BONANZA EN LOS ANDES – FINAL REPORT

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ABSTRACT

Zurite, Perú (3400 m.a.s.l.) is a rural village located in the southern Peruvian Andes. The village is dependent on agriculture and crops are irrigated in the seasonally dry environment with water sourced from the Ramuschaka River. In 2018, over 100 families in Zurite were without adequate irrigation canals, which negatively affected their livelihood. The headwaters of the Ramuschaka River are over 1000 m above Zurite in the *puna* biome. *Puna* grasslands are found in the Andes Mountains from central Perú to central Chile and Argentina. Despite being a significant water source to headwater catchments that drain to villages and cities throughout this region, there are very few hydrologic studies of *puna* grasslands. We completed a two-year project funded by Geoscientists Without Borders (GWB) that leveraged undergraduate and graduate geology and engineering students and community members from Zurite to design and construct 1.3 km of irrigation canals and used novel geophysical techniques to characterize the hydrology of the *puna* grasslands in the Upper Ramuschaka Watershed (URW). We found that the URW is underlain by Eocene carbonates, sandstones, and mudstones, and is intruded by an Oligocene quartz monzodiorite. Of 786 mm of annual precipitation falling in the URW, 657 mm runs off via the Ramuschaka River, 20% of which occurs over the dry season (May-October). We identified b*ofedales*, or peat forming wetlands, as important hydrologic features that store large amounts of water, sustain dry season runoff in streams and are therefore vital to downstream irrigation supply. Financing for the 1.3 km irrigation canal project was shared by the Municipality of Zurite, the Farmer's Union, local water users, and GWB. The project was completed in March 2020, and now benefits over 100 families. The project involved 29 students from Perú and the United States. Students guided research, performed field work and data analyses, and presented their work at local and international conferences. This project model successfully merged students' major learning objectives, cultural exchange and scientific research. Future work will combine geologic maps with geophysical measurements to quantify the total moisture stored and released from *bofedales* and explore the presence of *bofedales* within the *puna* biome.

BACKGROUND INFORMATION

The village of Zurite (population 4,000) is located on the edge of the Anta Plain, approximately 30 km northwest of Cusco (Figure 1). The town is located at approximately 3,400 meters above sea level (m.a.s.l.), and is built across alluvial fans that drain peaks rising to greater than 4,500 m.a.s.l. Over 70 % of the villagers in Zurite devote themselves entirely to agriculture and there is a rich history of agriculture and animal husbandry. Zurite receives approximately 700 mm of annual precipitation, the vast majority falling in the wet, warm summer months of October to May. Little to no precipitation falls over the cold, dry winter. Water for irrigation is primarily sourced from the Upper Ramuschaka Watershed (URW, 2.14 km^2, seen in Figure 2) and the extreme relief provides ample energy to flood irrigate agricultural plots via gravity fed canals. Figure 3 shows average monthly rainfall (blue line) and irrigation needs for different crops cultivated in Zurite. Whereas irrigation water is needed year-round, less irrigation water is needed to grow maize during the summer when rainfall is plentiful, and more water is required to irrigate dry season crops such as fava beans, onions and quinoa. In the fall of 2018, we identified three needs for our GWB proposal that guided the community, educational, and research objectives of our project.

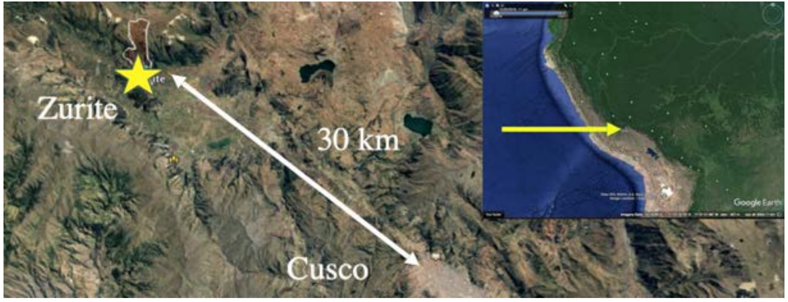

Figure 1: star indicates location of Zurite, approximately 30 km to the Northwest of Cusco. Yellow arrow shows the location of Zurite in the southern Peruvian Andes.

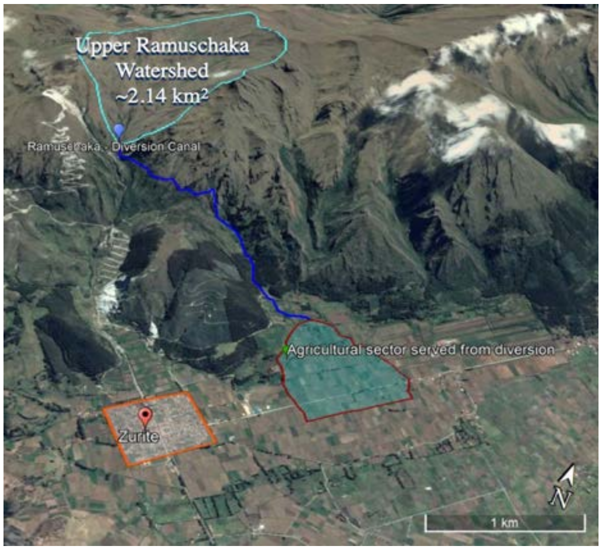

Figure 2: Oblique GoogleEarth image of Zurite, the agricultural sector where irrigation canals were built, and the Upper Ramuschaka Watershed URW). Zurite is located at approximately 3400 m.a.s.l. Over 1 km of relief exists between Zurite and the upper parts of the URW.

