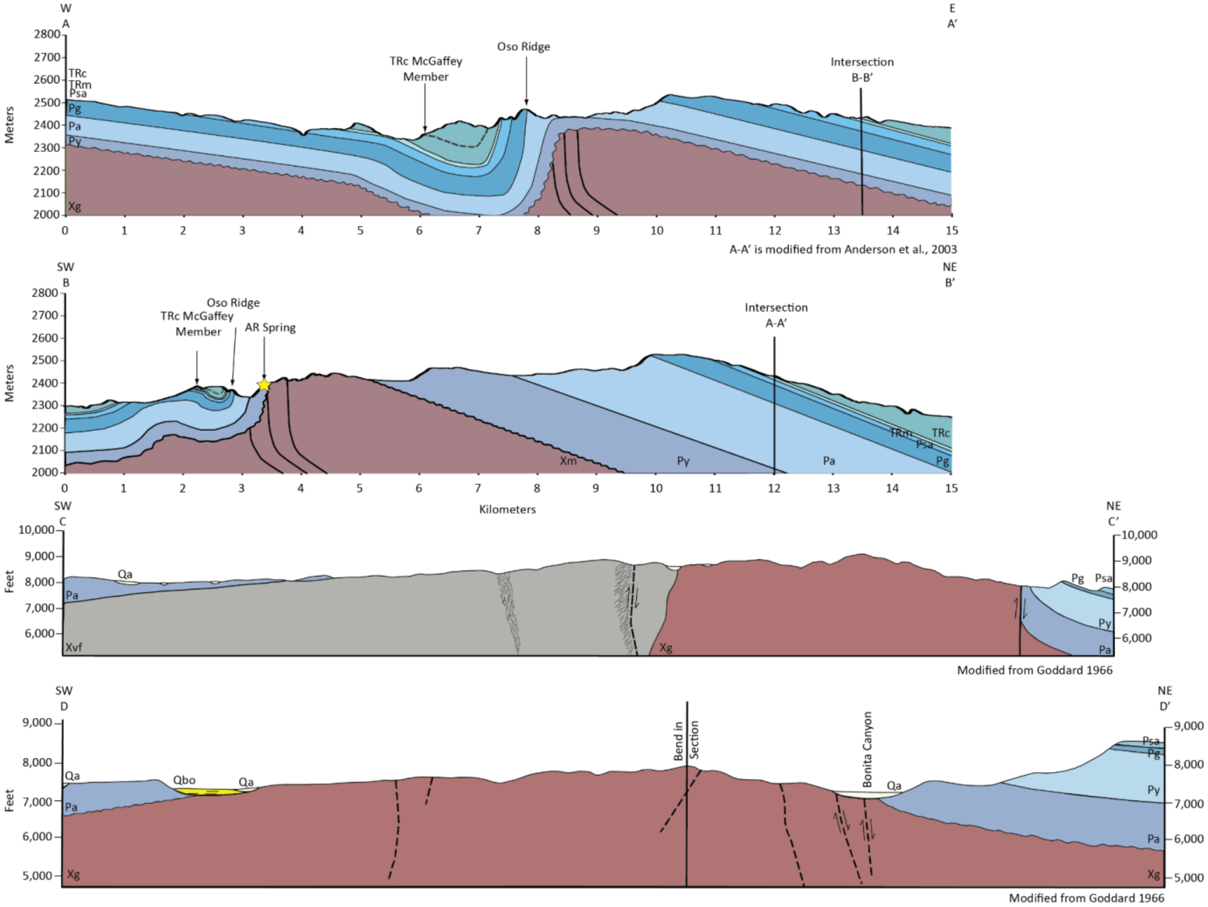


Figure 3. Geologic cross section of Zuni Mountains, New Mexico. Subsurface interpretations show folding, faulting and erosion of geologic layers. Line A-A' identifies Oso Ridge, a prominent geologic structures in the western Zuni Mountains. Line B-B' identifies AR spring relative to subsurface faults with erosion of Paleozoic and Mesozoic strata to expose Proterozoic metavolcanics (Xm). Lines C-C' and D-D' show significant subsurface faulting of Proterozoic crystalline rock overlain by sedimentary units. Cross section lines are found on Figure 2, geologic explanation is Figure 4 for unit descriptions.

Geologic Explanation

Modified from: NMBGMR, 2003 (Geologic Map of New Mexico; 1:500,000)

Quaternary

Qa	Alluvium
Qb	Andesite and basalt
Qe	Eolian
Ql	Landslide and colluvium

Quarternary and Tertiary

Qp	Piedmont alluvium
QTsf	Clastic and carbonate
QTs	Conglomerate and sandstone

Tertiary

Tus	Clastic and mixed clastic/volcanic (aphanitic)
Tsf	Coarse-grained mixed clastic and unconsolidated deposit
Tps	Medium-grained mixed clastic and tuff
Tmb	Basalt and andesite
Tnr	Felsic volcanic rock and intermediate volcanic rock
Tnv	Volcanic rock (aphanitic)
Tuau	Plutonic rock (phaneritic)
Tvs	Clastic and mixed clastic/volcanic

Cretaceous

Ku	**Upper Cretaceous rocks, undivided** Medium-grained mixed clastic and volcanic rock (aphanitic)
Kmv	**Mesaverde Group** Sandstone and fine-grained mixed clastic
Kpl	**Point Lookout Sandstone** Sandstone and arkose
Kms	**Satan Tongue of Mancos Shale** Shale
Kmm	**Mulatto Tongue of Mancos Shale** Shale and sandstone
Kcc	**Crevasse Canyon Formation** Fine-grained mixed clastic and coal
Kg	**Gallup Sandstone** Sandstone
Kmr	**Rio Salado Tongue of the Mancos Shale** Shale and limestone
Kpg	**Pescado Tongue of the Mancos Shale and Gallup Sandstone** Sandstone and shale
Kdm	**Intertongued Mancos Shale and Dakota Sandstone** Fine-grained mixed clastic and medium-grained mixed clastic
Kml	**Macos Shale, lower part** Shale and fine-grained mixed clastic
Kd	**Dakota Sandstone** Medium-grained mixed clastic

Jurassic

J	**Upper and Middle Jurassic, undivided** Clastic and sedimentary rock
Jm	**Morrison Formation** Fine-grained mixed clastic and limestone
Jmr	**Morrison Formation** Medium-grained mixed clastic and fine-grained mixed clastic
Jze	**Zuni and Entrada Sandstone** Sandstone and fine-grained mixed clastic
Jz	**Zuni Sandstone** Sandstone and shale

Triassic

TR	**Triassic rocks, undivided** Medium-grained mixed clastic
TRc	**Chinle Group, undivided** Medium-grained mixed clastic and fine-grained mixed clastic
TRm	**Moenkopi Formation** Sandstone and siltstone

Permain

P	**Permian rocks, undivided** Sedimentary rock
Psa	**San Andres Formation** Carbonate and fine-grained mixed clastic
Pg	**Glorieta Sandstone** Sandstone
Psg	**San Andres Limestone and Glorieta Sandstone** Fine-grained mixed clastic and carbonate
Py	**Yeso Formation** Sandstone and limestone
Pa	**Abo Formation** Sandstone and shale

Pennsylvanian

IP	**Pennsylvanian rocks, undivided** Sedimentary rock and medium-grained mixed clastic
IPm	**Madera Group** Limestone and fine-grained mixed clastic
IPs	**Sandia Formation** Sandstone and shale

Proterozoic

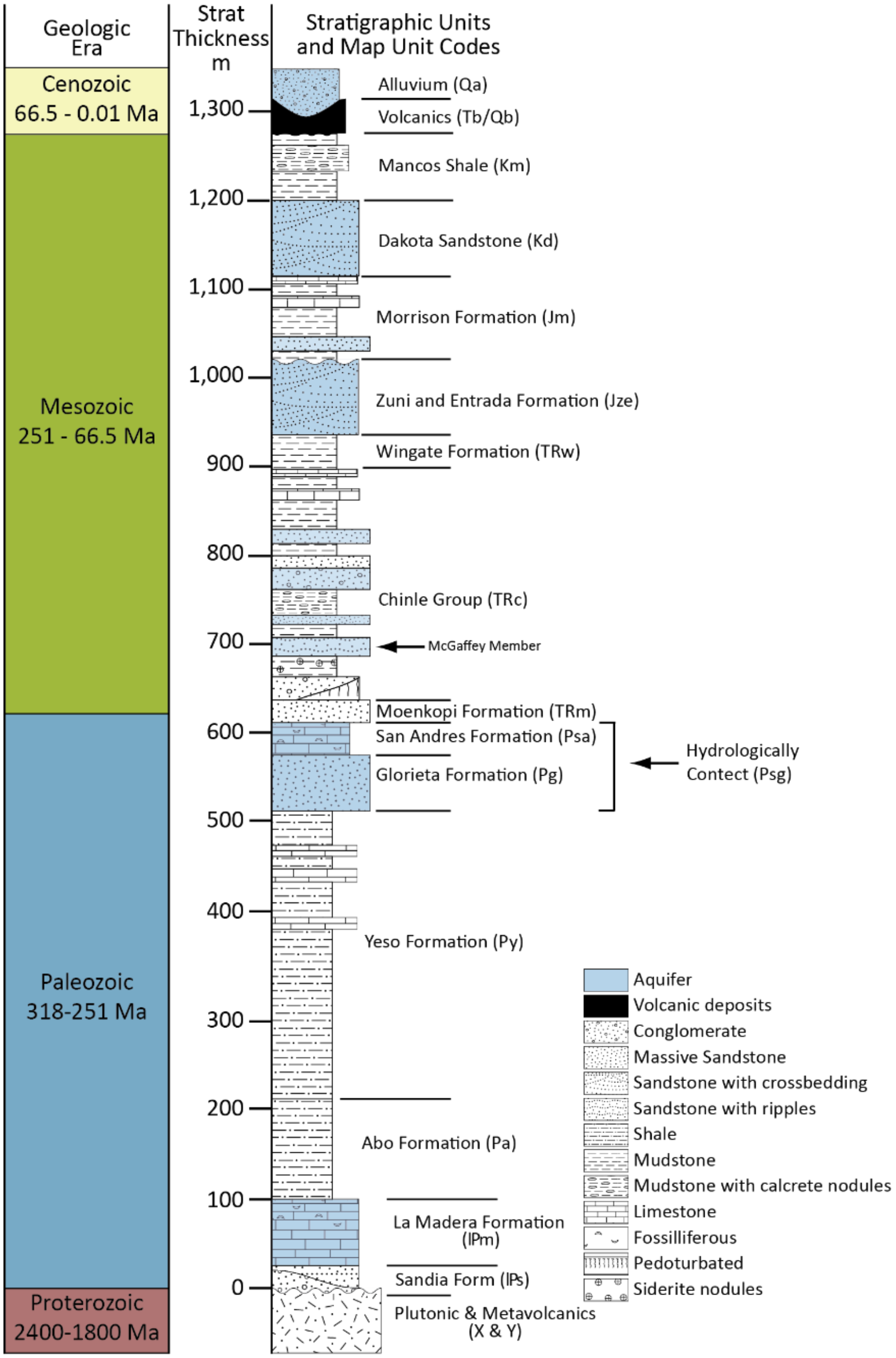
Yg	**Middle Proterozoic** Plutonic rock (phaneritic)
Xg	**Lower Proterozoic** Plutonic rock (phaneritic)
Xq	**Lower Proterozoic** Metasedimentary rock
Xvf	**Lower Proterozoic** Felsic metavolcanic rock and plutonic rock (phaneritic)
Xpc	**Lower Proterozoic** Mafic metavolcanic rock

Figure 4. Geologic explanation of geologic units and symbols from geologic maps and cross sections from New Mexico. Descriptions are arranged from oldest (bottom right corner) to youngest (top left corner) with unit names and rock descriptions.

Ground water hydrology

The modern hydrologic framework of the Zuni Mountains reflects the influence of the repeated deformation and magmatism from the early Proterozoic through Cenozoic times with springs concentrated along the fault plane (Aldrich et al., 1986; Anderson et al., 2003; Karlstrom et al., 1997; Strickland et al., 2003; Whitmeyer and Karlstrom, 2007). How ground waters are interacting along fault structures can help resource managers understand the flow paths and subsurface network of ground water resources. Determining aquifer and confining units (Figure 5) throughout west-central and central New Mexico allow for better understanding mixing of different units and the effects on water quality.

There are several different aquifers in the study area. The hydrologically connected Permian San Andres and Glorieta Sandstone (Psg) is the primary aquifer unit for the Cibola National Forest and surrounding areas within the Zuni Mountains. This aquifer has high permeability and storage, but has been structurally altered with complex networks of faults and folds (Baldwin and Anderholm, 1992; Baldwin and Rankin, 1995; Robertson et al., 2013; Shoemaker, 1971). Other geologic layers within the Zuni Mountains are limited to local differences where hydrological productivity varies widely. The Triassic Chinle Formation can locally store water (Baldwin and Rankin, 1995; Robertson et al., 2013), while the Permian Abo and Yeso Formations tend to have low conductivity and storage (Hood and Kister, 1962). The Quaternary alluvium is also a local resource for storage of ground waters (Baldwin and Rankin, 1995; Robertson et al., 2013). These local aquifers provide water that discharges to springs within the study area.



Modified from Roberston et al., 2013 and Connell, 2011

Figure 5. Stratigraphic column for west-central and central New Mexico. Geologic era, stratigraphic thickness and names as well as map unit codes help to determine when and how geologic units were deposited. Comparison of geologic maps (Figure 2, 7, 10) and cross sections (Figure 3, 8, 11) allow for understanding how contact between different rock types and aquifers.

Spring priorities for Zuni Mountains

Several perennial springs on the western side of the Continental Divide provide refugia for the endangered Zuni Bluehead Sucker (ZBS) (*Catostomus discobolus yarrowi*) (Carman, 2004; Gilbert and Carman, 2013; Orr, 1987; USFWS, 2014). The primary habitat that was studied was the population at Agua Remora. A low flow (<0.02cfs) hillslope spring (Springer and Stevens, 2009) discharges into the Upper Rio Nutria channel (Figure 1). Within the channel are four perennial pools, three downstream from the spring discharge and one upstream from the spring discharge. Seasonal visits and continuous monitoring of physico-chemical parameters beginning in 2012 was undertaken to identify the influence the spring has on the ZBS habitats. In 2013, additional ZBS habitats were investigated at the confluence of the Upper Rio Nutria to the Rio Nutria (Figure 1). A hanging garden spring (Springer and Stevens, 2009) was identified seeping from the walls of Tampico Draw within the Upper Rio Nutria, just above the confluence with the Rio Nutria. ZBS populations live at and below the hanging garden spring but have not survived in the Rio Nutria above the confluence since the 1990s (Carman, 2004). Results from work done specifically on the ZBS habitats will not be presented in this report. Refer to Frus et al., in review, for a detailed report on the habitat hydrogeochemistry and biodiversity.

Mount Taylor, New Mexico

Mount Taylor is located in the southern San Juan Basin and has a maximum elevation above sea level of 3,445 m (11,301 ft). The city of Grants is about 15 miles southwest of Mount Taylor and has an elevation of 1,970 m (6,460 ft). Mount Taylor is a composite volcano with the primary vent having the highest peak, but a large basalt capped lava field has preserved a high elevation mesa that extends to the northeast. Cibola National Forest boundaries contain the highest elevation points of the mountain range, including a large section of the mesa (Figure 6).

Climate and surface water hydrology

Local climate data for the city of Grants (1997 to 2008) at the base of Mount Taylor, has yearly precipitation averages of 21.4 cm (8.44 in). The ENSO climatic patterns have similar effects as described in the Zuni Mountain section with monsoonal precipitation at Mount Taylor having the highest proportion (46%) falling in July through September (Western Regional Climate Center, 2009). Winter months (December – February) represents 22% of yearly precipitation (Western Regional Climate Center, 2009). The precipitation for the higher elevations of Mount Taylor is expected to be higher due to the higher elevation, but seasonal proportions should be similar (Langman et al., 2012).

Surface waters for the Zuni Mountains are mapped on (Figure 6), including the major creeks and all spring sites. Spring sites identified in the protocol (Appendix I and II) are plotted within the Hydrologic Unit Codes for basin level (08). The work of springs is at the interface of surface and ground water hydrology and it is recognized that the subsurface hydrology is not necessarily reflected in the HUC boundaries for surface waters.

San Mateo Creek is an intermittent stream that drains large rain events and spring time snowmelt run off from the slopes of Mount Taylor. San Mateo Creek runs west out of the city of San Mateo (Figure 6). Between 1977 and 1982, USGS continuously monitored discharge at San Mateo Creek. The daily mean discharge (n=1963) averaged 0.03 m^3/sec (0.98 ft^3/sec) (U.S. Geological Survey, n.d.). Analysis of the daily mean data indicates that 44.63% of the days had zero (0) flow. The maximum discharge value was 2.27 m^3/sec (80 ft^3/sec) with the next largest discharge event being 0.85 m^3/sec (30 ft^3/sec) (U.S. Geological Survey, n.d.). Lobo Creek and Rinconada Creek are additional intermittent and ephemeral creeks which run south out of the National Forest boundaries (Figure 6). Springs of Mount Taylor are located at the head waters of these creeks. The majority of springs are intermittent and ephemeral.

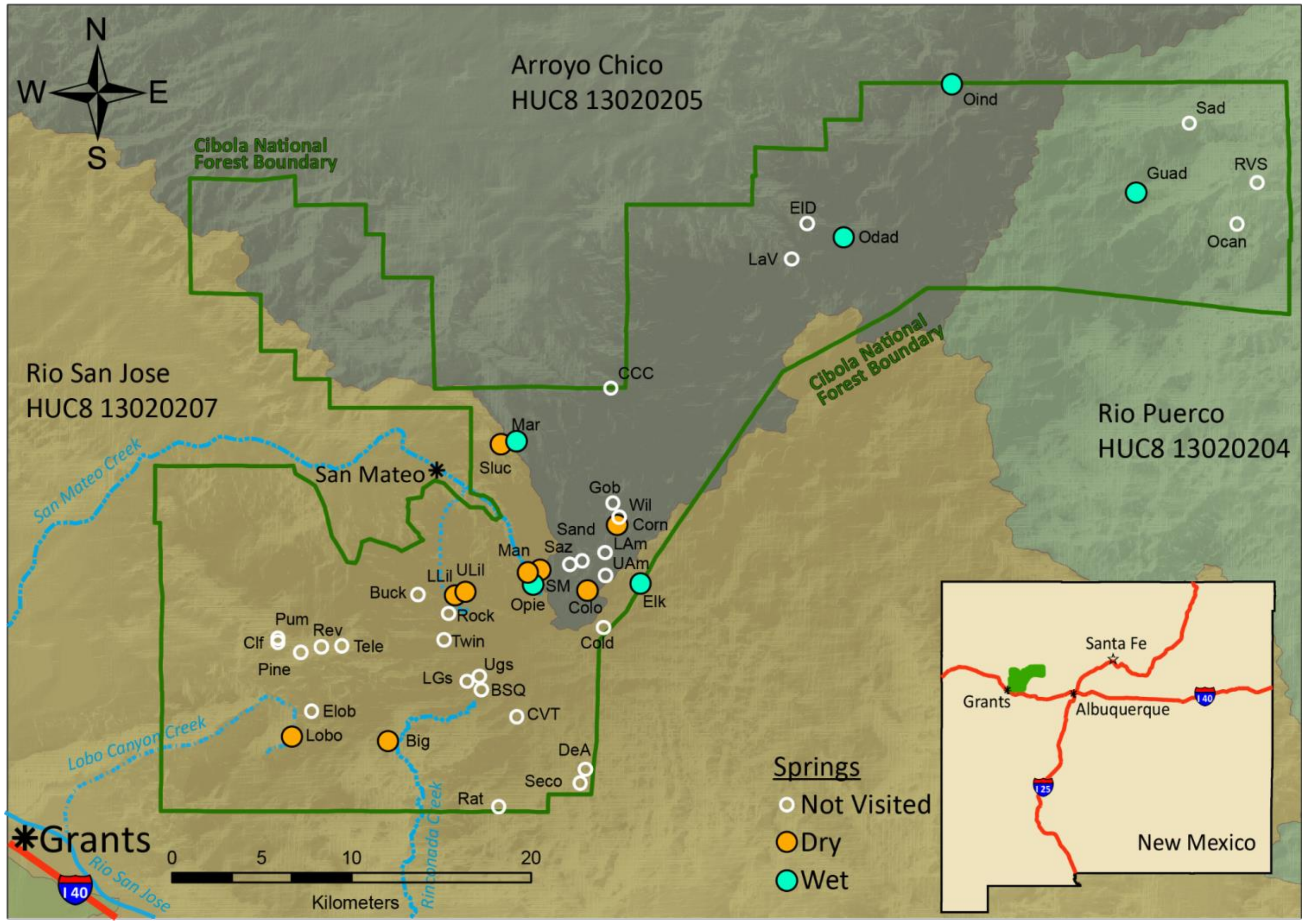
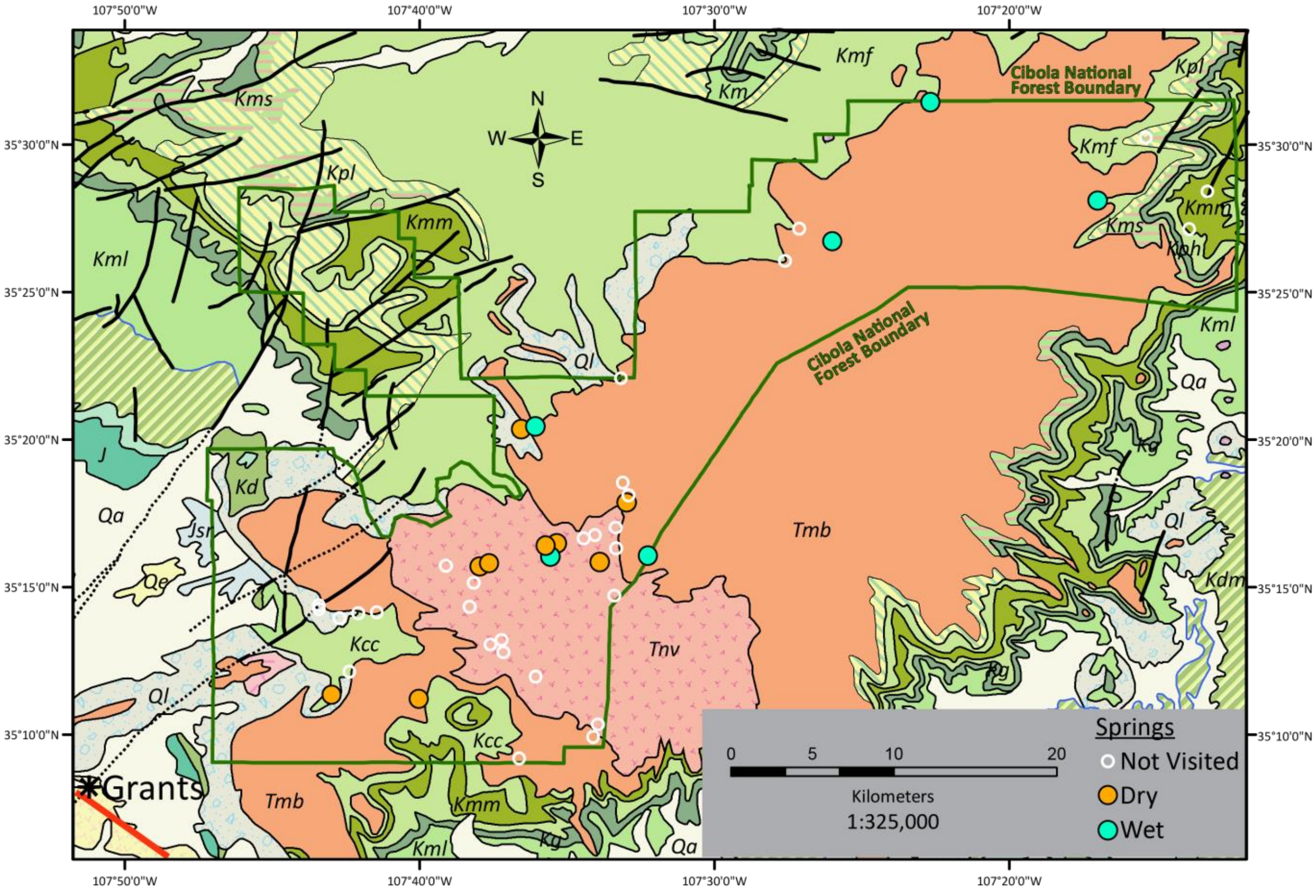


