

Isotopes, geochemistry, citizen science and local partnerships as tools to build upon a fractured understanding of the hydrology of the Patagonia Mountains

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Executive Summary

This work has been conducted to build upon existing knowledge of the groundwater hydrology of the Patagonia Mountains in southeastern Arizona. It is intended to advance not only the understanding of groundwater movement in the mountains by the scientific community, but also further develop a basic understanding of groundwater movement by residents within the area. This project was planned with residents living within the Sonoita Creek watershed and is intended to address some of the questions and concerns of those residents that were present at the time of the study's genesis. It is in part a traditional scientific project, by means of sample collection, analysis and interpretation; and in part a partnership that attempts to include existing social and political groups in the scientific process by means of inclusion and consideration in the formation, execution and interpretation of the work. The work is not complete; however this report includes some draft findings.

Changing groundwater recharge conditions due to drought and increasing demand of groundwater have residents that live within the boundaries of the Sonoita Creek Watershed in Southeastern Arizona concerned about future groundwater availability and dwindling spring flow. The Patagonia Mountains, which provide nearly a quarter of Sonoita Creek's flow (Ailiang 2005), are composed of fractured bedrock and little is known about how changing recharge conditions and increasing demand will affect spring flow and groundwater levels. This two-phase project addresses these concerns by means of advancing the hydrologic understanding of the mountains and producing action steps for the community.



Figure 1: Surface water in Alum Gulch, fed by springs

The first phase, which will be completed in February of 2020, analyzes isotope ratios and the geochemistry of local springs to better understand groundwater movement within the mountain's fracture system. Initial results indicate most springs discharging water recharged at a high-elevation during the winter months, an evaporation trend in spring water that is consistent with the literature, and hydrologic separation between the mountain block and the adjacent alluvial aquifer south of the Town of Patagonia. These insights have helped develop a more holistic conceptual model of groundwater flow within the Patagonia Mountains. This conceptual model will inform the second phase; which is the creation of a monitoring plan that is within a local citizen science group's resources, capabilities, and level of enthusiasm. Regular collection of data by the group will contribute to future hydrologic studies within the basin and

aid in making management decisions around water use by the Town Council. In addition, the project includes training for well owners and citizens in the watershed to empower citizens to be vigilant about monitoring their water supply through documenting and monitoring the effects of varying precipitation and groundwater use on spring flow and the groundwater table.

Hydrologic Motivations

(1) Assess the potential impact of drought and climate change in the mountain block on the local riparian area and basin aquifers

In the basin and range physiographic province, recent hydrologic studies indicate that mountain block recharge (MBR) or groundwater originating in the mountain block is responsible for between 5-50% of recharge in the adjacent low-lying alluvial basins. (Markovich, et al. 2019). Due to the orographic effect, mountains often receive disproportionately high precipitation, at colder temperatures, than the neighboring lowlands. Resultantly mountains act like a water towers, storing water in the mountain block either as snowpack or in the system of faults and fractures and release it to the basin slowly via MBR or Mountain Front Recharge (MFR). While this relationship between basin recharge and the mountain block is well recognized, it is an ongoing topic of study in hydrology due to a limited hydrogeologic, climatic and other data from the mountain block and mountain front (Markovich, et al. 2019).

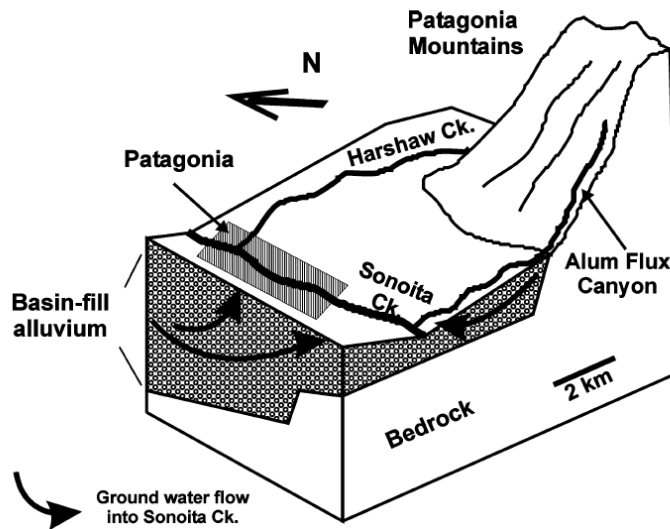


Figure 2: Conceptual Model of Groundwater and Surface Water Flow (Gu et al, 2018)