1. The community of Zurite had an immediate need for irrigation canals. Over 100 families were without a reliable and efficient canal network to irrigate their agricultural plots. The community also had a longer term need to quantify its water resources for effective management and equitable allocation.

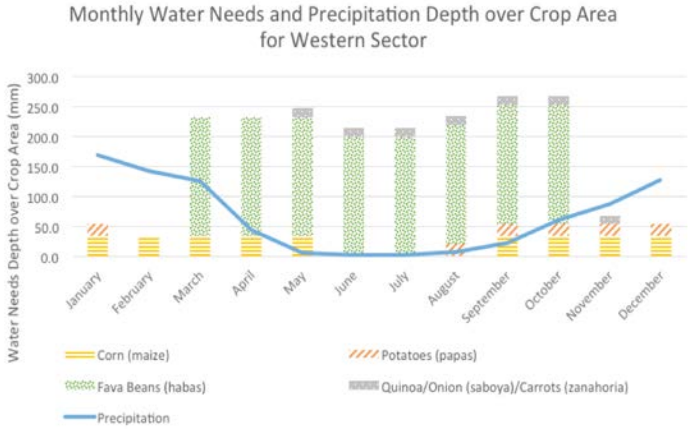

Figure 3: Mean monthly precipitation in Zurite shown with blue line. Bars show monthly irrigation needs of various crops in addition to precipitation. Data are plotted in mm. Whereas crops are irrigated year-round, irrigation needs are most acute over the dry season (March/April – October). Data compiled and figure constructed by Virgil, 2019 Zurite research class.

2. Environmental problems require collaboration across disciplines and across national frontiers. Collectively, we need scientists trained in multidisciplinary communication and multicultural collaborations. Furthermore, there were very limited international travel or research opportunities for students in the College of Natural Resources and Sciences at Humboldt State University.

3. *Puna* grasslands, a biome that exists above the tree line and below the permanent snow line along the spine of the southern Andes, are home to many headwater streams that supply water to downstream communities small and large. We identified an opportunity to explore the geohydrology of these understudied biomes using multiple methods (including geophysical techniques). Specifically, our objective was to determine where water was stored in the landscape and quantify seasonal dynamics in storage and water yield. This information would comprise a novel contribution to the scientific community and could inform land management decisions in Zurite and throughout the region.

Zurite is located at the north end of the broad Anta plain. The Ancahuasi Fault, a large range front fault, has caused over 1000 m of relief between Zurite and the headwaters of the Ramuschaka above (Figure 4). Zurite's drinking water is sourced from several springs along the Ancahuasi Fault. These springs also contribute smaller amounts of water to the lower Ramuschaka and thus augment irrigation supply. The region is composed of fractured and faulted Eocene to Oligocene sandstones, conglomerates, mudstones, limestones, and quartzites. The URW contains a large quartz monzodiorite intrusive complex along the western margin of the watershed, which is likely part of the Yauri Andahuaylas Batholith (42-30 Ma) (geologic mapping, Bonhomme and Carlier, 1988; Carlier et al., 1989; Carlier and Carlotto, 1990; Carlotto et al., 1999, Carlotto, 2010). Contact metamorphism is seen in alteration to the limestone and mudstone along a fault that forms the boundary with the quartz

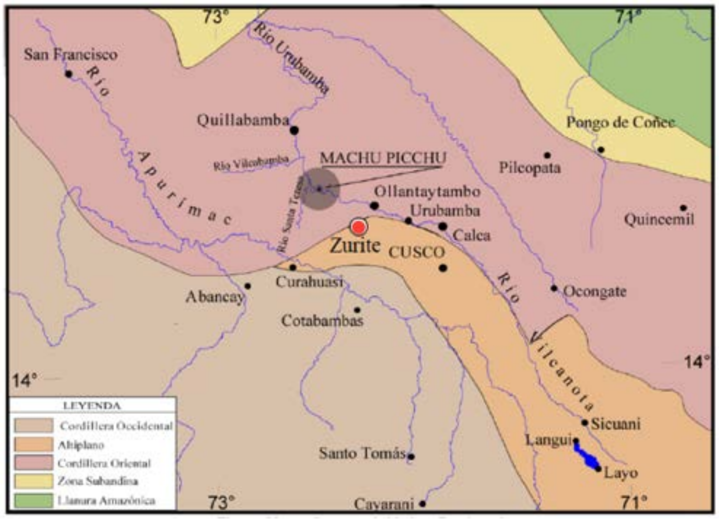

Figure 4: Regional geologic map. Location of Zurite is shown with red dot, straddling a major tectonic boundary between the Cordillera Oriental and Altiplano. Map from *Carlotto,* 2010.

monzodiorite in the URW. Heavy rains in January 2010 caused three separate failures along this fault and produced catastrophic mudslides that damaged much of Zurite, including the cathedral on the main plaza.