Figure 6. Map of Mount Taylor, Cibola National Forest. Inset: Map of New Mexico with major Interstates and location of Cibola National Forest, Mount Taylor Division boundaries. Hydrologic Unit (HUC08) boundaries, digital elevation model (DEM) showing topography and Cibola National Forest boundaries are mapped with surface water features including springs, streams and rivers. Spring locations are color coded based on type of visit (i.e., hollow white = not visited, blue = visited and wet, orange = visited and dry). A legend for complete spring name is found in Appendix II.

Geology

Mount Taylor is a composite volcano composed of trachydacitic and trachyandesitic lavas with local pyroclastic materials (Goff et al., 2013; Langman et al., 2012; Perry et al., 1990) and is interpreted to provide evidence of fractional crystallization of basaltic magmas (Crumpler, 1980; Perry et al., 1990). Springs that discharge from these different volcanic units have unique water chemistry and has helped to understand the geologic history of Mount Taylor (Goff et al., 2013). The volcanic deposits overlay the geologic materials that have a similar history to the neighboring Zuni Mountains. Proterozoic granites and metavolcanics unconformably overlain by Paleozoic and Mesozoic sedimentary strata (Langman et al., 2012) (Figure 7). The southern part of the Mount Taylor region has Permian Abo, Yeso, Glorieta and San Andres Formations as well as Triassic Moenkopi and Chinle Formation exposed (Baldwin and Anderholm, 1992; Baldwin and Rankin, 1995; Keating et al., 2008; Langman et al., 2012). Moving northward in the San Juan Basin, northwestern section of Cibola National Forest boundaries, the later Mesozoic strata is exposed in step like cliffs made up from the Jurassic Morrison Formation as well as the Cretaceous Entrada, Mancos, Gallup, Crevasse Canyon, Point Lookout and Menefee Formations (Baldwin and Anderholm, 1992; Goff et al., 2013; Langman et al., 2012).



Geologic Map Modified from:
NMBGMR, 2003 (Geologic Map of New Mexico; 1:500,000)
Stoeser et al., 2005 (Geologic Map Databases for the U.S. Central States)
-Note that the enlargement used here could cause misunderstanding in the detail of mapping and may result in erroneous interpretations.

Additional Principle Sources of Data:
Haller et al., 2005 (Quaternary Faults and Fold Database of the U.S.)
USEPA and USGS, 2005 (National Hydrogrphy Dataset)
USFS, 2011 (GIS property boundary layer)
USFS, 2011 (GIS Constructred_Feature_point_water tank, spring layer)
USGS in cooperation with BGN, 1988 (Geographic Names Information System)

Figure 7. Geologic map of Mount Taylor, New Mexico. Geologic units exposed at the surface with faults (black). Cibola National Forest Boundary (green) and springs within the National Forest boundary identified by protocol (Appendix II) are color coded to represent the work that has been completed. Geologic explanation is Figure 4 for unit descriptions.

The subsurface geology (Figure 8) reflects that complex history of folding and faulting that began with the Ancestral Rocky Mountains uplift, through the Laramide orogeny and into the formation of the Basin and Range (Laughlin et al., 1982; Perry et al., 1990). The Nutria Monocline (described in the Zuni Mountain geology section) represents the western boundary of Mount Taylor. The volcanic activity began in the Neogene and continued through the Quaternary and is related to the Basin and Range extension (Langman et al., 2012; Laughlin et al., 1982; Perry et al., 1990). Since the deposition of the volcanic materials, alluvial filled basins have been formed due to the erosion of 46 – 61 m (150 – 200 ft) of material (Langman et al., 2012).

Ground water hydrology

The hydrogeology of Mount Taylor has Paleozoic and Mesozoic strata that is fractured and faulted overlain by Cenozoic volcanic materials. The primary aquifers are within the Paleozoic and Mesozoic limestones and sandstones including the hydrologically connected Permian San Andres Limestone and Permian Glorieta Sandstone, as well as the Jurassic Morrison Formation (Baldwin and Anderholm, 1992; Baldwin and Rankin, 1995; Langman et al., 2012) (Figure 5). These aquifers are interbedded with confining units such as the Jurassic Chinle Group and Cretaceous Mancos Shale (Baldwin and Rankin, 1995; Langman et al., 2012; Zehner, 1985). Additional storage of ground water is in local alluvia.

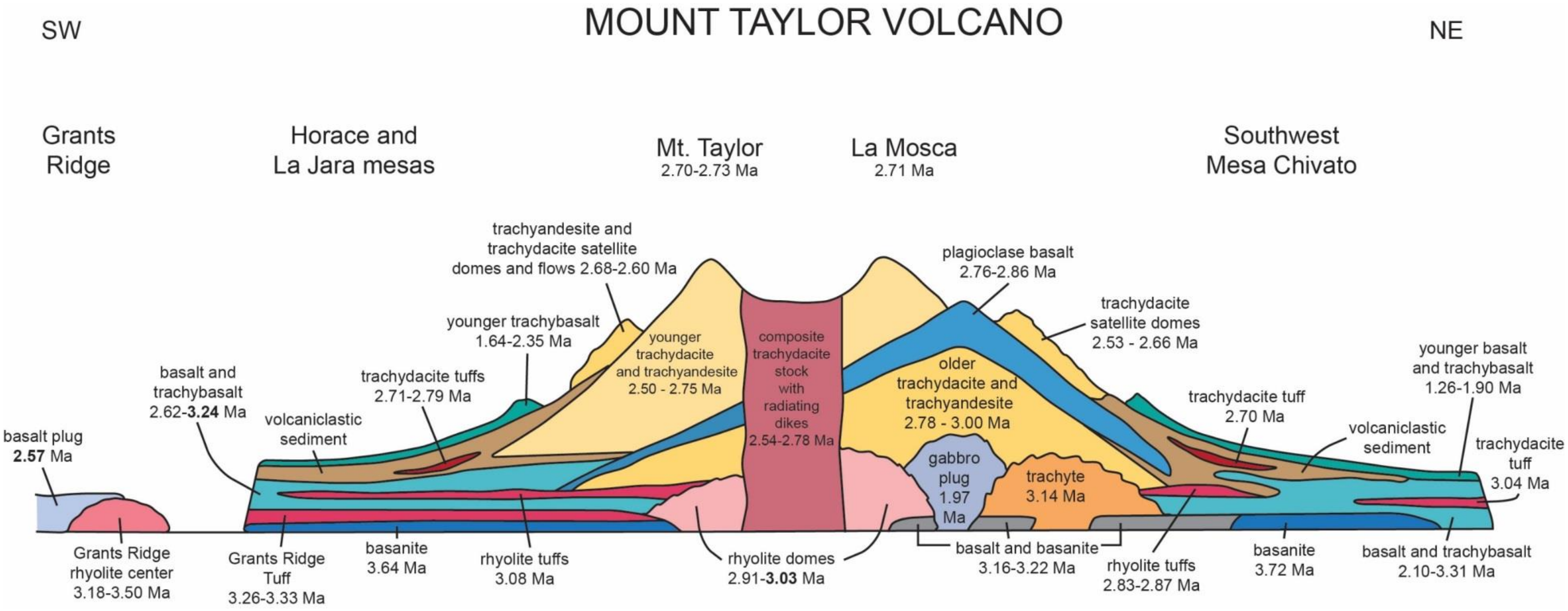


Figure 8. Schematic of geologic cross section, Mount Taylor, New Mexico. Subsurface interpretations show many flows of various mafic composition to form the composite volcano. Volcanic materials overlie Paleozoic and Mesozoic sedimentary units (not shown) that have been folded and faulted (refer to Figure 3 for sense of deformation(s)). Cross section is courtesy of Goff et al., in review.

which can store and produce important water resources for the area (Langman et al., 2012; Zehner, 1985) (Figure 5).

Additional smaller aquifer systems are found in the volcanic field within different volcanic flows of basaltic and pyroclastic materials (Crumpler, 1980; Perry et al., 1990). The volcanic materials have very little hydrologic research completed on them. In general, it would be expected that transmissivity and storage would be variable with heterogeneous volcanic materials creating differences between and within the different deposits. Jointing and fracturing post deposition could also influence the connectivity and heterogeneity of the ground water flow in the volcanic materials.

The Cibola National Forest boundaries are defined by two types of geologic units. The south and eastern sections of the Forest have surface volcanic materials, with very little exposed older sedimentary materials (Figure 7). The northwest area of the Cibola National Forest is where Cretaceous materials are exposed at the surface (Figure 7). The hydrochemistry from the lower Paleozoic and Mesozoic strata was incorporated into the spring hydrochemical work for all springs within the Forest boundaries to determine if any vertical migration of deeper waters was present at the spring sites.

The northwest area of Mount Taylor Cibola National Forest was identified as a priority for the spring surveys due to proposed uranium mining in the area. The protocol that was developed for verifying spring locations (Appendix I and II) showed that very few springs occur in the northwest section (Figure 6). These priority springs were visited, but due to the lack of springs in the northwest this research was mostly confined to the volcano proper and its deposits.

Sandia Mountains, New Mexico

The Sandia Mountains are in central New Mexico and represent the eastern edge of the Rio Grande Rift Valley. The Sandia's range in elevation from 3,255 m (10,678 ft) at Sandia Crest to about 1,550 m (5,100 ft) at the mouth of Las Huertas Creek in Placitas.

Climate and surface water hydrology

Annual precipitation is bimodal, occurring as snowfall from January through March and as monsoonal rainfall from July through August (Johnson and Campbell, 2002; McCoy and Blanchard, 2008) and variations are controlled by similar ENSO events explained in the Zuni Mountain section. The Sandia Mountains receive an annual rainfall of 560 mm (22 in) near the crest and 304 mm (12 in) at the base of the mountains (Johnson and Campbell, 2002).

Spring sites and major streams have been mapped along with Hydrologic Units, basin level 8 (Figure 9). The Rio Grande-Albuquerque region is the eastern and southern portions of the Sandia Mountains. This region has a concentration of springs and is populated by small towns and villages including the town of Tijeras. Tijeras Creek is intermittent and flows west parallel to Interstate 40 (Figure 9) with spring fed portions of the creek providing year round surface water (McCoy and Blanchard, 2008; Plummer et al., 2004). The East Mountain communities have developed spring sites (i.e. Cienga Spring) to support drinking water needs to different developments and cooperatives.

The Rio Grande-Santa Fe region includes Las Huertas Creek and the Placitas area. Las Huertas Creek has perennially wet sections within the Cibola National Forest boundaries. The headwaters of Las Huertas Creek are located in the southern extent of Las Huertas

Canyon where perennially springs contribute to flows for approximately three miles down Las Huertas Creek. Stream-flow data from 1999, for Las Huertas Creek, 0.3 miles south of Sandia Man Cave, shows a peak runoff in the month of May with a discharge of 0.85 m^3/sec (30 ft^3/sec) but flows during the remainder of the year are typically less than 0.06 m^3/sec (2 ft^3/sec) (Johnson and Campbell, 2002). Las Huertas is used for an acequia system and these measured flows do not reflect the unaltered potential. The acequia diverts most of the creeks baseflow and a portion of the peak flows.

Spring-fed reaches of Las Huertas Creek are important to the ecosystem as they support riparian areas and irrigation as well as redistribute water between the ground water and surface water systems in an otherwise poorly connected system (Johnson and Campbell, 2002). Large Quaternary and Tertiary travertine deposits at spring sites indicate that ground water has been actively flowing in these locations for tens of thousands to possibly a million years (Johnson and Campbell, 2002). Spring waters south of Las Huertas Creek (i.e. Tunnel Spring) are used by several small communities within the northern section of the Sandia Mountains.

Geology

The Sandia Mountains are an uplifted granite block of 2000 million year old Paleoproterozoic granites and metavolcanic rocks formed during island-arc accretion to the craton (Karlstrom et al., 1997; Strickland et al., 2003) (Figure 10). The Paleoproterozoic basements rocks are unconformably overlain by the eastward dipping beds of the local Pennsylvanian Sandia Formation and regional Madera Group (Armstrong et al., 1994; Mack, 2003). During late Pennsylvanian time regional basin deposits were formed related to the

Ancestral Rocky Mountain orogeny (Mack, 2003). This was followed by a transgression which deposited the Madera Group (Smith, 1999; Traverse and Ash, 1999). By late Paleozoic and into mid-Mesozoic time the environment for central New Mexico was similar and deposition was continuous over the region (Anderson et al., 2003; Heckert and Lucas, 2003; Heckert, 1999; Lucas et al., 1999; Mack, 2003).

Similar to the Zuni Mountains, the Paleozoic and Mesozoic rocks of the Sandia Mountains had repeated tectonic forces creating folding and faulting along reactivated fault zones (Figure 11) possibly related to Precambrian craton building and tectonic activity (Aldrich et al., 1986; Karlstrom et al., 1997). Several structural features that dominate the landscape of the Sandia Mountains include the Tijeras Fault, a NE/SW trending fault zone that is located at the southern end of the mountain range. The Tijeras Fault is exposed within the Proterozoic materials and is related to the extension of the Rio Grande Rift Valley (Aldrich et al., 1986; Karlstrom et al., 1997; Williams et al., 2013). In addition, a faulted and displaced syncline of Triassic and Jurassic materials is found on the northern Sandia Mountains in the Placitas area.

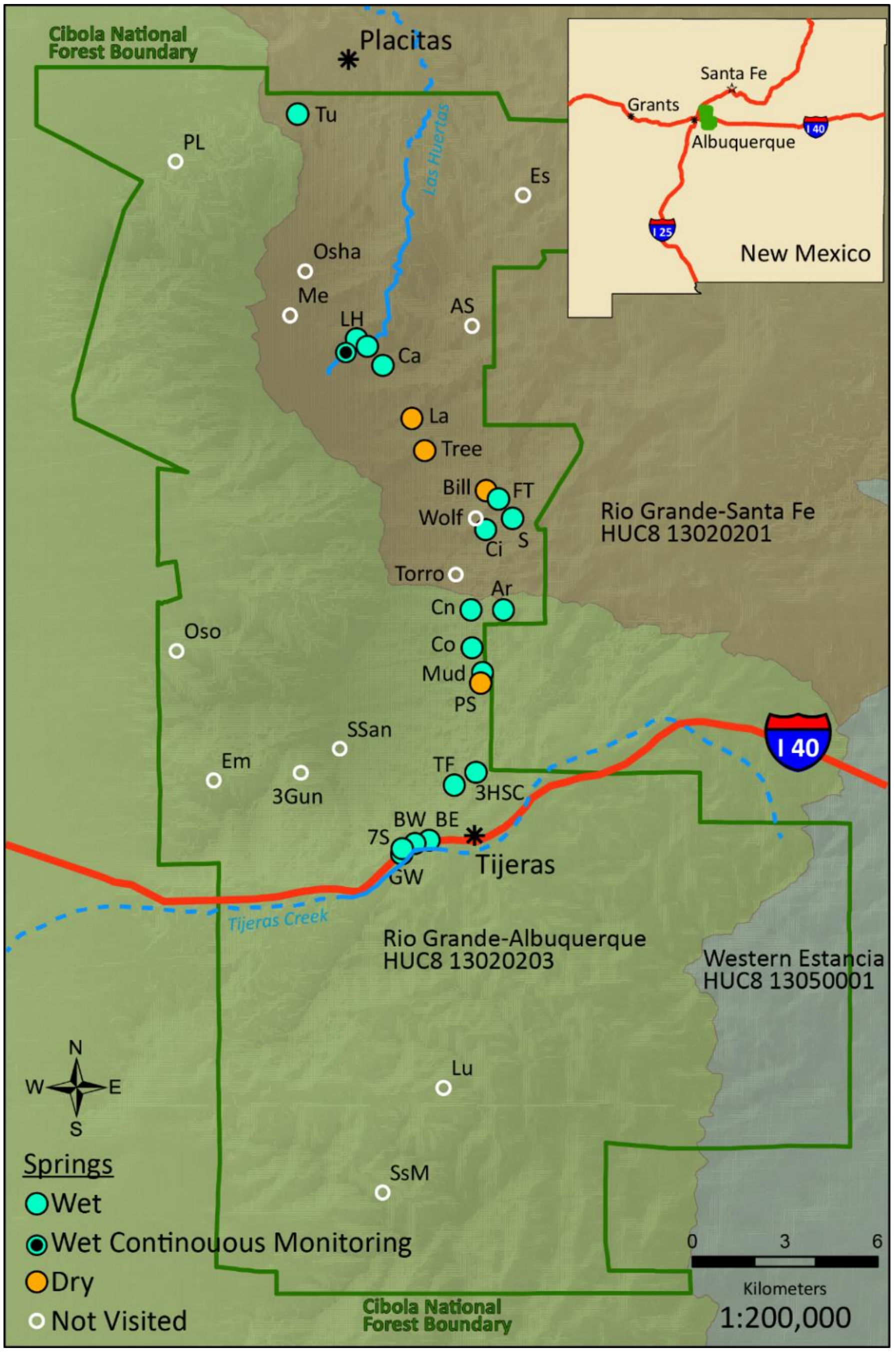
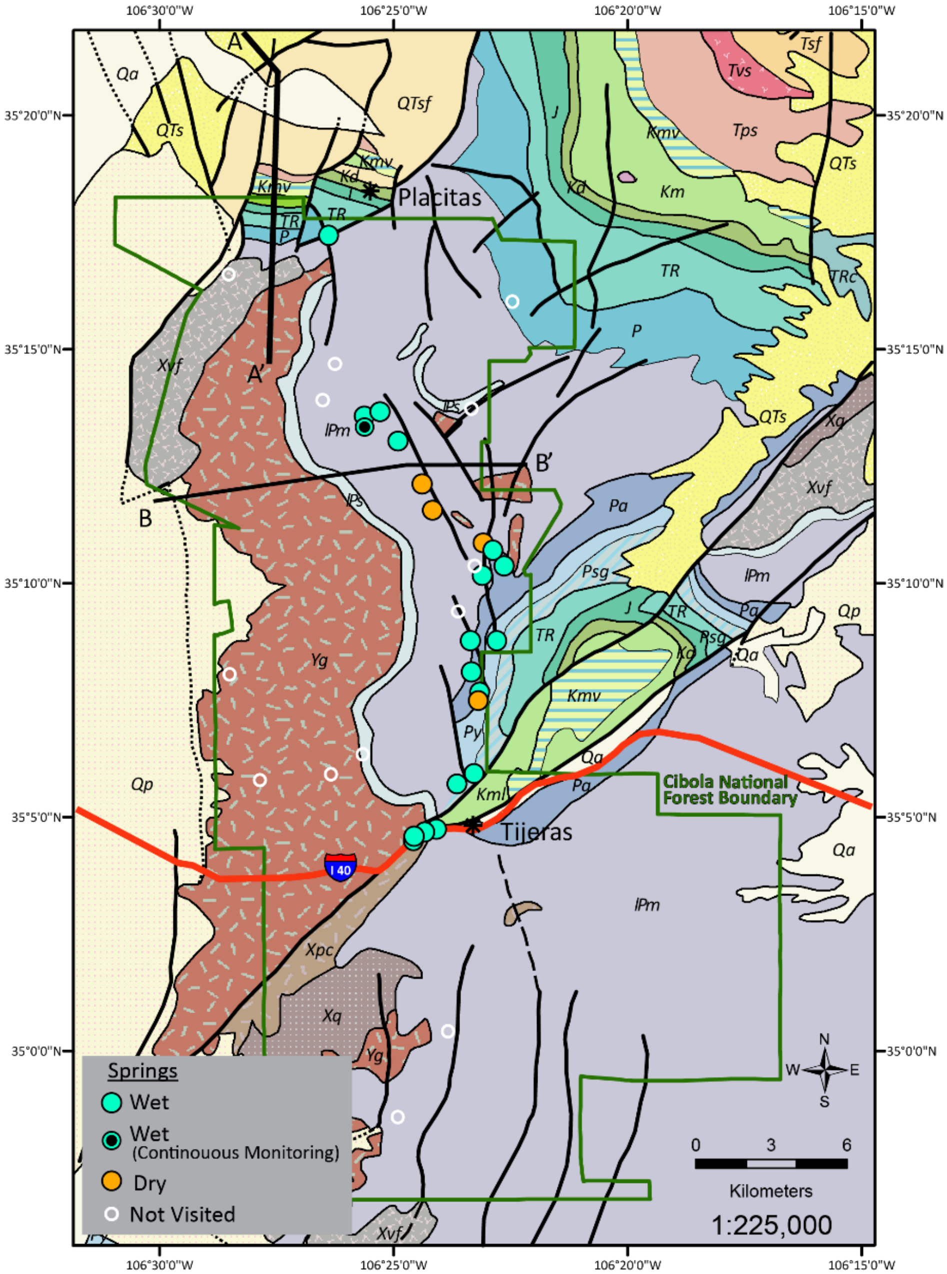