The Patagonia Mountains are an example of MBR and societal dependence on water recharged from the mountains. Through use of sulfate isotopes, base flow in the Sonoita Creek, which runs through the Town of Patagonia was determined to be composed of approximately 15-25% recharge from the Patagonia mountains. In addition, the Town's municipal water sources pumps groundwater that is partially recharged from the Patagonia Mountains (Gu, et al. 2008). Continued drought, large floods and an increase in demand on groundwater resources has already

decreased water availability in the southwest (Gonzalez, et al. 2018). This trend towards a more arid climate coupled with increased pumping of groundwater by industrial mining activities in the mountain block could directly impact groundwater recharge from the Patagonia Mountains and thus base flow in Sonoita Creek and the aquifer around the Town of Patagonia.

A decline in groundwater levels can have resounding effects on the ecosystem and livability of an area. As groundwater levels decline, discharge from aquifers to streams and creeks decline, stop or even reverse. As a result, streamflow can diminish, and once perennial creeks and streams can disappear underground. Recent modeling of the impact of volumetric streamflow from groundwater declines, show 10 – 50% decline in flow due to groundwater abstraction across the western United States (Condon and Maxwell 2019). As basins around the world are experiencing a decline in surface water flow due to groundwater extraction (de Graaf, et al. 2019, Condon and Maxwell 2019), understanding the connectivity of groundwater in the basin to recharge in the mountains is a key component in understanding future surface water and groundwater availability in riparian areas and basin aquifers.

(1) Advance hydrologic understanding of groundwater movement in fractured bedrock and assess vulnerability of springs in the mountain system.

Because the Patagonia Mountains are composed of primarily fractured rock, groundwater behaves differently than porous medium; flow is channeled through faults and fractures, discharging to the land surface as springs to sustain stream flow. Due to much of groundwater hydrology being focused on groundwater movement in alluvium and the inconsistencies of fracture systems, modeling of fractured bedrock is challenging, and empirical data can resultantly be a useful tool in understanding groundwater flow. However, few wells are drilled in the bedrock due to the high expense associated with bedrock wells and the typically low yield associated with wells in bedrock (Montgomery & Associates, Inc. 1999) and as a result data from springs can provide insight into groundwater movement in this complicated and data-limited environment. Unlike previous studies in the area, this study will produce data primarily from the mountain block system itself which can be used to conceptualize groundwater movement in the bedrock and assess the vulnerability of springs within the mountain system. Additionally, previous studies have seen that groundwater chemistry and isotopic signatures at the mountain front often are similar to the chemistry and isotopic signature of groundwater produced at springs in the mountain system (Markovich, et al. 2019). Resultantly, the productivity of the springs has been observed to be integral to recharge rate of the adjacent alluvial aquifer.

Societal Motivation

Residents within the Sonoita Creek Watershed are highly dependent upon groundwater. The Town of Patagonia's municipal water source draws from the local basin fill aquifer. The health of the Sonoita Creek riparian area, and alluvial aquifer that maintains the creeks base flow, is integral to the work of over 30 stakeholder groups in the area (NextGen Engineering 2017, Ailiang 2005). Ranches within the watershed depend on springs for water for their cattle. Residents draw water from alluvial aquifers within the mountain system. Changing conditions within the watershed, including extended drought and the return of mining operations to the area within the last decade have sparked concern among these groups about the future availability of groundwater in the basin. However, The Sonoita Creek Basin, including the Town of Patagonia is not located within an Arizona Department of Water Resources (ADWR) Active Management Area (AMA) and thus well owners and industry do not have to operate under the laws of the 1981 Groundwater Management Act (GMA). Resultantly, there are very few laws that apply to groundwater extraction in the Patagonia Area. In the winter of 2014, the Town Manager of Patagonia issued a "water alert" on the front page of the Town's local paper *The Patagonia Regional Times* due to the declining groundwater table (Reibslager 2014). The water table has since rebounded but residents living within the area, having limited legal protection of their groundwater resources, have organized to better understand and manage their groundwater resources.