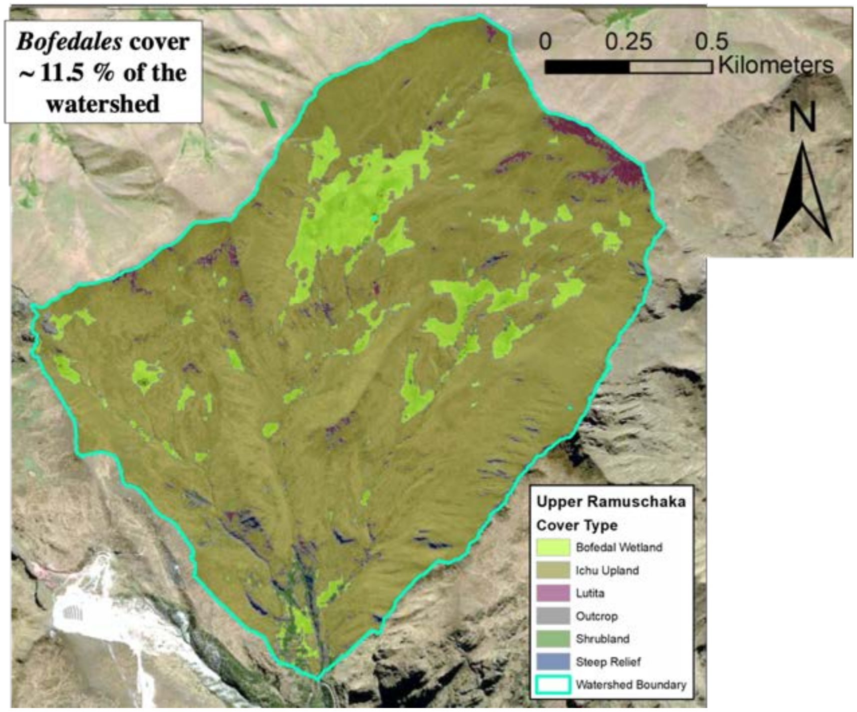

Figure 5: Landcover classification map for the 2.14 km^2 URW. *Bofedales,* shown here in bright green, cover 11.5 % of the URW. Map created by Wunderlich (2019), AGU Poster Presentation.

Geophysical Need: Quantifying Water Storage and Identifying where Water is Stored

Three geophysical methods were used to explore the water storing capacities of the URW's upper hillslopes and low gradient *bofedales.* Previous work has suggested that *bofedales* may be important regulators of dry season runoff (Célleri and Feyen, 2009; Buytaert et al., 2006). *Bofedales* comprise 11.5 % of the URW (Figure 5) and drain to streams that form a deeply incised network. The varied geomorphology and landcover of the URW (Figures 5 and 6) motivated us to ask: How much water does this watershed store? How is stored water released through the dry season? And, which parts of the landscape are the most hydrologically important? In 2018 and 2019 we ran approximately 2.2 km of seismic refraction lines. These data constrain the thickness of fractured weathered bedrock and the depth to the lower boundary of seasonal fluxes in groundwater flow, a low porosity layer of fresh bedrock often referred to as Z_b (Rempe and Dietrich, 2014). Seismic data are used to constrain our hydrologic model and to estimate the thickness of the *bofedal* water storage reservoir. In 2019 we also conducted 1.2 km of electrical resistivity tomography (ERT) across the upper and lower *bofedales*. ERT's sensitivity to saturated conditions allows us to define the saturated portion of the *bofedal* and determine the hydrologic relationship between the low gradient *bofedales* and the steeper uplands. In 2019 we drilled two boreholes: to 22 m on a ridge top and to 15 m through the lower *bofedal*. We ran 39 vertical

Figure 6: Photograph of URW showing steep grassy uplands (Puna -grasslands) and low gradient local basins (peat forming *bofedales*). The sandstone ridgeline in the distance is approximately 1 km away.

m of nuclear magnetic resonance (NMR) data in the boreholes as well as in holes augered through the upper and lower *bofedales* to depths of over 2 m. NMR data reveals volumetric water content in the surrounding media and can be used to estimate porosity in saturated porous media. We combine NMR data with ERT data, and direct observations to define the depth, porosity and dynamic water storage of the *bofedales*. Collectively, the geophysical data help us highlight the hydrologic importance of the *bofedales*, quantify water storage in the *bofedales,* inform our understanding of the history of glaciation and peat accumulation, and guide the development of a hydrologic model.

FIELD AND CLASSROOM STUDIES

We designed a year-long educational model centered on four weeks of field research in Zurite and the Ramuschaka Watershed. In the spring semesters, PI Oshun and co-PI Lang taught a preparatory class. The class cultivated communication and established a common knowledge base between engineers and geologists. We introduced students to independent research, guided students in literature reviews and hypothesis development, and explored existing data sets. We explored cultural practices related to water and water management and reviewed existing regional and local water infrastructure projects. We supported students in improving essential skills such as science communication, team building, and the Spanish language. By the end of the course, students were mentally and emotionally prepared to travel to and spend a month living in rural Perú.