Figure 9. Map of Sandia Mountains, Cibola National Forest. Inset: Map of New Mexico with major Interstates and location of Cibola National Forest, Sandia Mountain District boundaries. Hydrologic Unit (HUC08) boundaries, digital elevation model (DEM) showing topography and Cibola National Forest boundaries are mapped with surface water features including springs and streams. Spring locations are color coded based on type of visit (i.e., hollow white = not visited, blue = visited and wet, orange = visited and dry). A legend for complete spring name is found in Appendix II.



Geologic Map Modified from:
NMBGMR, 2003 (Geologic Map of New Mexico 1:500,000)
Stoeser et al., 2005 (Geologic Map Databases for the U.S. Central States)
-Note that the enlargement used here could cause misunderstanding in the detail of mapping and may result in erroneous interpretations.

Additional Principle Sources of Data:
Haller et al., 2005 (Quaternary Faults and Fold Database of the U.S.)
USEPA and USGS, 2005 (National Hydrogrphy Dataset)
USFS, 2011 (GIS property boundary layer)
USFS, 2011 (GIS Constructred_Feature_point_water tank, spring layer)
USGS in cooperation with BGN, 1988 (Geographic Names Information System)

Figure 10. Geologic map of Sandia Mountains, New Mexico. Geologic units exposed at the surface with faults (black) and cross section line (A-A', B-B'). Cibola National Forest Boundary (green) and springs within the National Forest boundary identified by protocol (Appendix II) are color coded to represent the work that has been completed. Geologic explanation is Figure 4 for unit descriptions.

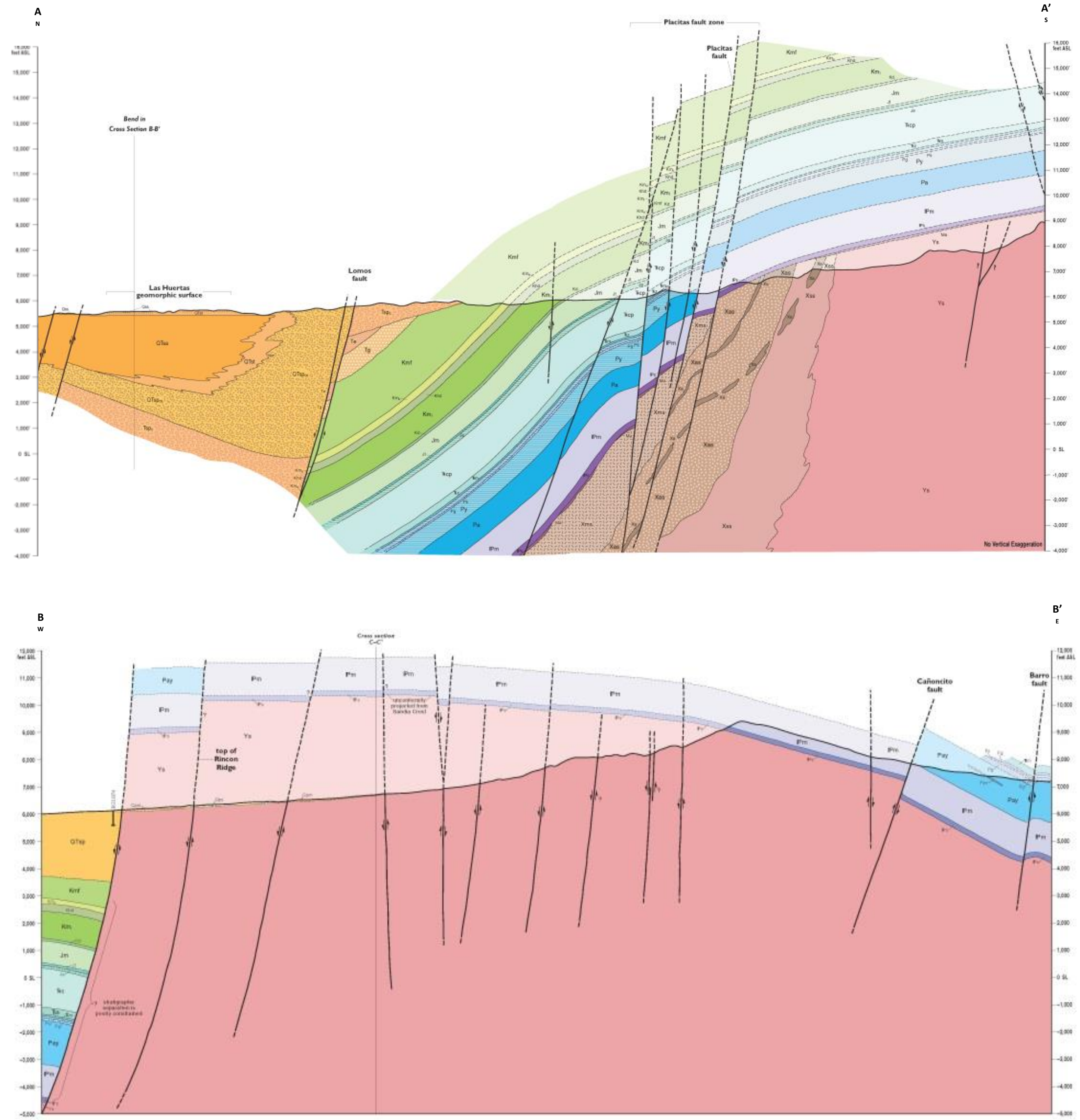


Figure 11. Geologic Cross Sections for the Sandia Mountains, New Mexico. A-A', Placitas Quadrangle (Connell et al., 1995). B-B', Sandia Crest Quadrangle (Read et al., 2005). Subsurface interpretations show folding, faulting and erosion of geologic layers. Cross section lines are found on Figure 10, geologic explanation is Figure 4 for unit descriptions.

Ground water hydrology

The modern geohydrologic framework of the Sandia Mountains is dominated by the Pennsylvanian Madera Group. This limestone aquifer provides perennial waters for the different communities and ecosystems within region. The limestone aquifer is influenced by the repeated deformation throughout geologic time (Johnson and Campbell, 2002; Plummer et al., 2004; Whitmeyer and Karlstrom, 2007; Williams et al., 2013) which resulted in fractures and faults that influence the movement of groundwater. A geologic map of the area (Figure 10) show the contacts, structures and how spring locations are concentrated along these fault zones. Cross sections (Figure 11) provide insight into the subsurface structures for both areas.

The La Madera Limestone (Pm) is the principal aquifer unit for the Cibola National Forest and surrounding areas within the Sandia Mountains (Figure 5). The Madera Limestone aquifer is compartmentalized so that ground water flows along fault planes resulting in an assortment of confined and unconfined aquifers that display varying degrees of hydraulic interconnection, recharge and residence time (Johnson and Campbell, 2002). Locations of springs within the Sandia Mountains were verified using the developed protocol (Appendix I and II) and are largely concentrated along faults (Figure 11). Some springs have large travertine deposits associated with discharge of ground waters that are supersaturated in calcium (Ca^{2+}) and carbon dioxide (CO_2).

Ground water levels in the complex aquifer system of the eastern Sandia Mountains have steep seasonal declines in water levels with recovery within 7-9 months (Kues, 1990). Ages of aquifer waters within the fractured rock aquifers of the Pm are 16-26 years old. The depth of water across the eastern Sandia Mountain area ranges from less than 1.5 m (5 ft) to greater than 60.96 m (200 ft) below the land surface (Blanchard, 2004; McCoy and Blanchard, 2008). Ground waters within the lower eastern slopes of Sandia Mountain, from Sandia Park to Tijeras Canyon flows eastward to discharge points located along complex faulting of the Tijeras Fault (McCoy and Blanchard, 2008). Ground water in the northern area of the Sandia Mountains flow north in the Las Huertas Creek bed or to contact springs that discharge above the city of Placitas (Johnson and Campbell, 2002).

New Mexico Stratigraphy

Descriptions of geologic units and map codes (Figure 4) and stratigraphy (Figure 5) has been consolidated to the west-central and central New Mexico due to the continuous nature of the rocks across the region (Connell 2011). A general description for each of the stratigraphic units in the study area can be useful to understanding hydrologic capabilities and potential mixing scenarios.

Proterozoic

The Proterozoic rocks of the Zuni and Mount Taylor Mountains are predominately quartz monzonite with U/Pb zircon dates of 1655 Ma. (Strickland et al. 2003) and are similar in age to the hornblendes and amphibolites in the Sandia-Manzano Mountains with 40Ar/39Ar dating of 1.6 Ga (Karlstrom et al., 1997; Strickland et al., 2003). The Proterozoic rocks for west central and central New Mexico, are highly fractured with evidence that fault zones have been reactivated throughout geologic time (Aldrich et al., 1986; Karlstrom et al., 1997). These deeply penetrating faults provide conduits for vertical movement of fluid.

Paleozoic

The Pennsylvanian Madera Group is overlying the Sandia Formation and is found in the Sandia Mountains. The Madera Group is a marine limestone that is subdivided into two groups consisting of the lower Gray Mesa Formation and the upper Atrasado Formation (Connell, 2011). This subdivision is based on the change from the thick, massive gray limestone beds to the interbedded limestone, shale and arkosic sandstone (Connell, 2011), indicating a regression and a drying of the environment. The stratigraphic thickness of the Madera Group ranges from 350 – 470 m (1,247-1,542 ft) (Connell, 2011).

The Permian Abo Formation lays unconformably on the Proterozoic basement rocks of the Zuni Mountains (Armstrong et al., 1994; Anderson et al., 2003) and conformably overlays the Pennsylvanian Madera Group in the Sandia Mountains (Krainer et al., 2003). At both locations, the Abo Formation represents a change to the entire region with successional increases of red-orange mudstone and a proportional increase in sandstone upsection (Connell, 2011). In the Zuni Mountains a basal unit to the Abo Formation has been identified as the Oso Ridge Member. The Oso Ridge Member represents an arkosic and conglomerate composed primarily of the underlying Proterozoic granites and metamorphic rocks. Thin beds of fossiliferous limestone have been found in the southern extent of the Zuni Mountains (Armstrong et al., 1994). The Abo Formation at both locations ranges from 165 – 210 m (541 – 689 ft) in thickness (Connell, 2011).

Conformably overlying the Abo Formation is the Permian strata of the Yeso Glorieta and San Andres Formations for both the Sandia and the Zuni Mountains. The Abo Formation consists of mudstones, siltstones and sandstones (Anderson et al., 2003). The

Yeso Formation conformably is subdivided into three members including the basal Meseta Blanca Member overlain by dolomite beds of the Torres Member and topped by the finer-grained Joyita Member (Anderson et al., 2003). Glorieta Sandstone conformably overlies the Yeso Formation and is 37 m (120 ft) thick sandstone with crossbedding. Very resistant to weathering the Glorieta typically forms ridges and benches where exposed. The Glorieta displays a diverse array of marginal- marine facies that are considered aeolian in origin, (Anderson et al., 2003) and follows the westward gradation into the fully aeolian Coconino Sandstone of Arizona (Anderson et al., 2003). The San Andres Formation is a limestone which consists of gray fossiliferous and dolomitic materials (Anderson et al., 2003).

Mesozoic

The rocks of the Mesozoic found within Cibola NF boundaries include; the Triassic Chinle Formation and the Triassic Wingate and hydrologically connected Jurassic Zuni Sandstone. The Chinle Formation consists of interbedded fluvial siltstone and shale with bedded channel sandstone (Orr, 1987) and is unconformably overlying the San Andres Limestone. The basal unit of the Chinle is the Shinarump Conglomerate and is locally present in the Ft. Wingate Quadrangle with several springs discharging from the contact with the San Andres Limestone. The Zuni-Zuni Sandstone is fluvial siltstone and sandstone (Orr, 1987) with massive cross bedded aeolian dunes and is found in the Hogbacks of the western Zuni Mountains.

Stratigraphic sections for the Central New Mexico region (Figure 5) provides descriptions of aquifer bearing units for both areas. Note that the symbols for the stratigraphic column match the symbols from geologic maps (Figures 2, 7 10). The geologic map and cross-sections provide the hydrologic framework for the study.

Methods

The primary objective for this project was to do a basic spring site inventory that included, verifying spring locations and performing hydrogeochemical analysis on spring waters to determine water quality and measuring spring discharge. Development of a procedure for verifying spring locations on Cibola NF was completed. Appendix I has a detailed explanation of spring verification protocol. Three digital resources including data from the United States Forest Service (USFS), National Hydrologic Data (NHD) and Geographic Names Information System (GNIS) were used to create a database of spring locations, which were then mapped onto geologic and hydrologic maps using Aeronautical Reconnaissance Coverage Geographical Information Systems (ArcGIS) (Figures 1, 2, 6, 7, 9, 10).

Naming for spring locations came initially from the digital resources. Given spring names were used. When springs were not named, a temporary name for the purposes of this study was assigned based on regional topographic features that were named, i.e. unnamed spring in Zuni Mountains in Peavine Canyon was named Peavine. Appendix II shows results from the spring location protocol (Appendix I), including spring names, assigned spring names, map abbreviations, protocol coordinates, protocol source, elevation, hydrologic units, geologic units and rock type.

This research used the spring ecosystem assessment protocol (SEAP), developed by Stevens and Springer (2005), to evaluate spring sites (Appendix III shows the SEAP form).

When water was present at the spring sites, water samples were collected for major ion concentrations, stable isotopes and some tritium analysis. USGS guidelines were followed in the collection of these samples (Myers, 2006). Along with collection of water samples, physico-chemical parameters (pH, temperature, conductivity and dissolved oxygen) were measured. Instruments taken into the field for measuring physico-chemical parameters were calibrated following manufacturers, instructions and using the highest quality industry standards (USEPA, 2002). Additionally, on site calibrations were performed when necessary, including on site calibrations for dissolved oxygen measurements.

Collection of surface and ground water samples followed USGS protocols (Myers, 2006) including using two 125 ml polypropylene bottles for collecting spring and surface waters. Both bottles were field washed three times. The first bottle was untreated and gathered with no head space (sample used for alkalinity, anion and isotope analysis). The second bottle was filtered through a 0.45 µm hydrophilic polyethersulfone filter and immediately treated with concentrated nitric acid (69.5% HNO_3) (sample used for cation analysis). In 2014 and 2015, several spring waters were also gathered in a third 500 ml polypropylene bottle, untreated with no head space for tritium analysis.

Precipitation events during field visits were also collected for analysis when possible. Water from rain, hail and snow events were gathered from the Zuni Mountains, Sandia Mountains and Albuquerque Basin throughout the study period. Table 1 gives dates and locations for collection of west-central and central New Mexico precipitation (rain, hail, snow) events. Precipitation samples were gathered for anion and stable isotope analysis using a 125 ml polypropylene bottle. The precipitation sample waters were untreated and collected with little or no headspace. USGS guidelines were followed (Myers, 2006) and field duplicates were gathered when enough water was available.

Water samples that were collected in the field were brought back to the University of New Mexico, Department of Earth and Planetary Sciences for analysis of major ions and stable isotopes. End point titration was performed using a weak acid to determine alkalinity (APHA, 1999). Inductively Coupled Plasma/Optical Emissions Spectroscopy (ICP/OES) (Martin et al., 1994) was used to determine cation concentrations. Ion Chromatography (IC) was used for anion concentrations (Hautman and Munch, 1997). Charge balance of major ions was then computed with all spring and surface water samples to be less than ±5%. Precipitation samples were unable to be balanced due to only analyzing anion concentrations. Duplicate analysis was routinely performed on 10% of all

Table 1. Precipitation Locations

Precipitation West-Central and Central New Mexico

ID Number	Sample Name	Sample Date	Location	Type	Time	Datum	Longitude (DD)	Latitude (DD)
D1207001	Sandia Mountain Snow	4/19/2012	Sandia Ranger District	snow	15:00	NAD83	-106.400972	35.220173
D1307079	LH Sandia Rain	7/13/2013	Cooper Homestead	rain	12:00	NAD83	-106.420852	35.225513
D1407112	AR Zuni Mountain Hail	5/23/2014	Zuni Mountain Division	rain	--	NAD83	-108.500231	35.326594
D1407122	Zuni Mountain Hail	10/19/2014	Zuni Mountain Division	rain	--	NAD83	-108.291858	35.173924
D1407123	Zuni Mountain Rain	10/19/2014	Zuni Mountain Division	rain	--	NAD83	-108.291858	35.173924
D1507129	AR Zuni Mountain Snow	2/21/2015	Zuni Mountain Division	snow	13:00	NAD83	-108.500231	35.326594
D1507147	ABQ North Valley Rain	5/4/2015	Zuni Mountain Division	rain	22:00	NAD83	-106.675828	35.108153
D1507154	UNM Hail	5/4/2015	Albuquerque	hail	17:30	NAD83	-106.622106	35.082944
D1507155	Aspen Campground Zuni Mountain Snow	5/9/2015	Zuni Mountain Division	snow	12:00	NAD83	-108.545714	35.413650
D1507156	Cottonwood Gulch Zuni Mountains Snow	5/9/2015	Zuni Mountain Division	snow	9:00	NAD83	-108.20332	35.313860
D1507158	ABQ North Valley Hail	5/16/2015	Albuquerque	hail	12:15	NAD83	-106.675828	35.108153
D1507157	ABQ North Valley Rain	5/16/2015	Albuquerque	rain	21:00	NAD83	-106.675828	35.108153
D1507159	ABQ North Valley Rain	5/19/2015	Albuquerque	rain	16:00	NAD83	-106.675828	35.108153
D1507161	ABQ North Valley Rain	5/21/2015	Albuquerque	rain	19:12	NAD83	-106.675828	35.108153
D1507160	ABQ North Valley Rain	5/24/2015	Albuquerque	rain	15:00	NAD83	-106.675828	35.108153
D1507152	McGaffey Campground Rain	6/5/2015	Zuni Mountain Division	rain	19:00	NAD83	-108.522394	35.365529
D1507167	McGaffey Campground Rain	7/3/2015	Zuni Mountain Division	rain	18:00	NAD83	-108.522394	35.365529
D1507168	McGaffey Campground Rain	7/3/2015	Zuni Mountain Division	rain	22:00	NAD83	-108.522394	35.365529
D1507169	McGaffey Campground Rain	7/4/2015	Zuni Mountain Division	rain	9:00	NAD83	-108.522394	35.365529
D1507171	ABQ North Valley Rain	7/7/2015	Albuquerque	rain	22:30	NAD83	-106.675828	35.108153
D1507172	ABQ North Valley Rain	7/8/2015	Albuquerque	rain	16:00	NAD83	-106.675828	35.108153

samples, and external reference standards were used to assure accuracy. Geochemical modeling of results was performed in Geochemist WorkBench (Bethke, 2008). Isotopologues of liquid water (δD and $\delta^{18}O$) were analyzed using untreated waters collected at the sites. Analysis was completed at the Center for Isotopic Studies at the University of New Mexico using laser ring-down cavity spectrometry (Gupta et al., 2009; Romanini et al., 1997) where the weighted mean values are reported. Mean tritium content, weighted for volume, was determined by the Environmental Isotope Lab at the University of Arizona using a LKB Wallace Quantulus 1220 spectrophotometer (Eastoe et al., 2012).