Often "environmental issues have been treated as the purview of experts, [even though,] local people know best what their problems are and how to solve them" (Austin 2004). Resultantly a key motivation of this study is to engage and educate residents within the watershed to increase the project's utility. As a result, a partnership with the a local water advisory committee, the Flood and Flow Committee (F&F Committee) and a local citizen science group, Patagonia Area Water Study (PAWS) was established, with the hope of including the groups in the research and passing on any future monitoring or inquiry. A partnership with the F&F Committee was also established to help facilitate meetings and trainings. Ultimately, the findings of this research will be used by these groups to better understand and manage groundwater resource in the Sonoita Creek basin.

Stakeholder Groups

The Town of Patagonia's Flood and Flow Committee

The Town of Patagonia's Flood and Flow Committee, formed in 2015, makes recommendations to the Patagonia Town Council with respect to best practices within its jurisdiction to manage erosion; to enhance water flow, and to create optimal flood mitigation; and, to promote the long-

term health of the riparian corridor. The Committee promotes the interests of the above mentioned 30 stakeholder groups within the Sonoita Creek Watershed that are intimately tied to and dependent upon the water in the creeks and aquifers. With this mission in mind, the F&F Committee depends on data and analysis to make management decisions within the watershed. For that reason, these stakeholders have a keen interest in how climate change and mining activity will affect water quantity and quality within the basin. Stakeholders are actively working to compile existing data and characterize water resource vulnerability due to these changed conditions, independent of the reports provided by the mining company. A partnership with the F&F Committee was also established to help propagate information and facilitate meetings and trainings.

Patagonia Area Water Study

A citizen science group, Patagonia Arizona Water Study (PAWS), was formed in 2018 to advance the local contribution to understanding the watershed. The group is working with the Arizona Department of Environmental Quality (ADEQ) to bolster the existing database of surface water quality and create a “pre-mining” data set for the watershed. In reality, historic mining and drought conditions has already impacted the Sonoita Creek watershed with reported break-outs of acid mine drainage following intense precipitation events (Dean 1982). However, continued drought and pumping of groundwater from deep wells within the mountain block by mining companies could further impact water availability in the watershed. Resultantly, PAWS plans to expand their efforts to monitor springs that may be vulnerable to dewatering due to drought or decrease in supply due to pumping by the mine. A key motivation of this study is to guide PAWS in selecting vulnerable springs and provide background for potential drivers for the drying up of selected springs. The impact of drying springs would immediately impact wildlife, ranchers, and farmers that work and live in the Patagonia Mountains, could decrease flow in ephemeral and perennial streams that originate as springs, and could impact groundwater recharge rates in the basin (Markovich, et al. 2019).



Figure 3: Red Mountain Spring

Objectives

Hydrologic Objectives

- (1) evaluate the elevation and seasonality of sampled groundwater
- (2) conceptualize groundwater flow path and travel times
- (3) assess hydrologic connectivity of aquifers within the mountain system,
- (4) determine connectivity of groundwater recharge in the Mountains to alluvial aquifers in the Sonoita Creek basin, specifically around the Town of Patagonia.
- (5) identify which springs are most vulnerable to drying up due to groundwater extraction and drought conditions.

Societal Objectives

- (1) educational outreach and dissemination of findings within the Sonoita Creek watershed
- (2) improve public understanding of groundwater movement in the mountains
- (3) provide guidance for further studies, monitoring and management

Project Design and Methodology

The project was broken into two stages. The first stage was the development of a conceptual model of the basin by means of data collection and analysis. At the time of writing this report, the first stage is nearly complete, and it will inform the second stage. The second stage is informing, and training concerned citizens on how to be vigilant well owners and how to monitor their groundwater supply.

Stage one, the development of a conceptual model, began a thorough review of data available in the study area and seeking guidance from United States Geological Survey researchers, and Dr. Chris Eastoe (retired from University of Arizona), and other experts who have done research in the area.

Following this guidance, a thorough review of maps and databases resulted in sample sites to complement existing data and reports. Samples were collected by the author and with the help of PAWS members from selected springs, mines and wells for analysis. Tritium and Oxygen-18 isotope ratios were measured to determine the age of the water since initial recharge, and elevation and seasonality of recharge. This analysis allows for characterization of spring vulnerability to variations in recharge rates as well as groundwater extraction. If the waters



Figure 4: PAWS member working in the field

contain no detectable tritium, carbon-14 will be analyzed to constrain older groundwater ages. A subset of springs and wells was selected for sampling and analysis of RCRA metals, boron, selenium and hardness. Information on lab techniques and methods can be obtained by directly contacting the author.