We conducted field campaigns in June-July 2018 and June 2019. In 2018, PI Oshun, Co-PI Lang, collaborator Keating, 9 students from Humboldt State University (HSU), and one student from the Universidad Nacional Mayor de San Marcos in Lima conducted field work in and above Zurite. In 2019, Oshun, Co-PI Lang, collaborator Keating, 11 students from HSU, one student from Temple University, one student from the University of Texas Austin, and 5 students from the Universidad Nacional San Antonio Abad de Cusco traveled to Zurite. For each field campaign we stayed with host families in Zurite and all of our meals were cooked by Gladis Quispe in the house of Gladis and Tomás.

The high altitude leads to dry and cold conditions that can make life uncomfortable. We managed difficult conditions by pacing ourselves, with frequent check-ins and by eating large meals. Students from the U.S. worked alongside Peruvian students.

In the lower Ramuschaka and in Zurite, engineers surveyed the existing canal infrastructure and the proposed pathway for the new irrigation canals, and completed hydraulic analyses of the canal systems. PI Oshun spent portions of each campaign meeting with local leaders to negotiate contributions to the canal project and gave two informational presentations to the community. In 2019, a film crew from HSU conducted interviews of student participants and community members. Part of the community interviews was also gathering input to understand the priorities for future community project needs. On the weekends, we visited local sites to better understand Inca culture and observe the feats of Incan engineering.

In the URW, U.S. and Peruvian geologists mapped the geology of the Ramuschaka, focusing on the URW. We installed tipping bucket rain gages and pressure gages in streams and in monitoring wells (Onset Corp.). In 2019, we began taking regular measurements of stream discharge using the salt dissolution technique. We continue to take monthly-bimonthly measurements with the help of a Peruvian geologist, Wilner Bandera. These data will be used to construct stage-discharge rating curves where our pressure transducer stage monitoring equipment is installed and will be used to determine which portions of the URW yield proportionally more water through the dry season. We installed sensors to measure volumetric moisture content and water potential in the soil and saprolite beneath the grasslands and native *queuña* forest.

In 2018, we conducted seismic refraction lines across the upper and lower *bofedales* (Figure 7). In 2019, we expanded our seismic refraction survey, and conducted ERT and NMR surveys. In 2019, Peruvian geologists drilled two monitoring wells. In 2019, we conducted a complete survey of the URW with ground control points to produce a DEM.

In the fall semesters following our two summer field campaigns, students enrolled in independent research courses. PI Oshun and Co-PI Lang guided students through data analysis, interpretation, figure development, abstract writing, and paper writing. Students produced written reports and gave presentations to the class. In December of 2018, one student presented the initial results of the seismic refraction surveys at the Fall AGU Conference in Washington, D.C (Helprin et al., 2018). In December 2019, two students presented interpretations of geophysical data (Davis and Murray et al., 2019) and one student presented the results of hydrologic measurements (Wunderlich et al., 2019) at the Fall AGU Conference in San Francisco, CA. PI Oshun also gave oral presentations with many student co-authors at AGU (2018 in Washington, D.C. and 2019 in San Francisco, CA) as well as a presentation at the SEG Annual Fall Conference (2019, San Antonio).

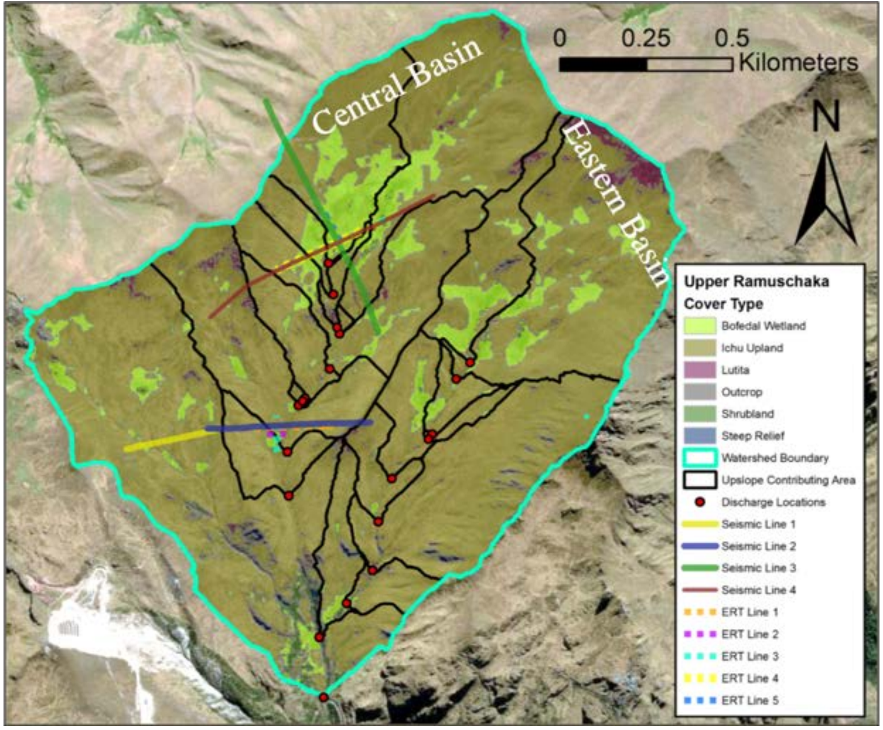

Figure 7: URW showing landscape classifications, the location of seismic surveys from 2018 and 2019, and ERT surveys from 2019. Red dots indicate locations of monthly discharge measurements and black lines outline sub-watersheds draining to the discharge measurement points.