Continuous monitoring of spring physico-chemical parameters for selected springs were collected in the Zuni and Sandia Mountains through the time of this study. In the Zuni Mountains (Figure 1), Agua Remora and Brennan Spring sites were prioritized by Cibola National Forest as areas of interest related to the endemic Zuni Bluehead Sucker (*Catostomus discobolus yarrowi*) habitats. Temporary shallow wells (<1 m) were installed at each spring site. The location for the wells were determined on-site by getting as close to the spring orifice as possible. In the Sandia Mountains (Figure 9), Las Huertas Creek was prioritized by Cibola National Forest. A desire to monitor the cluster of springs at the headwaters of the creek were monitored due to the importance of the creek to the water resources of the village of Placitas. Monitors were installed at the main spring, adjacent to the spring box. Calibration of monitors used high quality standards and procedures that were outlined in the instruments manuals (Canada, 2012) and followed USGS established guidelines (Wagner et al., 2006). Monitors were deployed to measure water temperature, water depth, specific conductance, air temperature and barometric pressure. Parameters were measured every 15 minutes. The continuous monitoring sites also had additional seasonal site visits for gathering water samples for hydrogeochemical analysis.

Continuous monitoring of surface waters within the Zuni Mountains was also collected related to ZBS habitat and forest management projects. Surface waters above and below the spring discharge at Agua Remora was monitoring with Solinst leveloggers installed from May 2012-October 2015. Additionally, Sonde Series 6 continuous monitors (YSI Incorporated, 2009) were deployed from July 2013-Feb 2015 measuring other physico-chemical parameters (pH, turbidity, dissolved oxygen and oxidation-reduction potential (ORP)) for the ZBS habitat at Agua Remora. Additional Solinst leveloggers were deployed in a cooperative agreement between the Forest Guild and Cibola National Forest, separate from the shared-cost agreement between Cibola and the University of New Mexico. Sites that were monitored by the Forest Guild were privately held including ZBS populations at Tampico Draw (land owned by The Nature Conservancy), Cottonwood Gulch (land owned by a private group) and Bluewater Creek (land managed by Cibola National Forest) above the reservoir. This data was collected using standard protocols and calibration standards (Canada, 2012; Wagner et al., 2006; YSI Incorporated, 2009) with seasonal visits for downloading data and collecting water samples. Data interpretations for ZBS habitat work can be found in Frus et al., in review A and B. This data will not be addressed in this report. Continuous monitoring for other locations within the Zuni Mountains (Brennan Spring, Cottonwood Gulch, Bluewater Creek) and Sandia Mountains (Las Huertas) will be discussed below.

Results

Zuni Mountains

Field work began in May 2012 and continued through October 2015 in the Zuni Mountains. Cibola National Forest identified the priority areas to include the Rio Nutria/Rio Puerco watershed and the Bluewater Creek watershed, central and western Zuni Mountains. The priority areas are part of a collaborative forest landscape restoration program (CLFRP) where thinning of the forest is being undertaken (Figure 1). The Forest Service wanted to characterize springs and surface waters to gain baseline data and to be able to understand source of surface waters and recharge areas, variability of flow regimes, and existing water chemistries. This information will assist in assessing potential changes and guiding management activities.

The Rio Nutria was specifically important because it provides the last remaining habitats for the endangered Zuni Bluehead Sucker, ZBS (*Catostomus discobolus yarrowi*). It is also the major surface water source for the Zuni Pueblo (west of the Zuni Mountains). The Bluewater Creek watershed is also within the Collaborative Landscape Forest Restoration Project (CLFRP) boundaries. Water from the Bluewater Creek area is stored in the Bluewater Creek reservoir and is the supply water for several small communities and agriculture in the area.

Using the SEAP protocol (Appendix I), a total of 62 spring sites were identified within the Zuni Mountains (Appendix II). Throughout the study, a total of 40 (65%) spring sites were visited. Some spring sites were visited more than once, for a total of 85 spring site visits (Appendix IV). With each spring visit the SEAP Level I and/or Level II spring inventory protocol was completed (Appendix V). Of the 40 spring sites that were visited, 25 (63%) were dry on at least one visit. Within the priority area of the CLFRP the Rio Nutria/Rio Puerco watersheds 18 springs were identified and all 18 (100%) were visited at least once, with a total of 56 spring site visits. Of the 18 springs that were visited, 13 (72%) were dry on at least one visit (Table 2). The Bluewater Creek watershed had 20 springs identified with 12 (85%) springs visited at least once, with a total of 16 spring sites visited. Of the 12 springs that were visited, 6 (50%) were dry on at least one visit (Table 2). The distribution of dry springs is concentrated in the western Zuni Mountains, which has the lowest elevation in the region.

The physico-chemical parameters and major ion chemistry from the different spring and surface waters collected within the Zuni Mountains were analyzed (Appendix VI) and plotted on Piper diagrams (Piper, 1944) (Figure 12). Review of the major cations indicates that the waters are concentrated in calcium and move in a linear trend towards sodium potassium waters. The anions are concentrated in bicarbonate and move in a linear trend towards sulfate waters. The parallelogram of the Piper diagram shows the proportional distribution of spring waters with 50% of spring sites having Ca_Mg_HCO_3 hydrochemical facies, 5.3% have Ca_Mg_Cl_SO_4 hydrochemical facies, 24.5% have Na_Cl_SO_4 hydrochemical facies and 20.2% have Na_HCO_3 hydrochemical facies (Figure 12A). Total dissolved solids for the waters collected in the Zuni Mountains range from 62-1628 mg/kg (Figure 12B).

Comparing results from this study to hydrogeochemical results from regional aquifers (Appendix VII) helps to understand flow paths for different spring waters. A majority of the spring waters represent the regional Permian San Andres/Glorieta (Psg) water bearing aquifer with the $Ca\_Mg\_HCO_3$ hydrochemical facies (Figure 12B). A second group of springs represent the local alluvium aquifers (Qa) including

Table 2. Zuni Mountain Spring Conditions Statistics

Spring Site Visit Summary Zuni Mountain, Mount Taylor Ranger District, New Mexico

	Number of Springs (#)	Number of Visits (#)	Percent of Total Number (%)	Number of Wet Spring Visits (#)	Percent of Wet Spring Visits (%)	Number of Dry Spring Visits (#)	Percent of Dry Spring Visits (%)	Number of Springs Dry on at least One Visit (#)	Percent of Springs Dry on at least One Visit(%)
Zuni Mountains									
Total Number of Springs from Protocol	62								
Springs Visited Once	22	22	35	10	45	12	55		
Springs Visited Twice	11	22	18	6	27	16	73		
Springs Visited Thrice	4	12	6	8	67	4	33		
Springs Visited > Thrice	3	29	5	25	86	4	14		
Total Number of Springs Visited	40		65					25	63
Total Number of Spring Visits		85		49	58	36	42		
Bluewater Creek									
Total Number of Springs from Protocol	20								
Springs Visited Once	10	10	50	5	50	5	50		
Springs Visited Twice	0	0	0	0	0	0	0		
Springs Visited Thrice	2	6	10	5	83	1	17		
Springs Visited > Thrice	0	0	0	0	0	0	0		
Total Number of Springs Visited	12		60					6	50
Total Number of Spring Visits		16		10	63	6	38		
Rio Nutria/Rio Pescado									
Total Number of Springs from Protocol	18								
Springs Visited Once	5	5	28	4	80	1	20		
Springs Visited Twice	8	16	44	1	6	15	94		
Springs Visited Thrice	2	6	11	3	50	3	50		
Springs Visited > Thrice	3	29	17	25	86	4	14		
Total Number of Springs Visited	18		100					13	72
Total Number of Spring Visits		56		33	59	23	41		

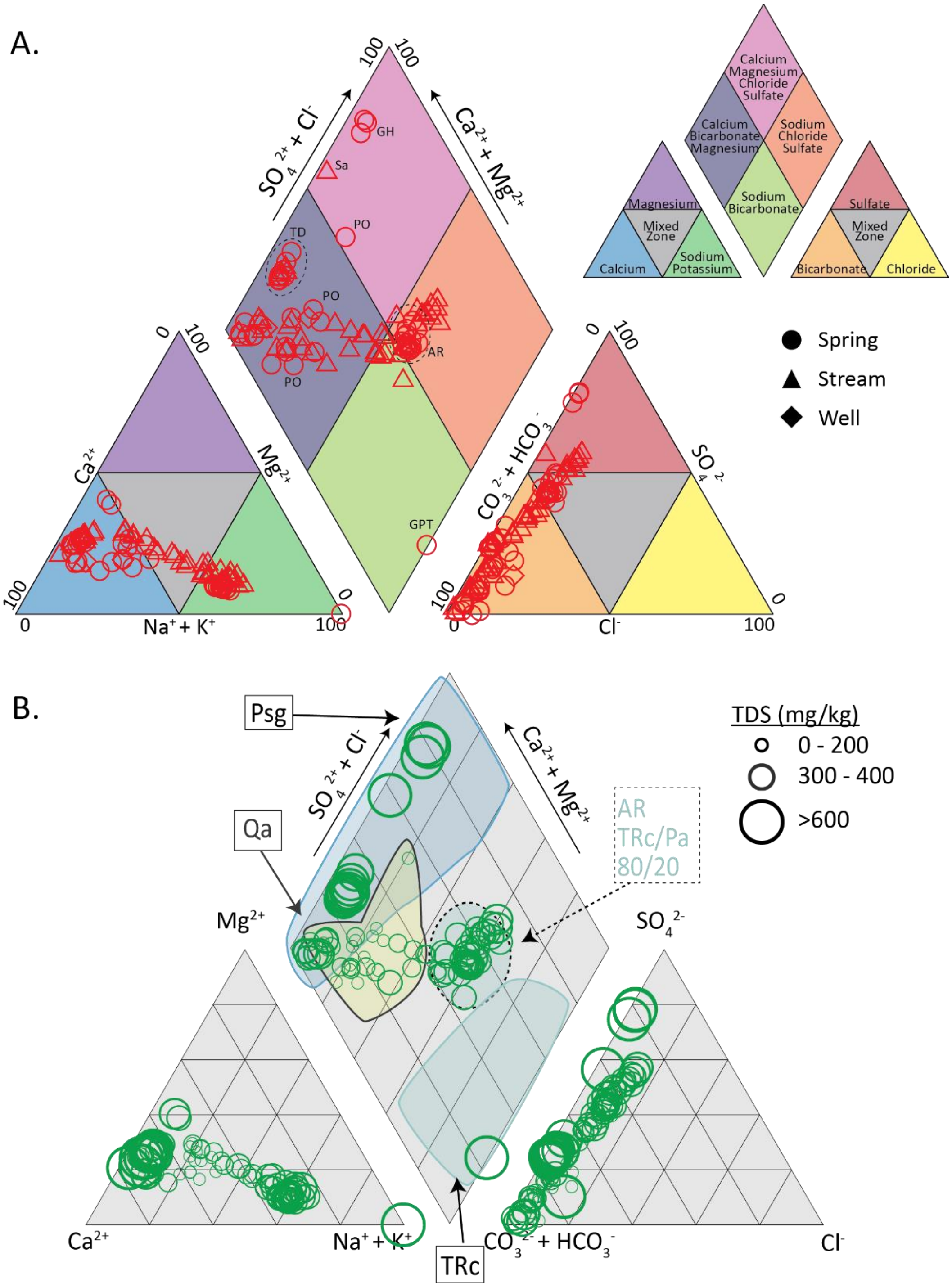


Figure 12. Piper diagram (Piper, 1944) of spring (circles), stream (triangles) and wells (diamonds) waters collected in the Zuni Mountain, New Mexico. A) Hydrochemical facies of different waters. B) Salinity and aquifer properties for different waters.

the $Ca\_Mg\_HCO_3$ and $Ca\_Mg\_Cl\_SO_4$ hydrochemical facies (Figure 12B). Of note is the variability of the Post Office Flat spring (PO) as well as the stream waters (triangles) (Figure 12A). The waters are from the Qa but migrate from $Ca\_Mg\_HCO_3$ to $Ca\_Mg\_Cl\_SO_4$ or $Na\_Cl\_SO_4$ hydrochemical facies. This migration is interpreted to be a result of the seasonal recharge of the alluvium. Each season will provide a different input and increases or decreases in residence time which explains the migration from the bicarbonate (HCO_3) to the chloride-sulfate (Cl_SO_4) hydrochemical facies.

Several spring waters are a-typical compared to the regional and local aquifers including the spring at Agua Remora (AR) and the Gravel Pit cattle tank (GPT). The AR spring was visited a total of 15 seasons and had very little variation in the hydrochemistry. Hydrochemical mixing models were run in Geochemist WorkBench (Bethke, 2008) and determined that the AR spring water is 80/20 proportions of Triassic Chinle Group and Permian Abo (Frus et al., in review). The Gravel Pit (GP) was visited twice (2012 and 2015). The spring box was dry on both visits. A spring development at this site supplies water to two metal nearby tanks, with stagnant water. This water was sampled. The results are significantly different from fresh surface or ground waters in the Zuni Mountains. These differences are the result of stagnant conditions, possibly influenced by a nearby salt lick. As such, this sample is not representative of the natural spring flow.

Isotopologues of water (δDSMOW and δ^{18}OSMOW) were analyzed (Appendix VI) and are plotted to determine recharge timing, atmospheric mechanisms and evaporation effects (Figure 13) (Glynn and Plummer, 2005; Sharp, 2006). The Global Meteoric Water Line (GMWL) is plotted as well to determine relationships of Zuni Mountain waters to global surface waters (Craig, 1961). Waters that fall on the GMWL represent little alteration from precipitation. Waters that are off of the GMWL with a slope of 3-4 represent evaporation of waters derived from precipitation (Craig, 1961; Glynn and Plummer, 2005; Sharp, 2006). A majority of water samples from the Zuni Mountains are clustered close to the GMWL with several off of the GMWL at a slope of 4.2 (Figure 13, inset). A zoomed in look at the majority of Zuni Mountain waters (Figure 13) shows that the $\delta^{18}O$ range is between -13‰ to 0‰ and the δD range is from -100‰ to -20‰.

Precipitation events collected in west-central and central New Mexico (Figure 13, squares) have a wide range of $\delta^{18}O$ and δD values (Table 3). Rain events are less negative, indicating that these waters are less fractioned, than the snow and hail events. Using the precipitation data, a seasonal recharge divide begins to take shape between the more fractionated winter recharge and the less fractionated monsoon recharge, begins to take shape (Figure 13, shaded areas). With the seasonal recharge established, it is interpreted that a majority of springs (AR, TD, and GH) within the Zuni Mountains are recharged primarily through snowmelt. These springs have hydrochemistry that is primarily located in the Psg or TRc aquifers and combined with the isotopes helps to determine that winter snow and rains are the principal components for recharging the confined aquifers. Hydrochemistry of several springs (PO, OJ, and N2) indicate that ground water is stored in the alluvium (Qa) and isotopes indicate that the Qa is recharged through both winter and monsoonal recharge.

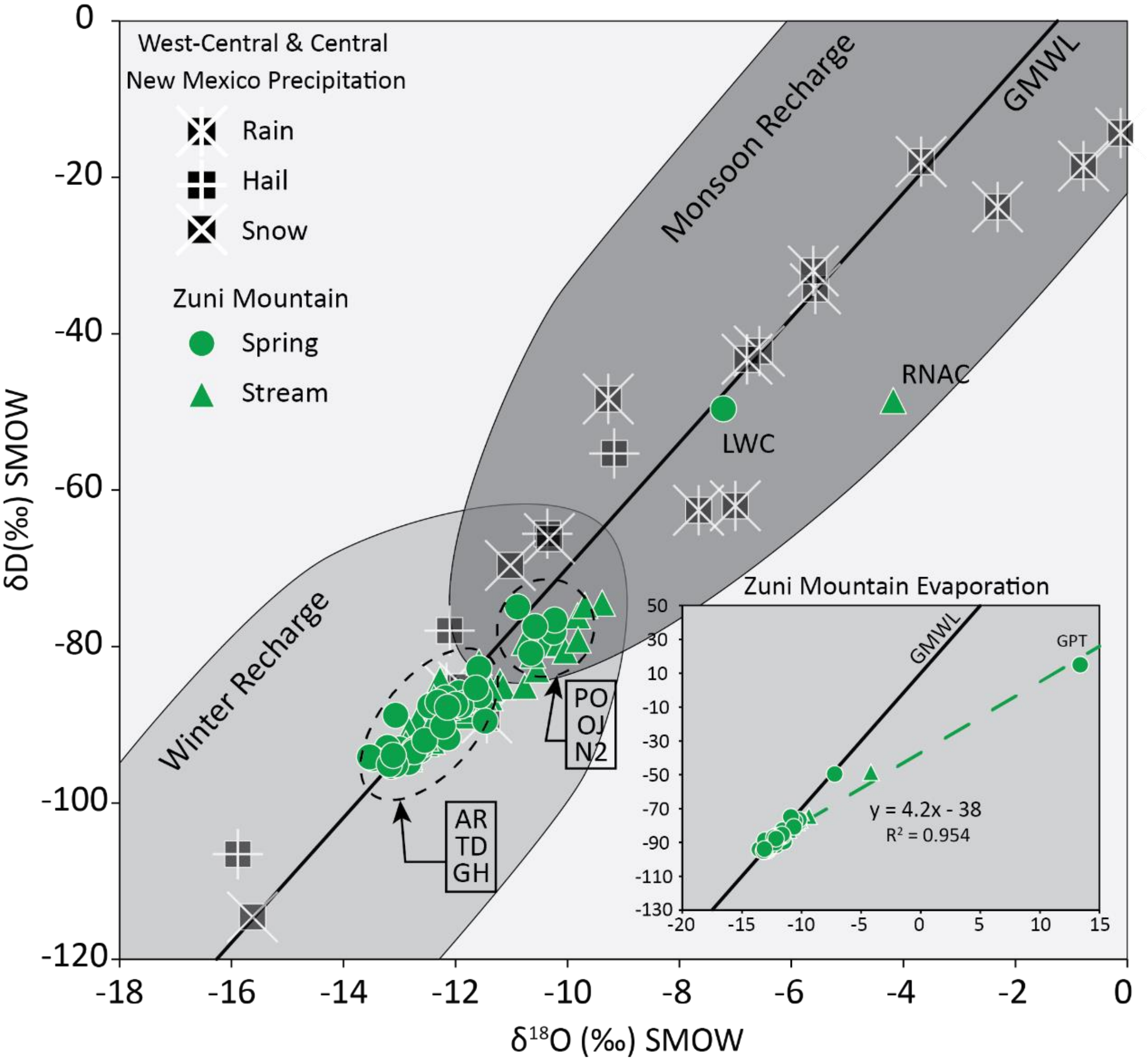


Figure 13. X-Y Plot of stable isotopes ($\delta^{18}O$‰ vs δD ‰, relative to the SMOW standard) for Zuni Mountains springs (circle) and streams (triangle) as well as west-central and central New Mexico precipitation (squares) that was collected during the study. The Global Meteoric Water Line, GMWL (Craig, 1961) is plotted to determine if Zuni Mountain waters are altered away from global precipitation values. Inset: Outlier identifies the trend for evaporation having a slope for 4.2. Precipitation values establish seasonal fractionation effects that determine timing of recharge for ground waters.