Figure 5: PAWS member working in the field

Initial review of the Wells55 data from the ADWR identified a deep limestone aquifer in the area. Further analysis of geochemical data will provide insight into whether the groundwater sustaining the springs is from this limestone or from the volcanic. The age and residence time of sampled water as well as geochemical analysis will provide insight into the fracture system in the mountains and generate data on the potential impact of deep groundwater pumping in the area

With a conceptual understanding of groundwater movement within the aquifer(s), trainings can commence, and a monitoring plan can be made. A well owner training is planned for February 29, 2020 and an overview of findings and next steps is planned to take place during Patagonia's EarthFest in April, 2020.



Field work

Hydrologic Insights

At the time of writing this report, analysis of isotopes was nearly complete, however analysis of the chemistry of water samples was pending. Data collected by the author was complimented by data from previously published reports (Ailiang 2005, Montgomery & Associates, Inc. 1999, Wanty, et al. 2001) in the area to make more robust conclusions. Resultantly, many of the stated objectives cannot be confidently addressed. Trends in isotopic data lead to a select few tentative conclusions that will be further supported by geochemical results.

(1) Most spring water from the Patagonia Mountains appears to be a mix of both modern (post 1960's) and pre-modern (post 1960s), leaning towards higher concentration of pre-modern water, with the exception of a Red Mountain Spring appears to contain just pre-modern water. Resultantly, springs in the mountains, if hydrologically connected to the aquifer that that are increase higher pumping rates, may not recover from the discharge of that water, depending on the rebound level of the water table. Red Mountain Spring is the most vulnerable to drying up as non-detect tritium indicates its water source is relatively old water. Carbon 14 analysis on the water from Red Mountain Spring is pending, which will provide further insight into the age of the water at the spring.

(2) Groundwater at the exit of Alum Gulch, in the alluvial valley, is isotopically distinct from groundwater in the mountain block of the Patagonia Mountains. The large fault system separating the mountains from the alluvium is likely an obstruction to flow. High water temperatures, artesian activity, as well as predicted old age of the water on the other side of the fault (within the alluvium) indicate high likelihood of water being forced downwards, and then resurfacing on the other side of the fault. Further investigation of this phenomenon is recommended. However, homeowners in this area, likely will not feel immediate effects of groundwater pumping and changing recharge conditions in the mountain block.