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Geologic Map

Six geology students developed geologic field maps that we have compiled to produce a composite geologic map. Our geologic map is layered over a drone derived 3D rendering of the URW (Figure 8). The vertical scale is exaggerated by 1.5 to accentuate geomorphic features bordering the *bofedales*. Total relief from the bottom to the top of the URW is greater than 500 m. Eocene sedimentary units include limestone, sandstone, and mudstone. The limestone unit along the western URW is a light to dark grey fine-grained massive cliff forming unit. It is highly fractured in outcrop and karsted. The sandstone unit is a hard cliff forming fine grained to conglomerate unit with bedding of medium thickness to massive. In the central part of the watershed, this unit is exposed as a sugary white crystalline quartzite. The mudstone is a sheared weak, and abundantly fractured slope forming unit. It is friable in outcrop and colored red to green/grey to beige/brown. An intrusive of Oligocene age outcrops in the western URW. Mapped previously as a quartz monzodiorite (Carlotto et al., 2010), this unit is fine to medium grained, and light to medium grey. Phenocrysts include hornblende, biotite, quartz, alkali feldspar, and secondary epidote. Outcrops are heavily weathered to saprolite. Quaternary deposits of peat up to 1.7 m thick underlain by subangular to subrounded clay rich colluvium form low gradient *bofedales.*

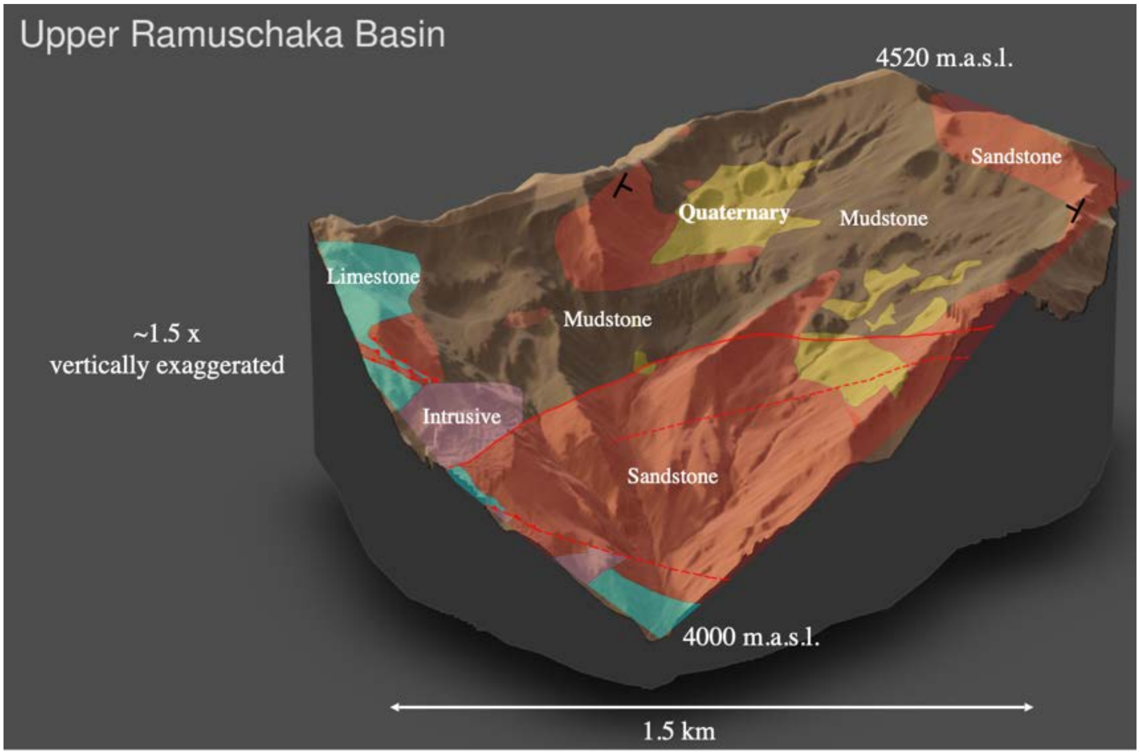

Figure 8: Geologic map draped over 3D rendering of the URW. 3D rendering was created from drone derived aerial imagery. Imagery collected by Smith in June 2019. Data processed and DEM created by Wunderlich, Fall 2019 Zurite research class. 3D rendering created by Davis, Fall 2019 Zurite research class. Geologic maps compiled by Oshun and projected here.