Table 3. Precipitation Isotope Data

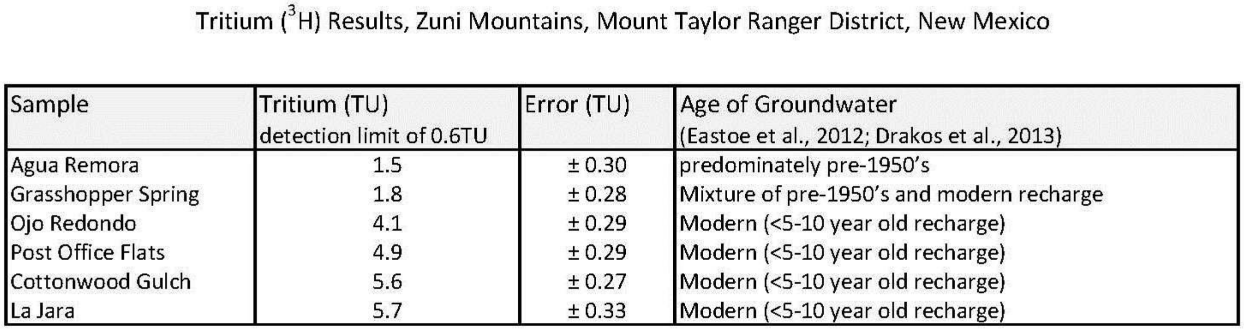
Stable Isotopes for Precipitation from West-Central and Central New Mexico

ID Number	Sample Name	Sample Date	$\delta^{18}O$ (‰ SMOW)	δD (‰ SMOW)	d-excess
D1207001	Sandia Mountain Snow	4/19/2012	-15.61	-114.51	10.3
D1307079	LH Sandia Rain	7/13/2013	-12.14	-85.20	11.9
D1407112	AR Zuni Mountain Hail	5/23/2014	-12.08	-77.89	18.8
D1407122	Zuni Mountain Hail	10/19/2014	-9.14	-55.23	17.9
D1407123	Zuni Mountain Rain	10/19/2014	-9.25	-48.27	25.7
D1507129	AR Zuni Mountain Snow	2/21/2015	-11.839	-85.075	9.6
D1507147	ABQ North Valley Rain	5/4/2015	-3.66	-17.9	11.4
D1507154	UNM Hail	5/4/2015	-10.34	-65.5	17.2
D1507155	Aspen Campground Zuni Mountain Snow	5/9/2015	-10.30	-66.1	16.3
D1507156	Cottonwood Gulch Zuni Mountains Snow	5/9/2015	-11.00	-69.6	18.4
D1507158	ABQ North Valley Hail	5/16/2015	-15.87	-106.5	20.4
D1507157	ABQ North Valley Rain	5/16/2015	-7.64	-62.5	-1.4
D1507159	ABQ North Valley Rain	5/19/2015	-5.55	-34.2	10.3
D1507161	ABQ North Valley Rain	5/21/2015	-5.59	-31.9	12.8
D1507160	ABQ North Valley Rain	5/24/2015	-6.99	-61.9	-6.1
D1507152	McGaffey Campground Rain	6/5/2015	-11.42	-89.1	2.3
D1507167	McGaffey Campground Rain	7/3/2015	-0.10	-14.3	-13.5
D1507168	McGaffey Campground Rain	7/3/2015	-0.77	-18.5	-12.4
D1507169	McGaffey Campground Rain	7/4/2015	-6.55	-42.2	10.3
D1507171	ABQ North Valley Rain	7/7/2015	-2.30	-23.7	-5.3
D1507172	ABQ North Valley Rain	7/8/2015	-6.77	-43.2	11.0

Results from the stable isotopes provide evidence that stream waters (triangles) undergo evaporation, including the Rio Nutria above the Confluence (RNAC) as well as the pools upstream from the spring at Agua Remora. Of note is the Little Water Canyon (LWC), which is on the GMWL but much less negative than the other surface and spring waters. Interpretation of the LWC waters is that this sample of the spring waters are significantly recharged by monsoonal rain. Continued seasonal sampling at LWC is would be able to determine if the spring is also possibly recharged through snowmelt.

In 2014 and 2015, six spring waters were analyzed for tritium (^3H) concentrations to determine the amount of young waters that were present in the system (Table 4). Tritium concentrations ranged from 1.5TU to 5.7TU. The lower tritium concentrations indicate that the waters were predominately recharged prior to the nuclear testing of the 1950's. The higher tritium values indicate the waters are modern with recharge occurring less than ten years ago (Eastoe et al., 2012; Drakos et al., 2013).

Table 4. Zuni Mountains Springs Tritium Results



Tritium (^3H) Results, Zuni Mountains, Mount Taylor Ranger District, New Mexico

Sample	Tritium (TU) detection limit of 0.6TU	Error (TU)	Age of Groundwater (Eastoe et al., 2012; Drakos et al., 2013)
Agua Remora	1.5	± 0.30	predominately pre-1950's
Grasshopper Spring	1.8	± 0.28	Mixture of pre-1950's and modern recharge
Ojo Redondo	4.1	± 0.29	Modern (<5-10 year old recharge)
Post Office Flats	4.9	± 0.29	Modern (<5-10 year old recharge)
Cottonwood Gulch	5.6	± 0.27	Modern (<5-10 year old recharge)
La Jara	5.7	± 0.33	Modern (<5-10 year old recharge)

The spring waters that had the oldest waters (Agua Remora and Grasshopper) were recharged from confined aquifers of the TRc and Psg. As a result, it is expected that the flow path would be relatively longer. Of note is the La Jara and Cottonwood springs, which are recharged in the confined Psg, but tritium results indicate a modern recharge. The geologic map of the Zuni Mountains (Figure 2) shows that the Psg section where the La Jara spring is located is a small section sandwiched between crystalline Xg and two regional fault systems. Similarly, Cottonwood Gulch is located on a contact between Psg and TRc with a fault just south of the spring orifice. On previous visits in 2014, to La Jara and Cottonwood Gulch (Appendix IV) the springs had been dry. On March 1 the Zuni Mountains had a late snow fall with a reported 10 in of snow depth recorded by the Natural Resources Conservation Service (NRCS) site at Rice Park. On the date of the visit to both La Jara and Cottonwood Gulch on March 23, 2015 the snow depth had decreased to <1 in. Both of the springs were discharging on that day and continued to discharge for approximately 2 weeks and went dry afterward. Water from both sites had considerably lower TDS and ion concentrations (relative to other Psg spring waters). It is interpreted that the isolated sections of Psg that supplies La Jara and separately Cottonwood Gulch had infiltration along fault zones that made for a rapid flow path. The rapid infiltration and movement through the isolated sections of Psg limited water-rock interaction and resulted in discharge of fairly unaltered snowmelt at these locations.

The other two springs that were analyzed for tritium concentrations (Ojo Redondo and Post Office Flat) had TU ranges (Table 4) that indicated modern recharge. Geochemical results (Figure 12) indicate that these two spring waters are recharged in shallow alluvium. Stable isotopes indicate that these spring waters are recharged from both snowmelt and monsoonal rain events (Figure 13). Tritium results help to identify the mechanisms for recharge and flow path and help to determine differences of confined regional and local aquifers as well as unconfined local aquifers.

Continuous monitoring sites, Zuni Mountains

Brennan Spring

Brennan Spring is located on the west side of Oso Ridge, and it discharges from the San Andres Limestone. Historically not identified as a habitat for the Zuni Bluehead Sucker (Carmen, 2004), Brennan Spring was selected as a site for continuous monitoring as a possible translocation habitat (Livia Crowley, personal communication). On May 25, 2012 the research team installed a shallow (<1 m, < 3.3 ft) well, hitting limestone bedrock, and on July 2, 2012 a continuous monitor was deployed at this site to measure daily maximum and minimum temperatures within the well. During the initial visit the Brennan Spring site was dry but it was determined to move ahead with the installation of the well and to record temperature within the well. Temperature was recorded at 12:00 am (midnight) every day to determine if there were any changes to flow and physico-chemical parameters (Appendix VIII). Throughout the field season, this site was visited four times and each time there was no flow on the surface (Appendix IV, see specific SEAP forms for Brennan Spring). The continuous monitoring of well maximum and minimum temperatures (Figure 14) has a range between 14.5°C and 5.9°C with no dramatic changes due to precipitation events. The air temperature has a range of -9.5°C to 21.6°C (Table 5) and has reduced temperatures after precipitation events. The difference between the well and the air temperatures indicates that the temperature in the well was insulated from the extreme high and low temperatures in the atmosphere, but remained dry.

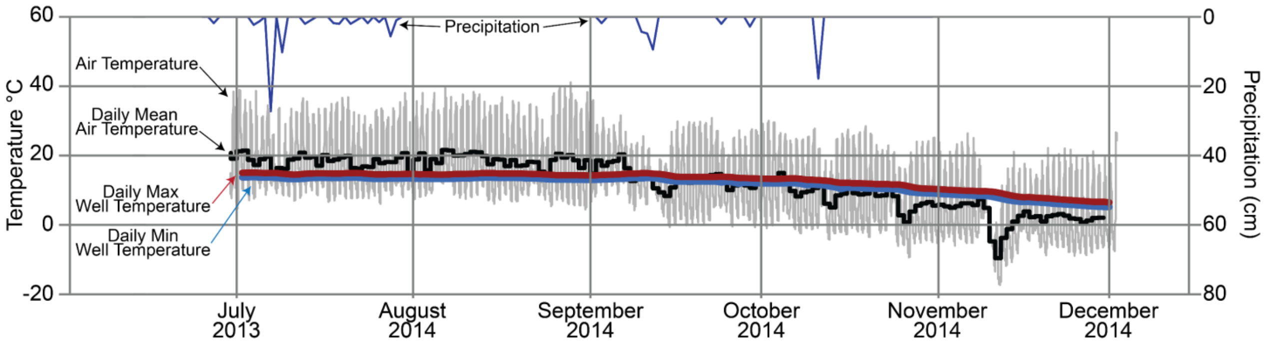


Figure 14. Time series graph of continuous monitoring of water temperature at Brennan Spring, Zuni Mountains, New Mexico. Reported here is the daily maximum and minimum temperature within a shallow (<1m) well at Brennan Spring. Graph also includes precipitation from McGaffey SE5 and continuous monitoring of 15 minute intervals for air temperature at Agua Remora.

Forest Guild continuous monitoring sites

Cottonwood Creek

Cottonwood Gulch is a spring located on private land south of Interstate 40 (Figure 1). There is summer camp that runs for most of the year on the property. Historically, a spring house was erected over the spring, but a small orifice has developed north of the spring house in the creek channel. Employees for the summer camp indicated that over the course of their five year tenure, the spring hadn’t discharged any water. A Solinst was deployed in the creek channel, downstream from the stream (Figure 15), May 2014 through October 2014 recording at 15 minute intervals water temperature, air temperature, specific conductance and water level (Appendix IX). Precipitation was recorded by Natural Resources Conservation Service (NRCS) at Rice Park, (Site 933) just east of Cottonwood Gulch.

Results from continuous monitoring indicated that the air temperature and water temperature (daily means) were the same until July 13, 2013 when several large rain events fell on the Zuni Mountains (Table 6). After the rain event the daily mean air and water temperatures slightly separated. The daily mean water temperature range was dampened by the presence of water in Cottonwood Creek (Figure 15A). The water level in the creek before July 13 was at zero, but post July 13 the water level maintains a mean depth range between 0.23 and 0.06 m (0.07 – 0.02 ft) (Figure 15B). This provides further evidence that water was in the Cottonwood Creek channel from July 13 through the end of the record in October.

Table 5. Brennan Spring, Zuni Mountain Continuous Monitoring Statistics

Continuous Monitoring Summary, Brennan Spring , Zuni Mountains, Mount Taylor Ranger District, New Mexico

Daily Maximum and Minimum n= 153 07/02/2012 to 12/01/2012

Water Temperature Maximum	n	Min	Max	Mean	median	STDEV	Inter Quartile*
Full Range	153.0	6.1	14.5	12.3	13.3	2.5	3.0
Seasonal June	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Seasonal Sept	61.0	13.7	14.5	14.1	14.2	0.2	0.3
Seasonal Dec	91.0	5.9	14.3	11.0	11.5	2.6	4.1
Seasonal March	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly May	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly June	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly July	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly August	30.0	13.9	14.5	14.2	14.2	0.2	0.3
Monthly Sept	31.0	13.7	14.4	14.0	14.1	0.2	0.3
Monthly Oct	30.0	12.8	14.3	13.6	13.3	0.5	0.7
Monthly Nov	31.0	9.7	12.8	11.6	11.5	0.9	1.5
Monthly Dec	30.0	5.9	9.7	7.8	7.4	1.3	2.4
Monthly Jan	1.0	5.9	5.9	n.a.	5.9	n.a.	0.0
Monthly Feb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly March	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly April	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Water Temperature Minimum	n	Min	Max	Mean	median	STDEV	Inter Quartile*
Full Range	153.0	5.9	14.4	12.2	13.2	2.6	3.1
Seasonal June	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Seasonal Sept	61.0	13.6	14.4	14.1	14.1	0.2	0.3
Seasonal Dec	91.0	5.8	14.2	10.8	11.4	2.6	4.1
Seasonal March	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly May	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly June	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly July	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly August	30.0	13.9	14.4	14.1	14.2	0.2	0.3
Monthly Sept	31.0	13.6	14.3	14.0	14.0	0.2	0.3
Monthly Oct	30.0	12.5	14.2	13.4	13.2	0.5	0.8
Monthly Nov	31.0	9.6	12.7	11.4	11.3	1.0	1.4
Monthly Dec	30.0	5.8	9.6	7.6	7.3	1.3	2.5
Monthly Jan	1.0	5.8	5.8	n.a.	5.8	n.a.	0.0
Monthly Feb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly March	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly April	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Air Temperature	n	Min	Max	Mean	median	STDEV	Inter Quartile*
Full Range	14629.0	-17.3	41.1	12.4	12.0	11.0	15.7
Daily Mean	153.0	-9.5	21.6	12.3	13.1	6.8	12.0

*Interquartile distance between the 25th and the 75th percentile of the empirical distribution function of the data within the bin.

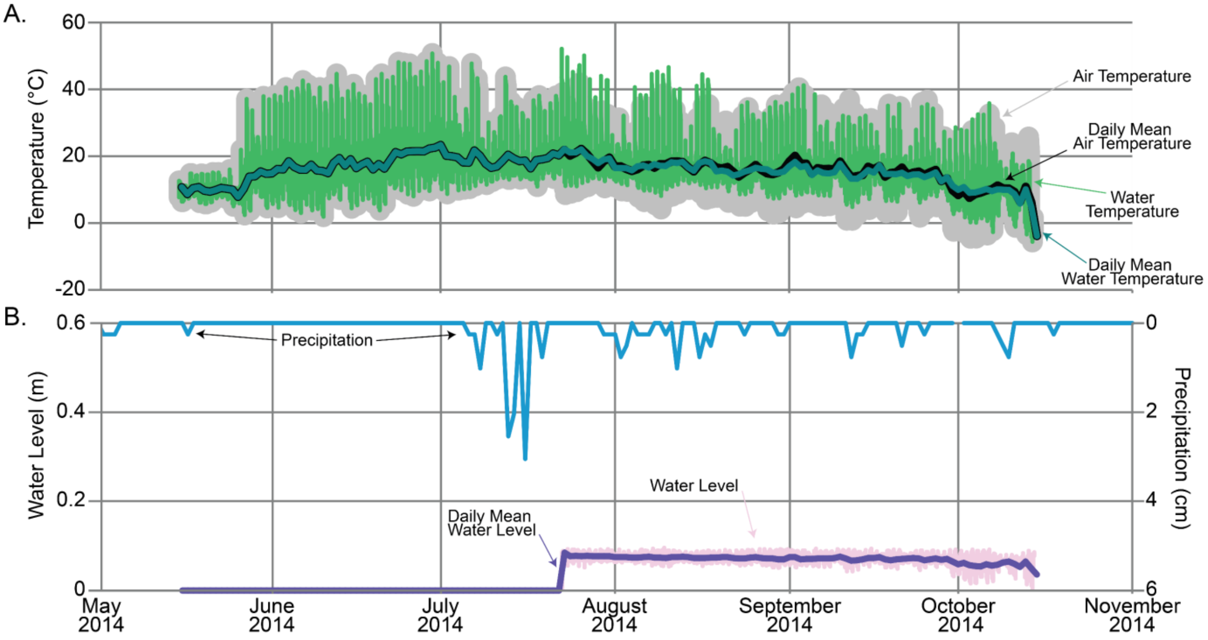


Figure 15. Time series graph of continuous monitoring of A) air and water temperatures and b) water level and precipitation for Cottonwood Gulch, Zuni Mountains, New Mexico. Reported here are the 15 minute intervals of continuous monitoring (lighter color) as well as the daily mean values for each of the parameters.

Table 6. Cottonwood Gulch Spring, Zuni Mountain Continuous Monitoring Statistics

Continuous Monitoring Summary, Cottonwood Creek, Zuni Mountains, Mount Taylor Ranger District, New Mexico

15 minute intervals n= 14702 05/15/2014 to 10/15/2014

Water Level	n	Min	Max	Mean	median	STDEV	Inter Quartile*
Full Range	14599	0.0	0.1	0.0	0.1	0.0	0.1
Daily Mean	153	0.0	0.1	0.0	0.1	0.0	0.1
Seasonal June	1582	0.0	0.0	0.0	0.0	0.0	0.0
Seasonal Sept	8831	0.0	1.0	0.0	0.0	0.0	0.1
Seasonal Dec	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Seasonal March	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly May	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly June	1582	0.0	0.0	0.0	0.0	0.0	0.0
Monthly July	2880	0.0	0.0	0.0	0.0	0.0	0.0
Monthly August	2975	0.0	0.1	0.2	0.0	0.0	0.1
Monthly Sept	2976	0.1	0.1	0.1	0.1	0.0	0.0
Monthly Oct	2880	0.0	0.1	0.1	0.1	0.0	0.0
Monthly Nov	1309	0.0	0.1	0.1	0.1	0.0	0.3
Monthly Dec	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly Jan	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly Feb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly March	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly April	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Water Temperature	**n**	**Min**	**Max**	**Mean**	**median**	**STDEV**	**Inter Quartile***
Full Range	14579	-5.6	52.1	15.8	14.3	8.0	9.1
Daily Mean	153	-3.9	15.8	16.1	4.0	3.9	
Seasonal June	1582	2.4	37.9	11.3	10.0	5.4	5.2
Seasonal Sept	8831	1.9	52.1	18.0	15.8	8.0	9.0
Seasonal Dec	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Seasonal March	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly May	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly June	1582	2.4	37.9	11.3	8.5	5.4	5.2
Monthly July	2880	1.9	50.7	18.4	16.1	10.0	13.2
Monthly August	2975	8.7	52.1	19.3	16.8	6.9	8.3
Monthly Sept	2976	7.3	46.6	16.5	14.5	6.4	6.6
Monthly Oct	2880	2.7	41.2	14.7	13.4	6.2	7.9
Monthly Nov	1286	-5.6	35.8	9.5	23.2	7.8	11.2
Monthly Dec	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly Jan	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly Feb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly March	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly April	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Air Temperature	**n**	**Min**	**Max**	**Mean**	**median**	**STDEV**	**Inter Quartile***
Full Range	14579	-5.7	50.7	16.0	14.4	8.7	11.8
Daily Mean	153	-3.9	23.3	15.9	4.6	4.0	4.0
Seasonal June	1582	2.4	37.9	11.3	10.0	5.4	5.2
Seasonal Sept	8831	1.9	50.7	18.1	16.2	8.2	11.2
Seasonal Dec	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Seasonal March	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly May	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly June	1582	2.4	37.9	11.3	8.5	5.4	5.2
Monthly July	2880	1.9	50.7	18.4	16.1	10.0	13.2
Monthly August	2975	8.5	47.7	19.2	17.0	6.8	9.1
Monthly Sept	2976	2.7	38.7	16.6	14.8	7.5	11.8
Monthly Oct	2880	-2.5	40.4	15.2	13.7	8.6	13.2

*Interquartile distance between the 25th and the 75th percentile of the empirical distribution function of the data within the bin.

Table 6. Cottonwood Gulch Spring, Zuni Mountain Continuous Monitoring Statistics (continued)

Continuous Monitoring Summary, Cottonwood Creek, Zuni Mountains, Mount Taylor Ranger District, New Mexico

Air Temperature	n	Min	Max	Mean	median	STDEV	Inter Quartile*
Monthly Nov	1286	-5.7	32.6	8.8	1.7	8.9	14.9
Monthly Dec	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly Jan	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly Feb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly March	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly April	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

*Interquartile distance between the 25th and the 75th percentile of the empirical distribution function of the data within the bin.

Bluewater Creek

Continuous monitoring at Bluewater Creek occurred from August 2013 to October 2014, not including the 2013 winter months. Solinst leveloggers were deployed to collect air and water temperatures, specific conductance and water level at 15 minute intervals (Appendix X). Precipitation from the NRCS Rice Park SNOTEL was used. During the deployment, there were only two major rain events, one in September 2013 and in July 2014 (Figure16C). Water level was significantly altered during these rain events, but recovery to pre-event water levels returns within days (Figure16C). Specific conductance has a mean of 440 µS/cm (Table 7) for the entire range with large variations (ranges 517 µS/cm to 23 µS/cm), mostly related to the large rain events (Figure16B). Air and water temperatures are closely tied with the full range of water temperature (0.1°C to 23.9°C) falling within the mean air temperature range (-2.9°C to 21.8°C) (Table 7), with only the exception of the large rain event in September 2013 (Figure16A). These results show that within the measured section of Bluewater Creek water was present year round.