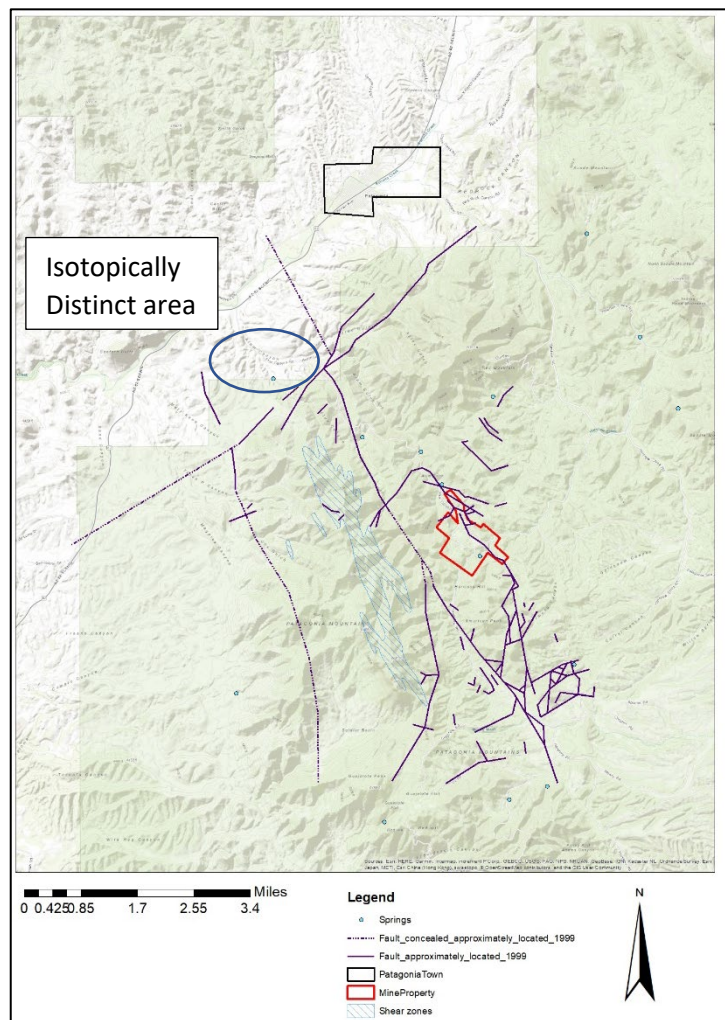


Figure 6: Map of Study Site

- (3) Springs at higher elevations, interestingly, plot on an evaporation trend. Unintuitively, this data, however limited, indicates that high elevation springs are more vulnerable to a more arid climate. Additional data would support this theory, however previous studies indicate that evaporation of surface water is common both in summer and winter as seen by analysis of stable water isotopes that fall to the right of the Global Meteoric Water Line (GMWL) in neighboring mountain systems (Eastoe and Wright 2019, Gray 2018).
- (4) No obvious trend is seen in groundwater along the large faults in the area, tentatively suspending the hypothesis that these faults are acting as high conduits of groundwater.

Discussion on Results, Use-Inspired Research, Outreach and Lessons Learned

As mentioned in the introduction, this work was put together to address the concerns of citizens adapting to new conditions in their watershed. The goal of the work was to produce results based on hydrologic principals and for those concerned citizens to use those results for informed decision making on management of groundwater in the watershed. Paralleling this work, I have plunged into literature and academic discourse on water policy, and I anticipate a limited number of viable action steps for the citizens in the Sonoita Creek Watershed to take to legally manage groundwater pumping in their region. While further collection of data is beneficial for future studies and better understanding of groundwater in the area, the legal framework around groundwater in many rural areas of Arizona (outside of Active Management Areas) is so weak that there are limited options for these concerned citizens. This type of work (hydrologic investigation) is important, but a key takeaway from this process is that a legal framework needs to be in place for citizens to protect their water resources for such work to be truly implementable. That legal framework currently does not exist.



Figure 7: Presentation during Patagonia's EarthFest

The level of complexity of the mountain system was a driver in approaching the hydrologic investigation using the method described above. Collection of empirical data would, ideally, reflect the level of complexity of the mountains however provide some clues into the plumbing of the mountains. With our limited dataset, at the time of writing this report, that same complexity makes it hard to draw any concrete conclusions. Our hope is that with additional data, and more time spent on analysis more concrete conclusions can be made.

I have been surprised and pleased by the interest of citizens in the study area in their water resources. Presentations, thus far, have had every seat filled and the curiosity from the community has appeared to be genuine. Because of this level of interest in answers, I found relationships with stakeholders to naturally develop, as we each were working towards answers. PAWS, however, is currently “on pause” and our hope is that the group will resume work when members of the group have found new motivation to continue.

With regards to the public understanding of the hydrology of the area, basic principles need to be communicated and a further education is needed. It is easy for scientists to get lost in the details of the work, when disseminating seemingly simple concepts, while not the novel component of their work, is of utmost importance.

The original goals of this project and the actual outcomes are not the same. While the general approach has stayed consistent throughout, relationships and partnerships have changed, or partner groups have lost membership or motivation. Adapting and reorienting has been key in completing the project and having some “use” at the end of a “use-inspired” project/partnership.

Next Steps

Work remains to complete this project. Lab reports have yet to be received that are required to address the mentioned hydrologic objectives. Presentations and trainings are planned for the spring in the Town of Patagonia. A formal monitoring plan and recommendations for the F&F Committee and PAWS has yet to be formulated. A thesis has to be completed and defended. Upon finishing this project, my hope is that another student will pick up this work and continue the partnerships that have been established. Working with the mentioned groups, in this beautiful part of Arizona, has been rewarding and further work and creativity is needed in the area.

Final Comments

Due to the incompleteness of data at the time of writing this report, figures and tables with data from labs was not included in this report. If the reader is interested in seeing tables, plots, and figures, please email the author at the email address listed below and they can be made available.

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