How much water is there? Water Balance

Figure 9 shows the rainfall – runoff response in the URW. We combine measurements of annual rainfall collected at the tipping bucket rain gage with nearby measurements of streamflow and seasonal changes in soil and saprolite moisture to calculate a water balance for the 2019 calendar year. We have runoff data and a rating curve to calculate discharge from July 2018 - January 2020, soil and saprolite moisture sensors were only installed in January 2019. At the end of this year, we will calculate water budgets based on the water year in Zurite (September-August). The results of the 2019 water budget are shown in Table 1. Most water (84%) leaves the watershed as runoff. Evapotranspiration accounts for 16% of annual precipitation. A small amount (4 mm) is not accounted for in our water budget and may represent inter annual storage, deep drainage, or error in our calculations. Dry season runoff (calculated over May-October and shaded orange in Figure 9) accounts for only 20% of total runoff, highlighting the limited dry season water resources in the Ramuschaka Watershed.

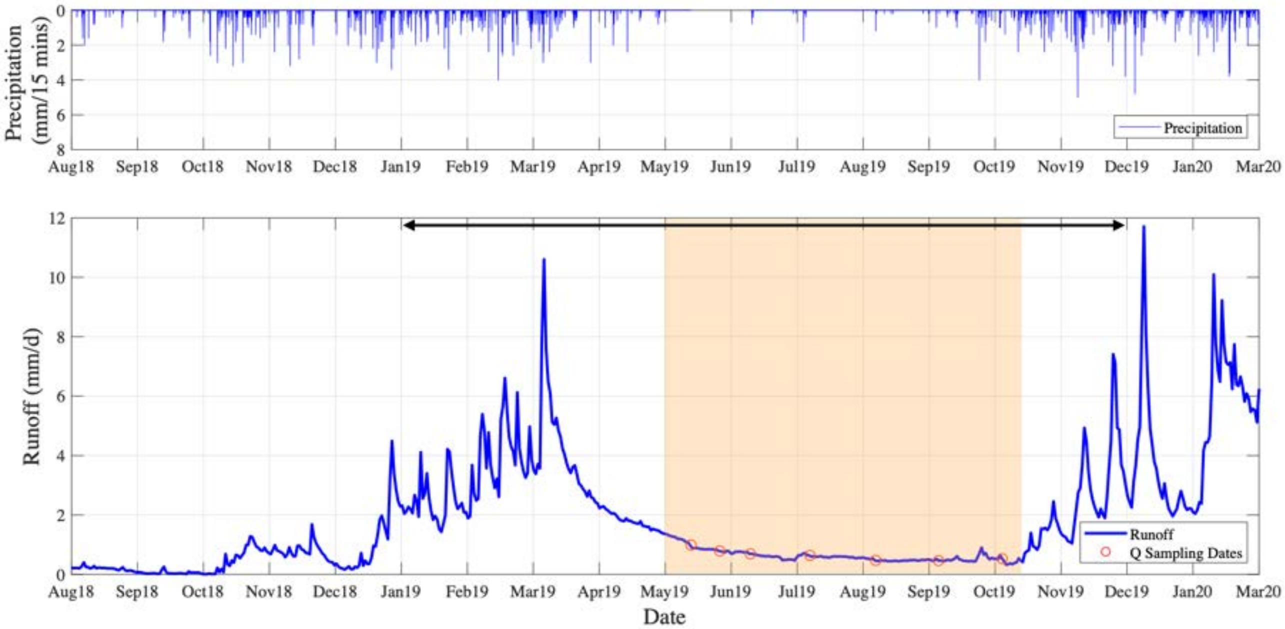

Figure 9: Rainfall – runoff response in the URW. Upper plot shows precipitation (mm/15 min) recorded via tipping bucket rain gage in the URW. Bottom plot shows runoff (mm/d) in the Central Basin of the URW. Black arrow shows span over which water balance was calculated (2019). Shaded area spans dry season. Open red circles indicate when discharge measurements were made up the Central and Eastern Basins of the URW.

Table 1: Water balance for 2019 (mm)

Precipitation	786
Evapotranspiration	125
Runoff	657
Storage/deep drainage	4
Dry season runoff	132

Where does the water come from? Runoff and the importance of bofedales

From May 2019 through March 2020 we took monthly measurements of stream discharge at locations up the Central and Eastern Basin of the URW. This effort began with PI Oshun and Wilner Bandera and has been continued by Wilner Bandera. The dates we took dry season discharge measurements in the nested sub-watersheds are represented as red circles in Figure 9. The drainage area of sub-watersheds decreases upstream. We use the land classification map to determine the percent of every sub-watershed covered in *bofedal* (Figure 7). We hypothesized that dry season flow in streams would be disproportionately fed from water draining *bofedales.* Runoff q, is discharge in the stream scaled by drainage area, $\frac{Q}{A}$. If every part of the landscape contributed water equally to discharge in the stream, runoff, q would remain constant up the watershed. An increase in runoff would indicate higher water yields from a given sub-watershed.

Figure 10 shows the relationship between the percent of a sub-watershed covered in *bofedal* and runoff from the sub-watershed. Symbols indicate data taken from the Central and Eastern Basins and color indicates progession into the dry season from May to October. As the dry season progresses, discharge in the stream and runoff decline. There is a consistent positive relationship between the percent of a sub-watershed covered in *bofedal* and runoff through the dry season. Water yield is not constant throughout the URW. Instead, our results show that *bofedales* supply more water to streams than hillslopes, and are thus of critical importance to sustained dry season flows in the Ramuschaka.