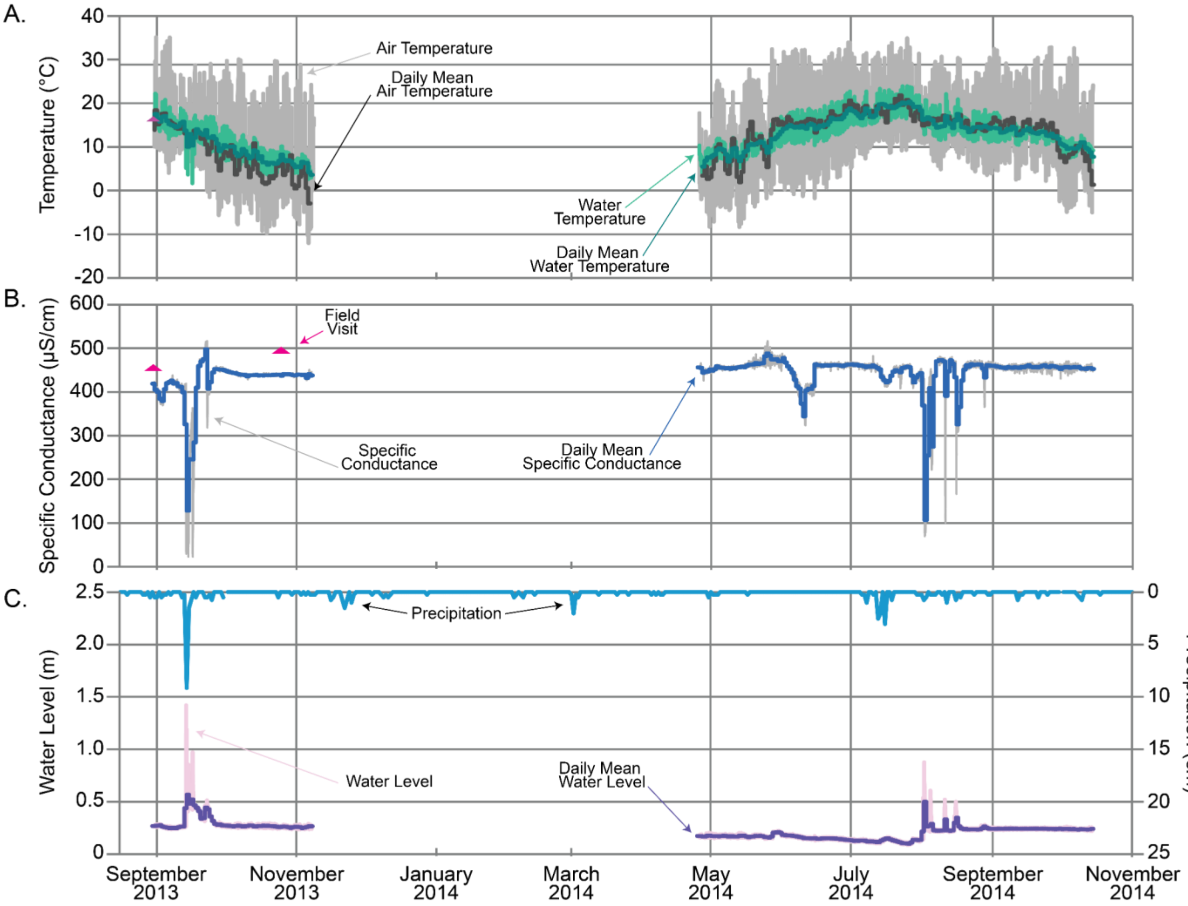


Figure 16. Time series graph of continuous monitoring of A) air and water temperatures, B) specific conductance and C) water level and precipitation for Bluewater Creek, Zuni Mountains, New Mexico. Reported here are the 15 minute intervals of continuous monitoring (lighter color) as well as the daily mean values for each of the parameters. Precipitation data is from NCRS Rice Park (site 933).

Table 7. Bluewater Creek, Zuni Mountain Continuous Monitoring Statistics

Continuous Monitoring Summary, Bluewater Creek, Zuni Mountains, Mount Taylor Ranger District, New Mexico

15 minute intervals n= 23088 8/30/2013 to 10-15-2014

Water Level	n	Min	Max	Mean	median	STDEV	Inter Quartile*
Full Range	23089	0.1	1.4	0.2	0.2	0.1	0.1
Daily Mean	243	0.1	0.6	0.2	0.2	0.1	0.1
Seasonal June	1739	0.1	0.2	0.2	0.2	0.0	0.0
Seasonal Sept	4469	0.1	0.9	0.2	0.2	0.0	0.1
Seasonal Dec	5335	0.2	1.4	0.3	0.3	0.0	0.0
Seasonal March	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly May	251	0.2	0.2	0.2	0.2	0.0	0.0
Monthly June	1488	0.1	0.2	0.2	0.2	0.0	0.0
Monthly July	1440	0.1	0.2	0.2	0.2	0.0	0.0
Monthly August	1487	0.1	0.2	0.1	0.1	0.0	0.0
Monthly Sept	1542	1.4	0.9	0.3	0.3	0.0	0.0
Monthly Oct	2880	0.2	1.4	0.3	0.3	0.1	0.1
Monthly Nov	2140	0.2	0.3	0.3	0.3	0.0	0.0
Monthly Dec	630	0.2	0.3	0.3	0.3	0.0	0.0
Monthly Jan	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly Feb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly March	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly April	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Specific Conductance	n	Min	Max	Mean	Median	STDEV	Inter Quartile*
Full Range	23088	22.6	516.7	439.9	453.5	50.2	21.8
Daily Mean	243	106.8	497.7	446.6	456.4	46.2	21.4
Seasonal June	1739	426.3	516.6	461.2	458.1	12.3	11.2
Seasonal Sept	4469	69.7	482.7	421.8	431.4	30.7	12.9
Seasonal Dec	5335	22.7	516.7	439.3	447.9	33.4	0.0
Seasonal March	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly May	251	426.3	465.8	449.4	448.6	6.0	7.3
Monthly June	1488	443.4	516.6	463.2	459.2	11.9	12.4
Monthly July	1440	323.5	482.7	442.7	459.7	32.2	43.0
Monthly August	1487	408.4	482.3	448.7	454.0	13.7	21.2
Monthly Sept	1542	69.7	480.9	413.2	432.0	46.4	21.9
Monthly Oct	2880	22.7	516.7	428.4	438.5	46.3	29.0
Monthly Nov	2140	429.0	470.6	447.8	447.3	3.8	4.8
Monthly Dec	630	427.2	450.7	438.5	439.1	3.5	2.6
Monthly Jan	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly Feb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly March	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly April	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Water Temperature	n	Min	Max	Mean	median	STDEV	Inter Quartile*
Full Range	23744	0.1	23.9	14.5	13.1	4.3	6.5
Daily Mean	250	4.2	20.4	11.7	9.7	4.0	6.0
Seasonal June	1739	4.1	16.9	9.4	9.3	2.3	3.3
Seasonal Sept	4469	10.4	23.9	17.0	16.7	2.5	3.7
Seasonal Dec	5663	0.1	23.6	11.4	11.2	3.3	5.3
Seasonal March	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly May	251	4.1	10.3	7.1	7.1	1.4	2.2
Monthly June	1488	5.3	16.9	9.7	9.7	2.2	3.1

*Interquartile distance between the 25th and the 75th percentile of the empirical distribution function of the data within the bin.

Table 7. Bluewater Creek, Zuni Mountain Continuous Monitoring Statistics (continued)

Continuous Monitoring Summary, Bluewater Creek, Zuni Mountains, Mount Taylor Ranger District, New Mexico

Water Temperature	n	Min	Max	Mean	median	STDEV	Inter Quartile*
Monthly July	1440	10.4	22.7	15.5	15.5	2.5	3.6
Monthly August	1487	14.9	23.9	18.5	18.5	2.0	2.9
Monthly Sept	1542	11.1	22.2	16.0	16.0	2.1	3.3
Monthly Oct	2880	1.7	20.8	13.6	13.6	2.2	3.0
Monthly Nov	2140	3.7	14.7	8.9	8.9	1.6	2.3
Monthly Dec	1286	0.1	23.6	7.7	7.7	6.5	12.3
Monthly Jan	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly Feb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly March	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly April	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Air Temperature	n	Min	Max	Mean	median	STDEV	Inter Quartile*
Full Range	23744	-12.0	35.1	15.8	17.7	8.9	13.1
Daily Mean	250	-2.9	21.8	12.0	11.2	5.3	8.0
Seasonal June	1739	-8.3	32.4	9.0	8.3	8.8	13.8
Seasonal Sept	4469	-1.7	35.1	17.4	15.7	7.1	10.8
Seasonal Dec	5663	-12.0	35.1	10.7	10.8	8.4	13.0
Seasonal March	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly May	251	-8.3	17.7	4.1	3.9	5.5	8.7
Monthly June	1488	-8.3	32.4	9.8	9.3	9.0	14.8
Monthly July	1440	-1.7	33.9	16.3	17.9	9.4	17.3
Monthly August	1487	5.1	34.9	18.6	17.2	6.2	10.6
Monthly Sept	1542	3.6	35.1	16.7	14.8	6.3	9.7
Monthly Oct	2880	-5.6	35.1	13.5	12.8	7.1	10.2
Monthly Nov	2140	-9.7	32.6	6.6	5.4	8.3	13.1
Monthly Dec	1285	-12.0	28.8	9.5	13.6	10.0	17.5
Monthly Jan	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly Feb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly March	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly April	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

*Interquartile distance between the 25th and the 75th percentile of the empirical distribution function of the data within the bin.

Mount Taylor

The springs of Mount Taylor were visited in the 2013 field season. The priority for the Mount Taylor division were springs on National Forest System lands north of San Mateo Creek due to potential uranium mining in the area. In addition, the basalt capped El Dado Mesa (northeastern Mount Taylor) area was targeted for the spring site inventory (Figure 6 and 7).

Forty fours springs within Cibola National Forest on Mount Taylor (Appendix II) were confirmed using the developed protocol (Appendix I). This research visited 15 (34%) of the identified spring sites (Appendix XI). The SEAP Level I and II protocols were completed with each visit (Appendix XII for individual spring forms). Some of the springs sites had been developed similar to that for the Zuni Mountains: Earthen dams, spring boxes, cattle troughs and piping were found at most spring sites. Of the 15 spring sites that were visited in the Mount Taylor area, ten (66.7%) were dry (Table 8). Of the five springs visited in the San Mateo area three (60%) were dry. For El Dado Mesa, nine springs were identified with three (33%) being visited and all three (100%) were wet (Table 8).

For the five wet springs, ion concentrations were analyzed (Appendix XIII) and are plotted on a Piper diagram (Figure 17). Physico-chemical parameters were also collected for the five wet springs to understand relationships between the different ground water sources (Piper, 1944). All five springs have a Ca_Mg_HCO_3 Hydrochemical facies (Bethke, 2008) with a mixed cation ratios and anions that are bicarbonate (HCO_3) concentrated (Figure 17A). Total dissolved solids range between 50-341 mg/kg and all are identified to be from the Quaternary basalt aquifers (Figure 17B).

Isotopologues of water ($\delta^{18}O$ and δD) were analyzed (Appendix XIII) and are graphed in relation to the GMWL (Craig, 1961) (Figure 18). Several of the springs plot off of the GMWL at a slope of 3.9 and are interpreted to have been highly evaporated (Figure 18, inset). The three springs with $\delta^{18}O$ and δD values that are close to the GMWL, have a $\delta^{18}O$ range of -14‰ to -11‰ and δD -90‰ to -80‰. The relationship to the precipitation events collected in west-central and central New Mexico during the study create areas that describe temporal recharge (Figure 18). The interpretation of the isotopic data indicates that visited springs within the Mount Taylor USFS District are primarily recharged through snowmelt.

Table 8. Mount Taylor Spring Conditions Statistics

Spring Site Visit Summary Mount Taylor, Mount Taylor Ranger District, New Mexico

	Number of Springs (#)	Number of Visits (#)	Percent of Total Number (%)	Number of Wet Spring Visits (#)	Percent of Wet Spring Visits (%)	Number of Dry Spring Visits (#)	Percent of Dry Spring Visits (%)
Mount Taylor							
Total Number of Springs from Protocol	44						
Springs Visited Once	15	15	34	5	33	10	67
Springs Visited Twice	0	0	0	0	0	0	0
Springs Visited Thrice	0	0	0	0	0	0	0
Springs Visited > Thrice	0	0	0	0	0	0	0
Total Number of Springs Visited	15		34				
Total Number of Spring Visits		15		5	33	10	67
San Mateo							
Total Number of Springs from Protocol	5						
Springs Visited Once	5	5	100	2	40	3	60
Springs Visited Twice	0	0	0	0	0	0	0
Springs Visited Thrice	0	0	0	0	0	0	0
Springs Visited > Thrice	0		0	0	0	0	0
Total Number of Springs Visited	5		100				
Total Number of Spring Visits		5		2	40	3	60
El Dado Mesa							
Total Number of Springs from Protocol	9						
Springs Visited Once	3	3	33	3	100	0	0
Springs Visited Twice	0	0	0	0	0	0	0
Springs Visited Thrice	0	0	0	0	0	0	0
Springs Visited > Thrice	0	0	0	0	0	0	0
Total Number of Springs Visited	3		33				
Total Number of Spring Visits		3		3	100	0	0

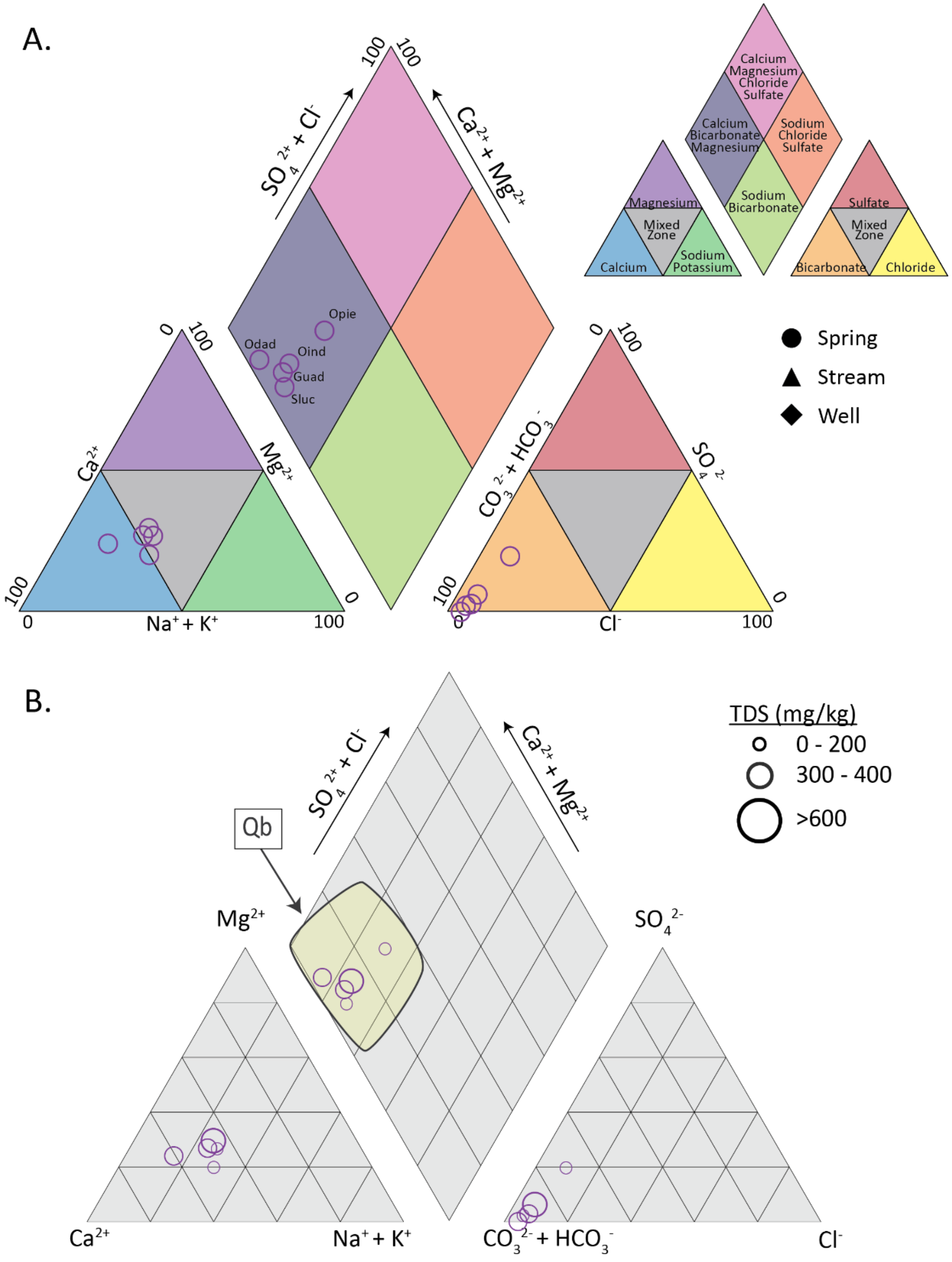


Figure 17. Piper diagram (Piper, 1944) of spring (circles) and stream (triangles) waters collected in Mount Taylor, New Mexico. A) Hydrochemical facies of different waters. B) Salinity and aquifer properties for different waters.

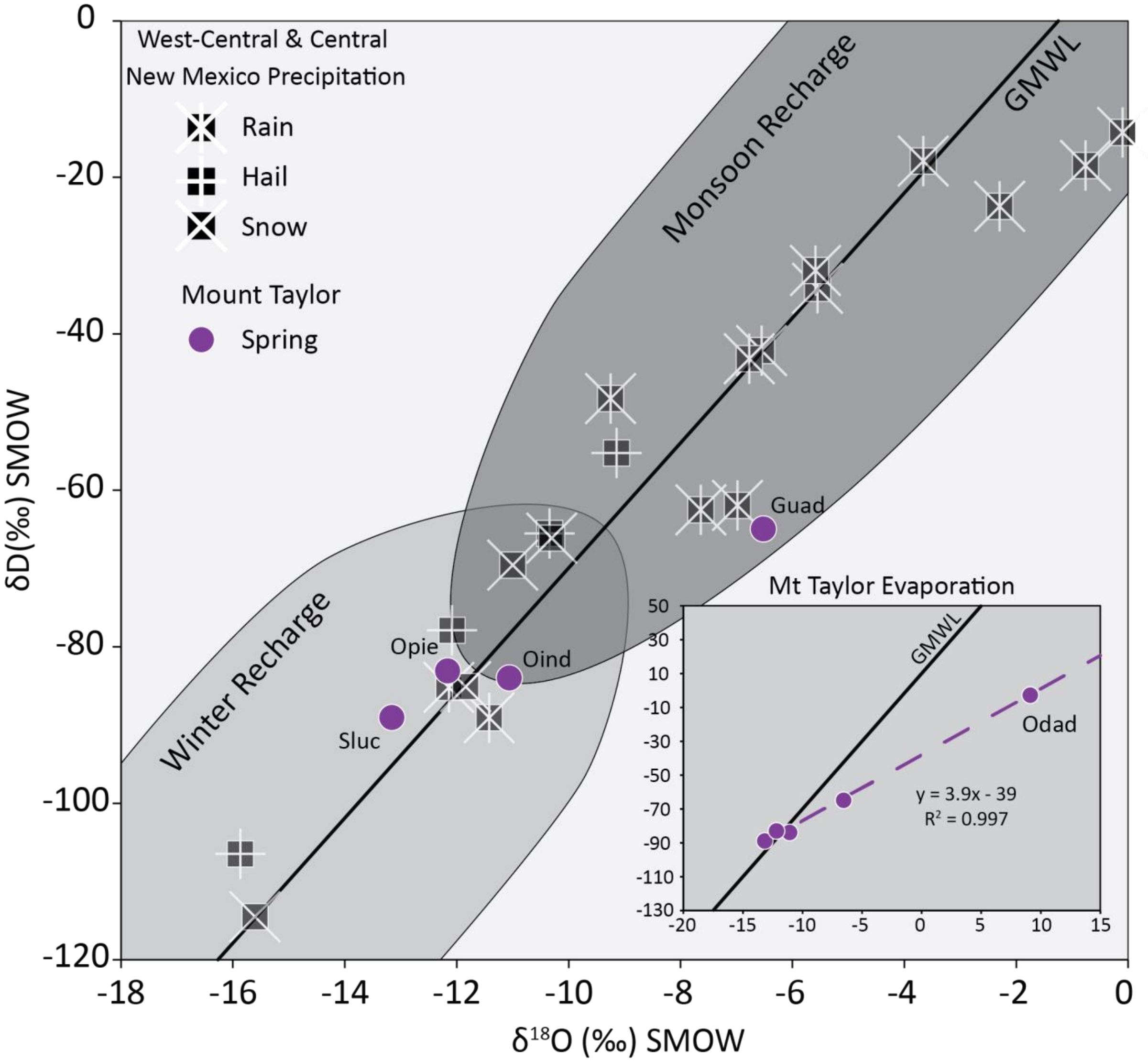


Figure 18. X-Y Plot of stable isotopes (δ18O‰ vs δD ‰, relative to the SMOW standard) for Mount Taylor springs (circle) and streams (triangle) as well as west-central and central New Mexico precipitation (squares) that was collected during the study. The Global Meteoric Water Line, GMWL (Craig, 1961) is plotted to determine if Mount Taylor waters are altered away from global precipitation values. Inset: Outlier identifies the trend for evaporation having a slope for 3.9. Precipitation values establish seasonal fractionation effects that determine timing of recharge for ground waters.

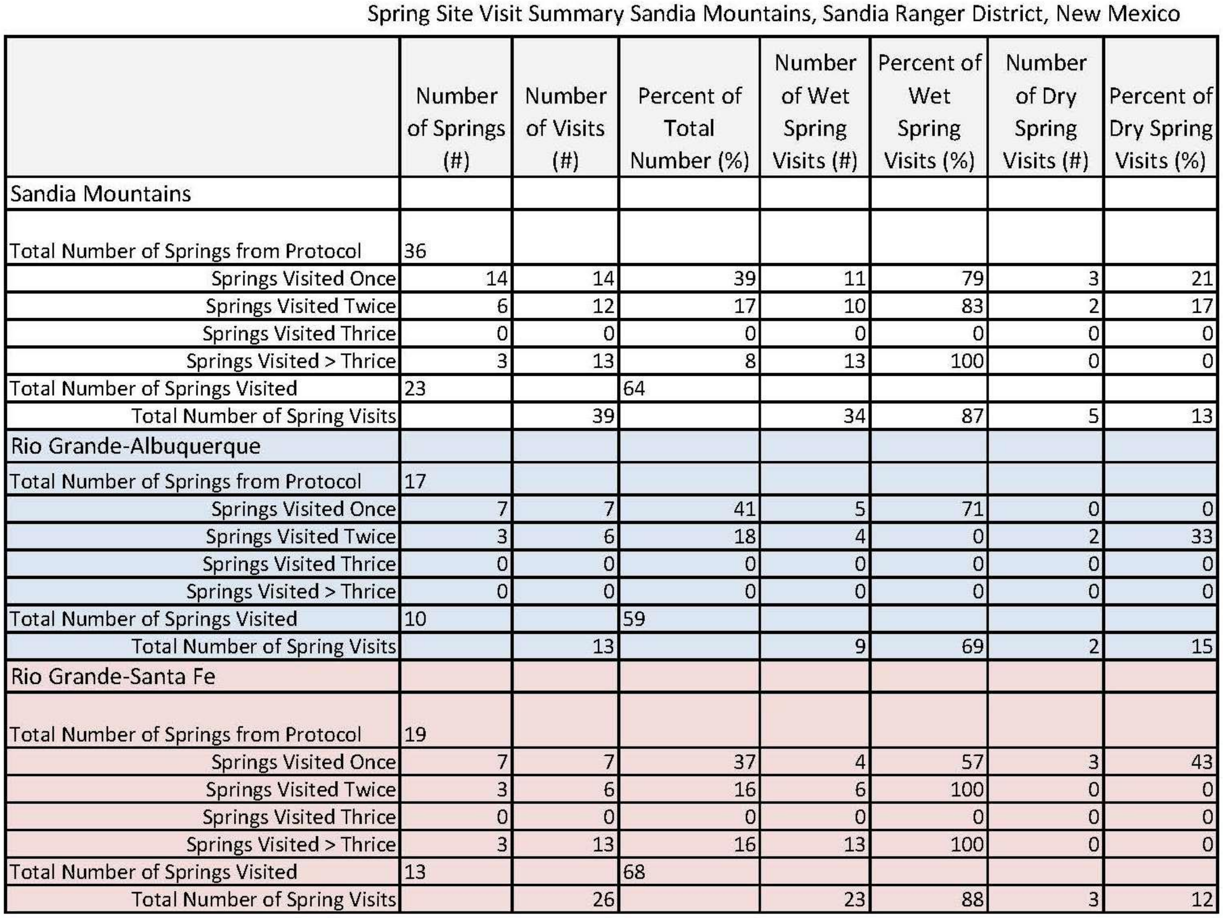
Sandia Mountains

Spring sites within Cibola National Forest, Sandia Mountain District, were visited in 2012-2013 field seasons. The priority for the forest was to target Las Huertas Creek and springs that provide discharge for perennially wet sections of the creek. Additionally, several high flow springs on the east slope of the Sandia Mountains were selected for assessment. Several of the springs around the Sandia Mountains are used for different communities within the region including, Tunnel Spring for the Placitas area and Cienga Spring for the East Mountains area.

There were 36 springs verified within the Cibola National Forest, Sandia Mountain District boundaries (Appendix II) using the described protocol (Appendix I). Of the identified springs, 23 (64%) sites were visited at least once (Table 9) and evaluated using the SEAP assessment (Appendix XIV), individual spring SEAP forms). Some springs were visited more than once with 39 total spring site visits (Appendix XV). Of the spring site visits, 34 (87%) were wet (Table 9). For the different priority areas, the northern Sandia Mountain area had 19 springs identified with 13 (68%) of these visited at least once. There were a total number of 26 site visits within the northern mountain area where 23 (88%) were wet. The eastern and southern areas had 17 springs identified with 10 (59%) of these visited at least once. There were a total number of 13 site visits with 9 (69%) of these being wet (Table 8).

Physico-chemical and major ion chemistry was analyzed (Appendix XVI) and plotted on a Piper diagram (Figure 19) to allow for relational comparisons of the different waters throughout the Sandia Mountains (Piper, 1944). The analysis of the cation and anion concentrations indicates that all of the waters are calcium concentrated with most of them being bicarbonate dominated (Figure 19A). The parallelogram identifies two main hydrochemical facies with the Ca_Mg_HCO3 being the waters from the east and northern mountain areas. The second hydrochemical facies is the Ca_Mg_Cl_SO4 and are waters from the southern mountain area, Tijeras Creek (Figure 19A). Total dissolved solids for the Sandia Mountain springs range from 372 to 930 mg/kg. Hydrochemical analysis indicates that the majority of springs have waters that flow through the Pennsylvanian La Madera Limestone with one exception (Sulphur spring) that is recharged in the alluvium (Figure 19B).

Table 9. Sandia Mountain Spring Conditions Statistics



Spring Site Visit Summary Sandia Mountains, Sandia Ranger District, New Mexico

	Number of Springs (#)	Number of Visits (#)	Percent of Total Number (%)	Number of Wet Spring Visits (#)	Percent of Wet Spring Visits (%)	Number of Dry Spring Visits (#)	Percent of Dry Spring Visits (%)
Sandia Mountains							
Total Number of Springs from Protocol	36						
Springs Visited Once	14	14	39	11	79	3	21
Springs Visited Twice	6	12	17	10	83	2	17
Springs Visited Thrice	0	0	0	0	0	0	0
Springs Visited > Thrice	3	13	8	13	100	0	0
Total Number of Springs Visited	23		64				
Total Number of Spring Visits		39		34	87	5	13
Rio Grande-Albuquerque							
Total Number of Springs from Protocol	17						
Springs Visited Once	7	7	41	5	71	0	0
Springs Visited Twice	3	6	18	4	0	2	33
Springs Visited Thrice	0	0	0	0	0	0	0
Springs Visited > Thrice	0	0	0	0	0	0	0
Total Number of Springs Visited	10		59				
Total Number of Spring Visits		13		9	69	2	15
Rio Grande-Santa Fe							
Total Number of Springs from Protocol	19						
Springs Visited Once	7	7	37	4	57	3	43
Springs Visited Twice	3	6	16	6	100	0	0
Springs Visited Thrice	0	0	0	0	0	0	0
Springs Visited > Thrice	3	13	16	13	100	0	0
Total Number of Springs Visited	13		68				
Total Number of Spring Visits		26		23	88	3	12

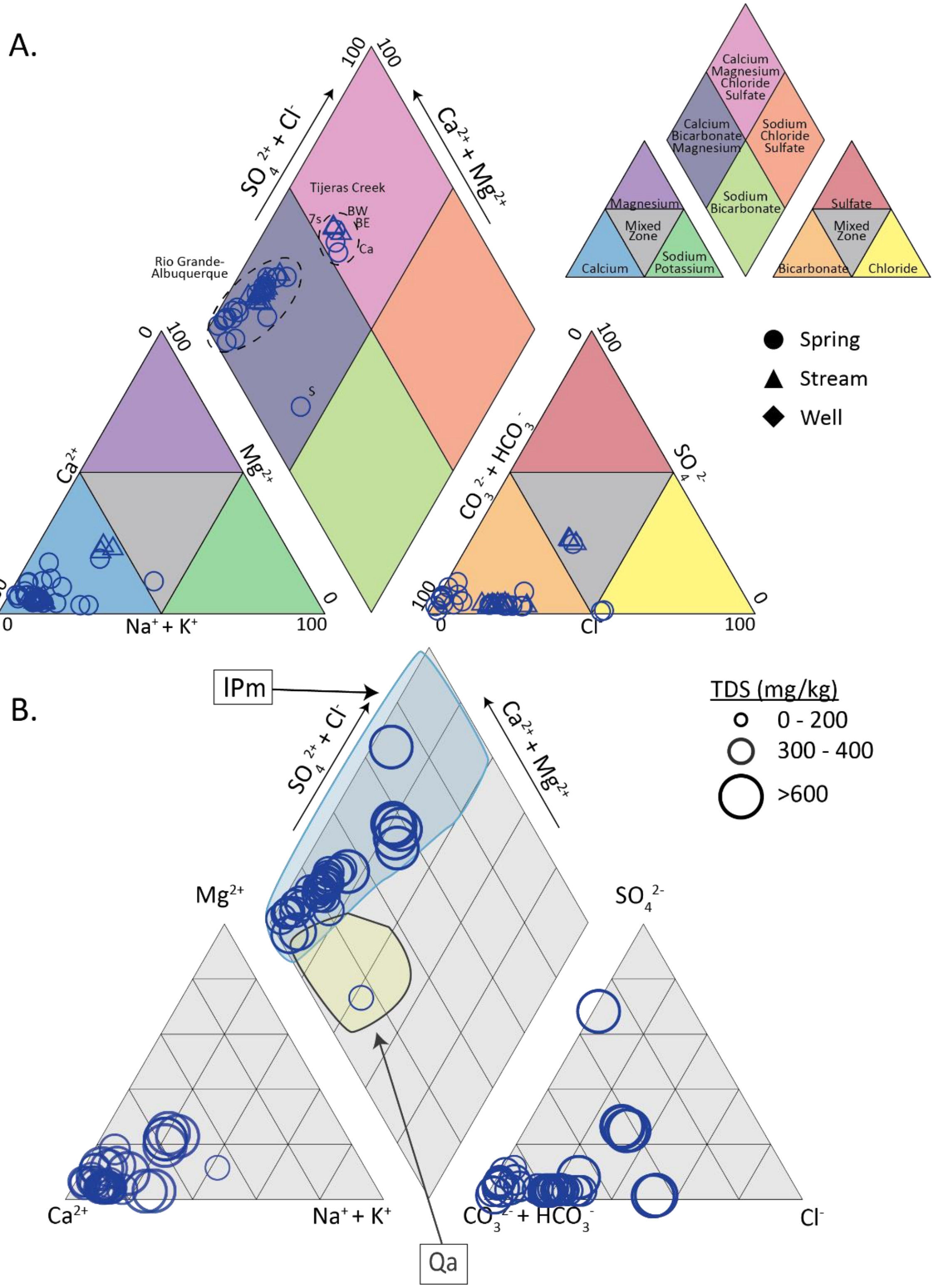


Figure 19. Piper diagram (Piper, 1944) of spring (circles) and stream (triangles) waters collected in the Sandia Mountains, New Mexico. A) Hydrochemical facies of different waters. B) Salinity and aquifer properties for different waters.

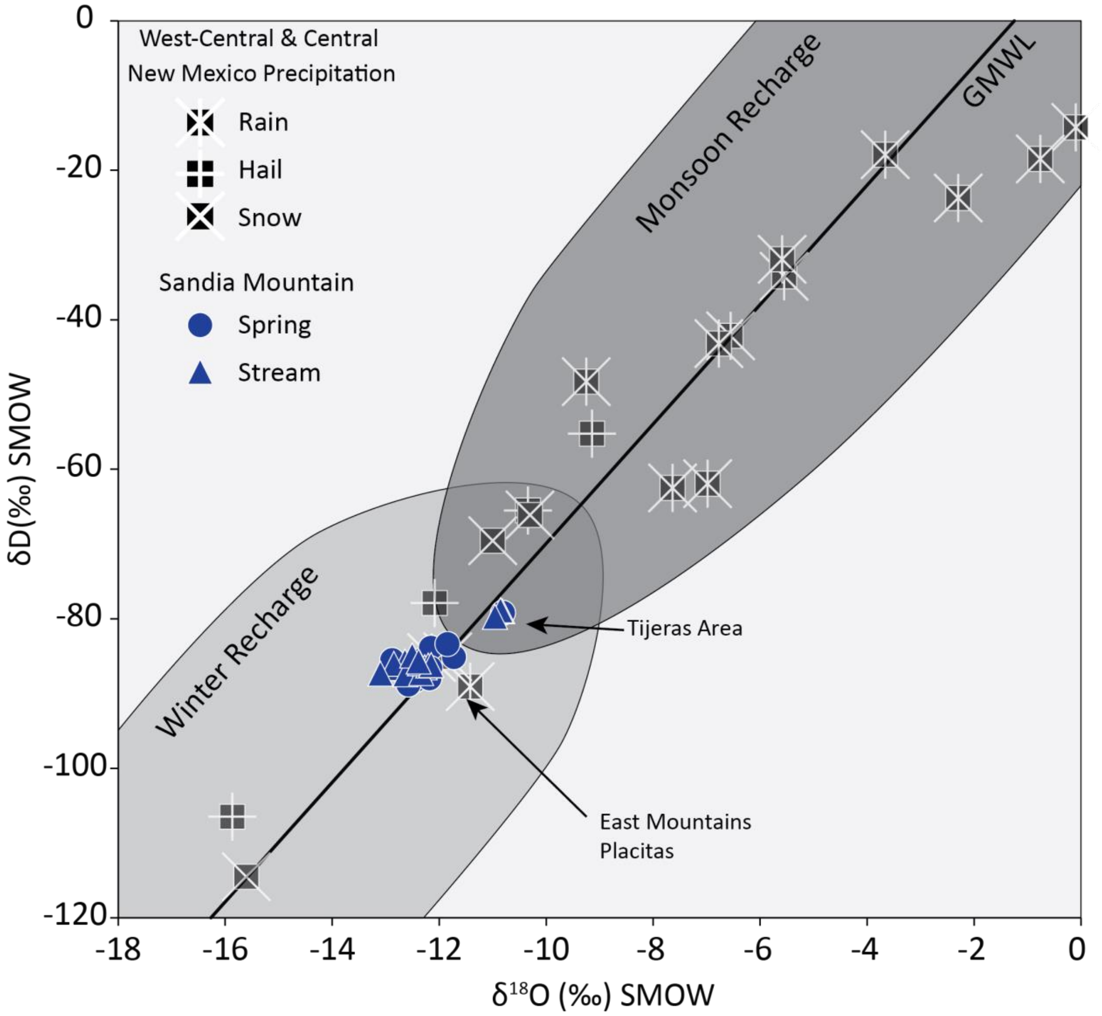


Figure 20. X-Y Plot of stable isotopes (δ^{18}O‰ vs δD ‰, relative to the SMOW standard) for Sandia Mountain springs (circle) and streams (triangle) as well as west-central and central New Mexico precipitation (squares) that was collected during the study. The Global Meteoric Water Line, GMWL (Craig, 1961) is plotted to determine if Sandia Mountain waters are altered away from global precipitation values. Precipitation values establish seasonal fractionation effects that determine timing of recharge for ground waters.

Stable isotopes of water (δD and δ^{18}O) for the Sandia Mountain springs range from -95‰ to -80‰ and -14‰ to -10‰ respectively (Appendix XVI). The distribution of values is relatively close to the GMWL with very little evaporation effects for any of the waters. West-central and central New Mexico precipitation is plotted to determine approximate isotopic differences to be associated with seasonality of recharge. Using these areas to define timing of recharge events the majority of waters from the Sandia Mountains are primarily recharged through winter recharge (Figure 20). Of note is the Tijeras Creek springs which represent a possible mixed recharge mechanism of both winter and monsoonal rains.

Continuous monitoring sites, Sandia Mountains

Las Huertas Creek

Las Huertas Creek is located on the northern flanks of the Sandia Mountains and is the primary water source for the acequia in the Village of Placitas (Figure 9). The creek was designated as a priority for Cibola National Forest. A Solinst levelogger was deployed for the continuous monitoring of air and water temperature, specific conductance and water levels (Appendix XVII). Data was collected every 15 minutes from July 2013 to February 2014 (Figure 21). The levelogger was deployed in the creek, 2 m (6.56 ft) downstream from a large spring box. Water levels remained very consistent with a mean of 0.22 m (0.72 ft) and a standard deviation of 0.014 (Table 10). Water levels really only changed during the large events in September 2013 (Figure 21C). Specific conductance wandered around the mean 591µS/cm but was variable with a standard deviation of 75.5 (Figure 21B). Of note is the increase in daily mean specific conductance closely related to the timing of rain events (Figure 21B). Water temperature is dampened relative to the air temperature (Figure 21A) where the range for water is 1.1°C to 15.4°C while the air temperature ranges -16.8°C to 30.0°C (Table 10). Combining the consistent depth, specific conductance and water temperature indicates that the primary source for water in this section of the creek is dominated by perennial spring waters. Additional monitoring of the site will help to determine if there is any seasonality differences to these physico-chemical parameters.

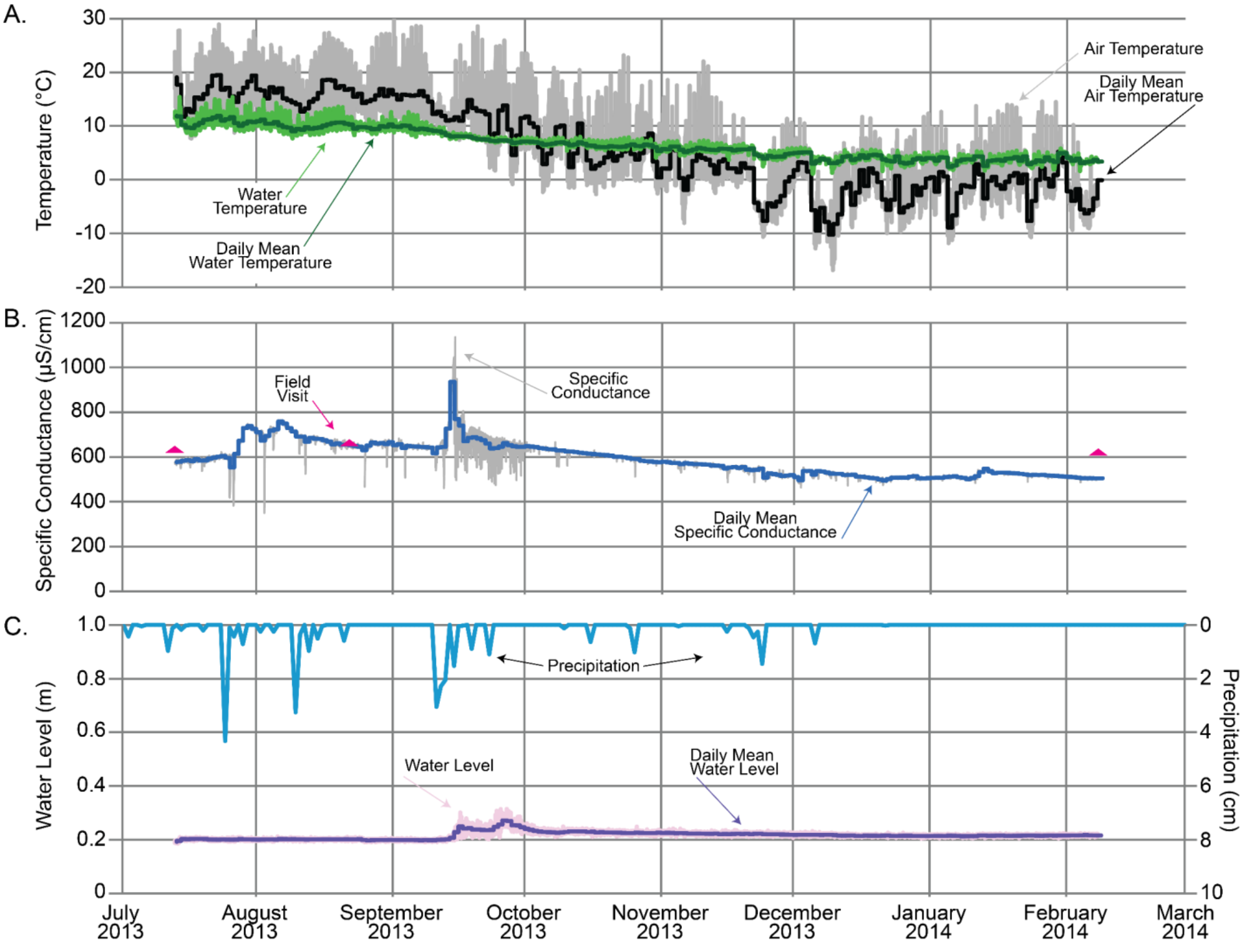


Figure 21. Time series graph of continuous monitoring of A) air and water temperatures, B) specific conductance and C) water level and precipitation for Las Huertas Creek, Sandia Mountains, New Mexico. Reported here are the 15 minute intervals of continuous monitoring (lighter color) as well as the daily mean values for each of the parameters. Precipitation data is from WRCC, Estancia, New Mexico (site 293060).