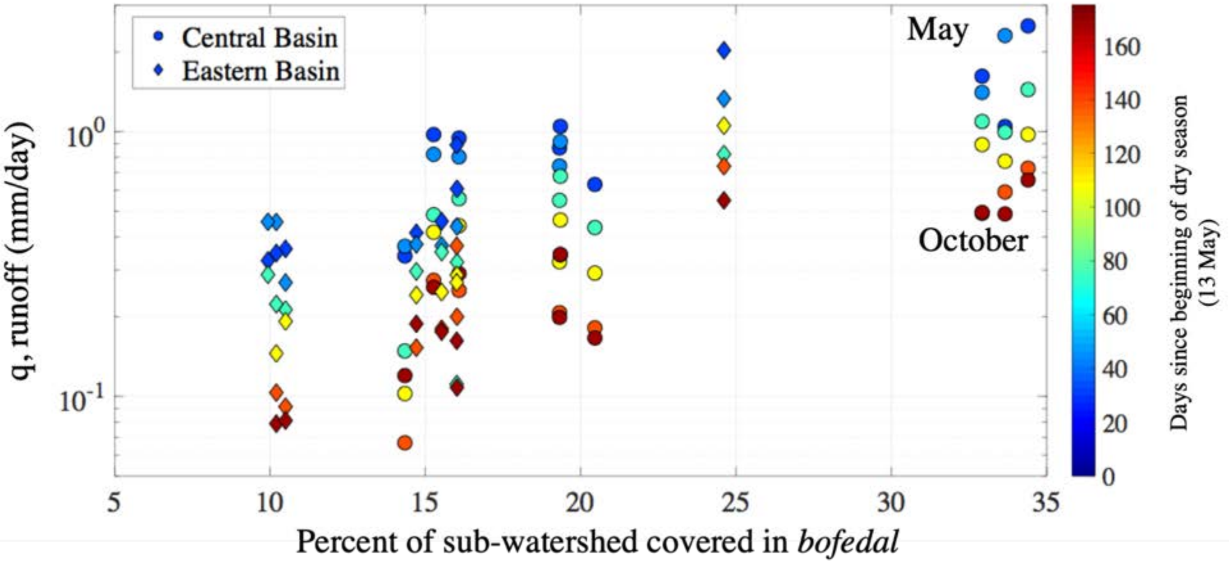

Figure 10: Relationship between the percentage of sub-watershed drainage area covered in *bofedal* and runoff from that sub-watershed. Symbols indicate measurement location in the Central or Eastern Basin of the URW. Symbols are colored to show decrease in runoff in the URW from the beginning of the dry season (May) to the end of the dry season (October).

Hydrologic connection between the hillslope and bofedal

The results of seismic refraction lines 3 and 4 (Figure 11) show thick low velocity layers below both the quartzite and mudstone ridges. Here, we interpret that the underlying bedrock is weathered and fractured to approximately 50 m. We observe high velocity layers closer to the surface beneath the *bofedales.* The data inform our understanding of subsurface hydrologic flow paths. Precipitation falling on the ridges drains through a deeply fractured subsurface. At depth, infiltrating water encounters a low porosity, high seismic velocity layer (3.2 km/s) and drains along this boundary. This low porosity boundary is closer to the surface beneath the *bofedal*, which forces subsurface water draining through surrounding hillslopes to the surface. The presence of saturated or near saturated conditions allows for the accumulation of peat and the growth of the *bofedal.*

Bofedales – dynamic storage capacity

Bofedales cover 11.5 % of the URW, and sub-watersheds with higher percentage *bofedal* land cover yield more water. How much water is stored and released from bofedales? We augered holes in transects across multiple *bofedales* to determine the thickness of peat and underlying clay. The peat layer increases in thickness from the margins of the *bofedal,* reaching thickness of 1.7 m. We were not able to auger through the clay layer in the center of the *bofedal.* Geophysical surveys and drilling results indicate that clay deposits are at least several meters thick, and perhaps up to 7 m.