Table 10. Las Huertas Creek, Sandia Mountain Continuous Monitoring Statistics

Continuous Monitoring Summary, Las Huertas Creek, Sandia Mountains, Sandia Ranger District, New Mexico

15 minute intervals n= 20124 7-13-2013 to 2-8-2014

Water Level	n	Min	Max	Mean	median	STDEV	Inter Quartile*
Full Range	20124	0.2	0.3	0.2	0.2	0.0	0.0
Daily Mean	211	0.2	0.3	0.3	0.2	0.0	0.0
Seasonal June	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Seasonal Sept	4736	0.2	0.2	0.2	0.2	0.0	0.0
Seasonal Dec	8736	0.2	0.3	0.2	0.2	0.0	0.0
Seasonal March	6652	0.2	0.2	0.2	0.2	0.0	0.0
Monthly July	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly August	1772	0.2	0.2	0.2	0.2	0.0	0.0
Monthly Sept	2964	0.2	0.2	0.2	0.2	0.0	0.0
Monthly Oct	2880	0.2	0.3	0.2	0.2	0.0	0.0
Monthly Nov	2976	0.2	0.3	0.2	0.2	0.0	0.0
Monthly Dec	2880	0.2	0.2	0.2	0.2	0.0	0.0
Monthly Jan	2976	0.2	0.2	0.2	0.2	0.0	0.0
Monthly Feb	2976	0.2	0.2	0.2	0.2	0.0	0.0
Monthly March	700	0.2	0.2	0.2	0.2	0.0	0.0
Monthly April	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly May	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly June	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Specific Conductance	**n**	**Min**	**Max**	**Mean**	**Median**	**STDEV**	**Inter Quartile***
Full Range	20124	350.7	1135.9	590.9	579.7	75.5	126.1
Daily Mean	211	495.4	935.5	591.0	581.5	73.5	125.9
Seasonal June	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Seasonal Sept	4736	350.7	763.8	656.7	662.8	55.5	88.1
Seasonal Dec	8736	461.1	1136.0	612.1	609.9	65.4	78.0
Seasonal March	6652	464.1	553.3	516.0	513.2	12.1	17.6
Monthly July	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly August	1772	383.3	747.9	616.8	595.8	58.7	28.4
Monthly Sept	2964	350.7	763.8	680.5	673.0	36.7	43.4
Monthly Oct	2880	461.1	1136.0	671.7	654.8	69.3	31.4
Monthly Nov	2976	512.9	666.1	613.0	613.6	21.6	34.4
Monthly Dec	2880	488.1	587.7	551.5	557.2	21.5	34.8
Monthly Jan	2976	464.1	553.3	514.9	510.6	13.1	17.9
Monthly Feb	2976	484.4	553.1	519.2	518.6	11.0	16.6
Monthly March	700	486.8	515.6	507.2	507.1	4.2	5.2
Monthly April	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly May	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly June	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Water Temperature	**n**	**Min**	**Max**	**Mean**	**median**	**STDEV**	**Inter Quartile***
Full Range	20124	1.1	15.4	6.5	6.2	2.7	4.8
Daily Mean	211	2.4	11.9	6.6	6.2	2.7	5.3
Seasonal June	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Seasonal Sept	4736	7.7	15.4	10.3	10.1	1.3	1.6
Seasonal Dec	8736	2.5	12.6	6.7	6.5	1.5	1.8
Seasonal March	6652	1.1	6.0	3.8	3.8	0.8	1.0
Monthly July	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly August	1772	8.3	15.4	10.8	11.6	1.4	1.7

*Interquartile distance between the 25th and the 75th percentile of the empirical distribution function of the data within the bin.

Table 10. Las Huertas Creek, Sandia Mountain Continuous Monitoring Statistics (continued)

Continuous Monitoring Summary, Las Huertas Creek, Sandia Mountains, Sandia Ranger District, New Mexico

Water Temperature	n	Min	Max	Mean	median	STDEV	Inter Quartile*
Monthly Sept	2964	7.7	14.9	10.0	9.8	1.1	1.4
Monthly Oct	2880	6.6	12.6	8.3	8.1	1.1	1.7
Monthly Nov	2976	4.1	8.0	6.5	6.5	0.5	0.8
Monthly Dec	2880	2.5	7.3	5.3	5.4	0.8	1.0
Monthly Jan	2976	1.1	6.0	4.0	3.9	0.8	1.2
Monthly Feb	2976	1.7	5.8	3.7	3.8	0.8	1.0
Monthly March	700	1.6	4.9	3.6	3.3	0.5	0.7
Monthly April	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly May	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly June	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Air Temperature	n	Min	Max	Mean	median	STDEV	Inter Quartile*
Full Range	20122	-16.8	30.0	5.9	4.8	8.8	13.5
Daily Mean	211	-10.2	19.5	5.9	4.1	8.0	14.7
Seasonal June	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Seasonal Sept	4734	7.7	28.9	16.1	15.0	4.6	7.3
Seasonal Dec	8736	-10.6	30.0	6.4	6.0	6.9	10.4
Seasonal March	8640	-16.8	17.9	-0.8	-0.8	5.0	6.7
Monthly July	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly August	1772	7.7	28.9	16.3	17.4	4.9	7.8
Monthly Sept	2962	7.9	27.3	15.9	15.0	4.4	7.0
Monthly Oct	2880	-0.8	30.0	12.6	12.2	4.9	5.3
Monthly Nov	2976	-2.7	23.5	5.8	5.6	4.9	7.5
Monthly Dec	2880	-10.6	22.0	0.7	0.7	4.8	5.8
Monthly Jan	2976	-16.8	12.3	-2.7	-2.8	4.8	6.8
Monthly Feb	2976	-11.8	14.5	-0.7	-0.6	4.3	5.6
Monthly March	2688	-9.3	17.9	1.3	1.2	4.9	6.9
Monthly April	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly May	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Monthly June	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

*Interquartile distance between the 25th and the 75th percentile of the empirical distribution function of the data within the bin.

Conclusions

In desert environments, springs can provide perennial waters in otherwise dry ecosystems. In the water limited southwestern United States, it is imperative to understand the subsurface controls on the hydrochemistry and recharge mechanisms for spring waters, as well as the surface ecosystems that are reliant on the ground water discharging from the spring. Combining geologic, hydrologic, geochemical and ecologic information, a robust understanding of spring systems can be obtained. This research confirms that many of the historically productive springs in the Zuni Mountains (Baldwin and Anderholm, 1992; Shoemaker, 1971) were dry during the study time. In addition to the complete drying of springs at the time of the inventory, the Sandia Mountains and Mount Taylor are also experiencing reduced flow on major springs (Cienga Spring, Tunnel Spring and San Mateo Spring). These current changes to ground water availability due to drought will be compounded as the climate continues to warm (Brekke, 2011). In addition to water availability, reduction of ground water will also impact water quality (Crossey et al., 2009, Brekke, 2011). This research provides a baseline inventory of spring sites to resource managers. Continuation of this project will provide early indicators of changes to water quality and availability due to drought, climate change and resource practices. These early indicators can help to guide future projects to maintain and improve water resources.

References

Aldrich, M.J., Chapin, C.E., Laughlin, A.W. 1986. Stress history and tectonic development of the Rio Grande Rift, New Mexico. Journal of Geophysical Research. Vol. 91. p. 6199-6211.

Armstrong, A.K., Stamm, R.G., Kottlowski, F.E., Mamet, B.L., Durtro, J.T., Weary, D.J. 1994. Facies and age of the Oso Ridge Member (new), Abo Formation, Zuni Mountains, New Mexico. New Mexico Geology. May. p. 25-30.

Anderson, O.J., Maxwell, C.H., Lucas, S.G. 1998 Geologic Map of Fort Wingate quadrangle, McKinley County, New Mexico. Scale 1:24,000. Published in Anderson, O.J., Maxwell, C.H., Lucas, S.G. 2003 Geology of Fort Wingate Quadrangle, McKinley County, New Mexico. New Mexico Bureau of Geology and Mineral Resources Open-file Report 47. p.16.

Anderson, O.J., Maxwell, C.H., Lucas, S.G. 2003. Geology of Fort Wingate Quadrangle, McKinley County, New Mexico. New Mexico Bureau of Geology and Mineral Resources Open-file Report 47. p.16.

Blanchard, P.J. 2004. Precipitation; ground water age; ground water nitrate concentrations, 1995-2002; and ground water levels, 2002-03 in Eastern Bernalillo County, New Mexico: U.S. Geological Survey Scientific Investigations Report 2004-5189. p. 36.

Brekke, L.D. 2011. Addressing climate change in long-term water resources planning and management. User needs for Improving tools and information. Prepared by and for: U.S. Army Corps of Engineers and U.S. Department of the Interior Bureau of Reclamation.

Carman, S.M. 2004. Zuni Bluehead Sucker (*Catostomus Discobolus yarrowi*) Recovery Plan. Conservation Services Division, New Mexico Department of Game and Fish. Santa Fe. p. 41.

Connell, S.D., Cather, S.M., Ilg, B., Karlstrom, K.E., Menne, B., Picha, M., Andronicus, C., Read, A.S., Bauer, P.W., Johnson, P.S. 1995. Open file geologic map-2. Geology of the Placitas 7.5 minute quadrangle. Scale 1:24,000. New Mexico Bureau of Mines and Minerals.

Connell, S.D., 2011. Preliminary study of the geologic framework of the Colorado Plateau-Middle Rio Grande Basin transition, New Mexico. New Mexico Bureau of Geology, Open-file Report 539. 80 p

Eib, D., Stringer, S., Joseph, S. 2007. Water quality survey summary of the Rio Nutria and Rio Pescado Watersheds above and within Zuni Pueblo. Monitoring and Assessment Section Surface Water Quality Bureau New Mexico Environment Department. p. 158.

Drakos, P., Riesterer, J. 2009. Assessment of springs on Zuni Tribal Land. McKinley and Cibola Counties, New Mexico. Glorieta Report Geoscience prepared for Zuni Pueblo. Santa Fe. p.112.Duff, J. H., and Triska, F. J., 1990. Denitrification in sediments from the hyporheic zone adjacent to a small forested stream. Can. J. Fish Aquatic Science Vol. 47 p. 1140-1147.

Goddard, E.N. 1966. Geologic map and sections of the Zuni Mountains fluorspar district. Valencia County, New Mexico. Scale 1:31,680. Department of the Interior, U.S. Geological Survey.

Grimm, N. B., Chacón, A., Dahm, C.N., Hostetler, S.W., Lind, O.T., Starkweather, P.L., Wurtsbaugh, W.W. 1997. Sensitivity of Aquatic Ecosystems to Climatic and Anthropogenic Changes: The Basin and Range, American Southwest and Mexico.

Haller et al. 2005. Quaternary Faults and Fold Database of the United States.

Hornberger, G.M., J.P. Raffensperger, P.L. Wiberg, K.N. Eshleman. 1998. Elements of Physical Hydrology. Johns Hopkins University Press. Baltimore, MD USA.

Heckert, A.B. 1999. Upper Triassic Tetrapods from the Lucero Uplift, Central New Mexico. . New Mexico Geological Society Guidebook, 50th Field Conference, Albuquerque. P. 311-315.

Heckert, A.B. & Lucas, S.G. 2003. Triassic stratigraphy in the Zuni Mountains, West-Central New Mexico. In New Mexico Geological Society Guidebook, 54th Field Conference, Geology of the Zuni Plateau. p. 245-262.

Hynes, H.B.N. 1983. Ground water and stream ecology. Hydrobiologia. Vol. 100 p. 93-99.

Johnson, P.S., Campbell, A. 2002. Hydrogeology and water resources of the Placitas area, Sandoval County, New Mexico. New Mexico Bureau of Geology and Mineral Resources Open-file Report 469. p. 191.

Karlstrom, K.E., Dallmeyer, R.D., Grambling, J.A. 1997. 40Ar/39Ar evidence for 1.4 Ga regional metamorphism in New Mexico: Implications for thermal evolution of lithosphere in the Southwestern USA. The Journal of Geology, Vol. 105, p. 205-224.

Krainer, K., Lucas, S.G, Kues, B.S.2003. Upper Pennsylvanian strata in the Zuni Mountains, west-central New Mexico. In New Mexico Geological Society Guidebook, 54th Field Conference, Geology of the Zuni Plateau. p. 219-229.

Kues, G.E. 1990. Ground water availability and quality in eastern Bernalillo County and vicinity, central New Mexico: U.S. Geological Survey Water-Resources Investigation Report 89-4127. p. 82.

Loaiciga, H.A. 2003. Climate change and ground water. Annals of the Association of American Geographers. Vol. 93. p. 30-41.

Lucas, S. G., Rowland, J.M., Kues, B.S., Estep, J.W., Wilde, G.L. 1999a. Uppermost Pennsylvanian and Permian stratigraphy and biostratigraphy at Placitas, New Mexico. New Mexico Geological Society Guidebook, 50th Field Conference, Albuquerque. P. 281-292.

Lucas, S.G., Estep, J.W., Anderson, O.J. 1999b. Correlation of Jurassic strata from the Colorado Plateau to the High Plains, across the Rio Grande Rift, North-Central New Mexico. New Mexico Geological Society Guidebook, 50th Field Conference, Albuquerque. P. 317-326.

Mack, G.H. 2003. Lower Permian terrestrial paleo climatic indicators in New Mexico and their comparison to paleoclimate models. In New Mexico Geological Society Guidebook, 54th Field Conference, Geology of the Zuni Plateau. p. 231-240.

McCoy, K.J., Blanchard, P.J., 2008. Precipitation, ground-water hydrology and recharge along the eastern slopes of the Sandia Mountains, Bernalillo County, New Mexico. USGS Scientific Investigations Report 2008-5179. 34 p.

New Mexico Bureau of Geology and Mineral Resources, 2003, Geologic Map of New Mexico, 1:500,000: New Mexico Bureau of Geology and Mineral Resources.

Orr, B.R. 1987. Water resources of the Zuni tribal lands, McKinley and Cibola Counties, New Mexico. U.S. Geological Survey Water-Supply Paper 2227. p. 83.

Palaniappan, M., Gleick, P.H., Allen, L., Cohen, M.J., Christian-Smith, J., Smith, C. 2010. Clearing the Waters. A focus on water quality solutions. A report for the United Nations Environmental Programme. p. 91.

Phillips, F.M., M.A. Walvoord, E.F. Small. 2004. Effects of environmental change on ground water recharge in the desert southwest. In Ground water Recharge in a Desert Environment: The Southwestern United States (Hogan, J.F.; Phillips, F.M.; and Scanlon, B.R; eds.), American Geophysical Union, Water Science and Applications Series, Vol. 9:273-294.

Piper, A.M. 1944. A graphical procedure in the geochemical interpretation of water analyses: Geophysical Union Transactions. Vol. 25. p. 914-923.

Read, A.S., Karlstrom, K.E., Connell, S.D., Kirby, E., Ferguson, C.A., Ilg, B., Osburn, G.R., Van Hart, D., Pazzaglia, F.J., 1995. Open file geologic map-6. Geology of the Sandia Crest 7.5 Minute Quadrangle. Scale 1:24,000. New Mexico Bureau of Mines and Minerals.

Sharp, Z. Principles of Stable Isotope Geochemistry. Pearson Prentice Hall. Upper Saddle River, New Jersey.

Smith, G.A. 1999. The nature of limestone-siliclastic “cycles” in Middle and Upper Pennsylvanian strata, Tejano Canyon, Sandia Mountains, New Mexico. In New Mexico Geological Society Guidebook, 54th Field Conference, Geology of the Zuni Plateau. p. 269-280.

Springer, A.E., L.E. Stevens. 2008. Spheres of discharge of springs. Hydrogeology Journal. Vol. 17:83-93.

Stevens L.E., A.E., Springer. 2004 Conceptual model of spring's ecosystems ecology: Task 1B Final Report CA 1200-99-009. National Parks Service, Cooperative Ecosystem Studies Unit. Northern Arizona University, Flagstaff, Arizona, USA.

Stevens, L.E., Meretsky, V.J., 2008. Springs Ecosystem Ecology and Conservation. In Stevens, L.E., Meretsky, V.J. (Eds). Aridland Springs in North America. Ecology and Conservation. The University of Arizona Press. Tucson, Az.

Stevens, L.E., Springer, A.E., Ledbetter, J.D. 2008. SEAP: An integrated spring's ecosystem assessment protocol. http://springstewardship.orgZektser, S., Loaiciga, H.A., Wolf, J.T. 2005. Environmental impacts of ground water overdraft selected case studies in the southwestern United States. Environmental Geology. Vol. 74. p. 396-404.

Stoeser et al., 2007.Geologic Map Databases for the United States Central States.

Strickland, D., Heizler, M.T., Selverstone, J., Karlstrom, K.E. 2003. Proterozoic evolution of the Zuni Mountains, western New Mexico: Relationship to the Jemez Lineament and implications for a complex cooling history. In New Mexico Geological Society Guidebook, 54th Field Conference, Geology of the Zuni Plateau. p. 109-117.

Traverse, A., Ash, S.R., 1999. Preliminary assessment of the age of the palynoflora of the Red Tanks member, Madera, Formation, Carrizo Arroyo, New Mexico. New Mexico Geological Society Guidebook, 50th Field Conference, Albuquerque. P. 293-296.

USDA-NRCS, USGS, EPA, 2012. State watershed boundary hydrologic unit code at the 08, 10 and 12th level.

USEPA and the USGS. 2005. National Hydrography Dataset.

USFS. 2011. GIS property boundary layer.

USFS. 2011. GIS Constructed _Feature_point, water tank, spring layer.

USGS in cooperation with BGN. 1988. Geographic Names Information System.

Whitmeyer, S.J., Karlstrom, K.E. 2007. Tectonic model for the Proterozoic growth of North America. Geosphere. Vol. 3. p. 22-259

Zektser, S., Loaiciga, H.A., Wolf, J.T. 2005. Environmental impacts of ground water overdraft selected case studies in the southwestern United States. Environmental Geology. Vol. 74. p. 396-404.

Appendices

The following appendices have been submitted separately from this dissertation as supplemental material.

Appendix I. Spring Location Digital Protocol

Appendix II. Cibola Forest Spring Locations from Digital Protocol

Appendix III. Spring Ecosystem Assessment Protocol (SEAP) Form

Appendix IV. Spring Visits and Conditions, Zuni Mountains, Mount Taylor Ranger District, New Mexico

Appendix V. Individual Spring Assessment Pictures and SEAP Form for Zuni Mountains, Mount Taylor Ranger District, New Mexico

Appendix VI. Hydrochemistry for Zuni Mountains Springs, Mount Taylor Ranger District, New Mexico

Appendix VII. Regional Ground Water Hydrochemistry

Appendix VIII. Brennan Spring Continuous Monitoring Data, Zuni Mountains, Mount Taylor Ranger District, New Mexico

Appendix IX. Cottonwood Gulch Spring Continuous Monitoring Data, Zuni Mountains, Mount Taylor Ranger District, New Mexico

Appendix X. Bluewater Creek Spring Continuous Monitoring Data, Zuni Mountains, Mount Taylor Ranger District, New Mexico

Appendix XI. Spring Visits and Conditions, Mount Taylor, Mount Taylor Ranger District, New Mexico

Appendix XII. Individual Spring Assessment Pictures and SEAP Form for Mount Taylor, Mount Taylor Ranger District, New Mexico

Appendix XIII. Hydrochemistry for Mount Taylor Springs, Mount Taylor Ranger District, New Mexico

Appendix XIV. Individual Spring Assessment Pictures and SEAP Form for Sandia Mountains, Sandia Mountain Ranger District, New Mexico

Appendix XV. Spring Visits and Conditions, Sandia Mountain Springs, Sandia Mountain Ranger District, New Mexico

Appendix XVI. Hydrochemistry for Sandia Mountain Springs, Sandia Mountain Ranger District, New Mexico

Appendix XVII. Las Huertas Creek Spring Continuous Monitoring Data, Sandia Mountains, Sandia Mountain Ranger District, New Mexico