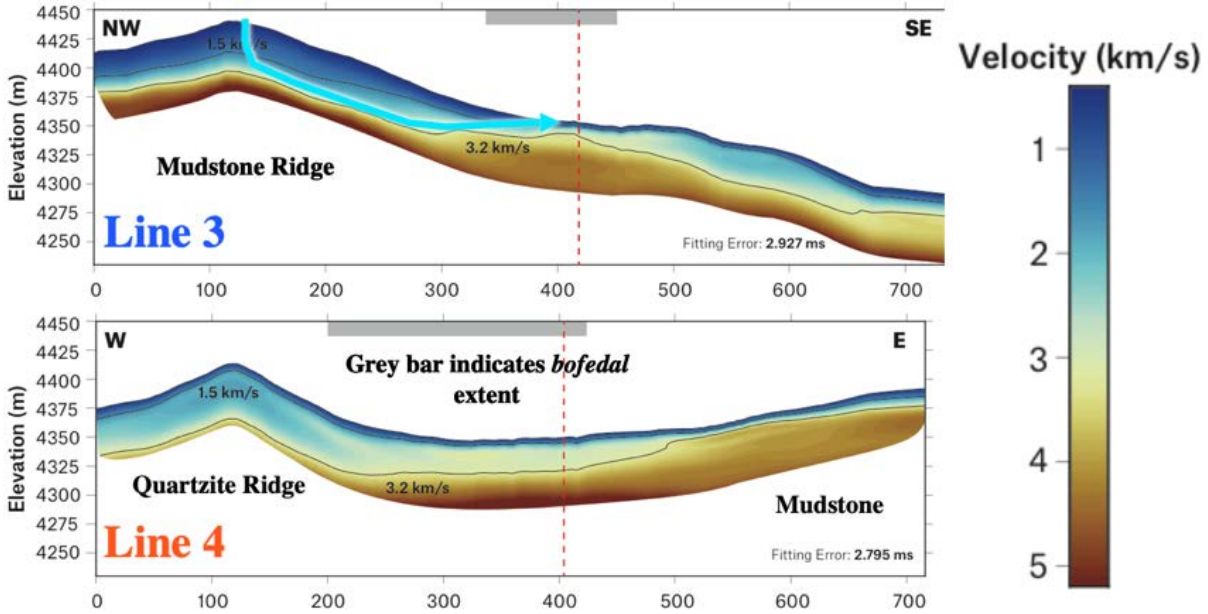

Figure 12: Results of seismic refraction survey lines 3 and 4 across the upper and largest bofedal in the URW. Location of lines shown in Figure 7. Deep, low velocity zones were found beneath the mudstone and quartzite ridges. Shallow, high velocity zones were found beneath the *bofedal*, and near the surface on the gently sloping mudstone on the eastern portion of Line 4. Blue arrow suggests hydrologic flow path through ridges to *bofedal*.

In June 2019, the water table was at the surface of the *bofedales* to depths of 70 cm. An NMR survey from the upper *bofedal* of the Central Basin is shown in Figure 13. The average porosity of the peat is 94%. We observed that the peat is spongy and would depress as we walked across. Our NMR surveys of the underlying clay revealed an average porosity of 54%. In January 2020, in the middle of the wet season, the water table had risen to the surface across many of the *bofedales.* Our current understanding points to three factors determining the hydrologic importance of the *bofedales.* First, the landscape has been sculpted by glaciers, leaving cirque floors and other low gradient sub-basins in the upper landscape. Water from the surrounding hillslopes drains to these features. Second, the incredibly high porosity of the peat provides an immense storage reservoir. Thirdly, despite relatively high hydraulic conductivity in the peat, (up to 10-50 m/day), water does not rapidly drain from the *bofedales*. Water draining from the *bofedales* to streams must pass through the lower porosity, lower conductivity clay layer. Thus, the low porosity clay serves as a natural release valve that prevents rapid drainage of water from the *bofedal*. Slow drainage from the *bofedales* is an important component of dry season flow in the Ramuschaka (Figure 10). We are currently working to

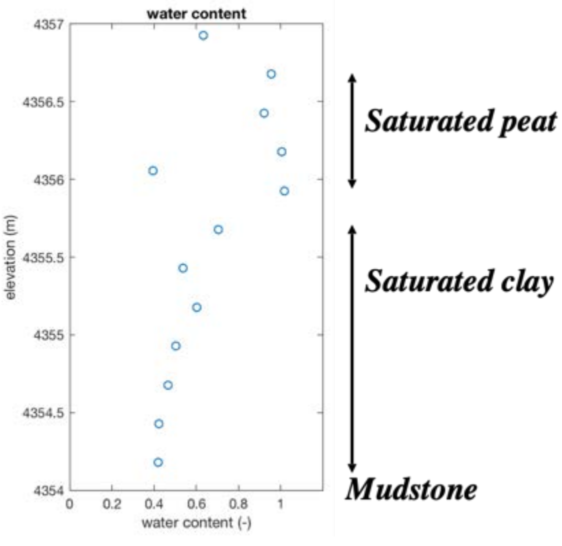

Figure 13: NMR survey of water content from upper *bofedal* of Central Basin. Arrows indicate layers of saturated peat and saturated clay. Hole underlain by mudstone. Data processed and figure made by Keating, 2019.

quantify total *bofedal* water storage across the landscape, and to determine relationships between upslope contributing area and *bofedal* size. We are pursuing funding to use C^{14} dating on peat samples to determine rates of peat accumulation and reconstruct the geomorphic history of the URW.

THE HUMAN ELEMENT

This project has had a positive impact on all involved parties. Figure 14 shows pictures of some of the many people involved in our project.

Community Impact

The community of Zurite completed 1.3 km of irrigation canals in March, 2020. GWB contributed engineering design work. Over 100 families directly benefit from the new canals carrying irrigation water to their fields. The Municipality of Zurite received a progress report of our work in early March 2020. The report presents initial results, including the water budget, the importance of *bofedales* in sustaining flow in the URW, and a brief assessment of landslide hazards along the range front. The hydrologic results will help guide sustainable water management. Furthermore, we have trained two members of the community to take simple water level measurements. We plan to share our rating curve so that the community might continue monitoring water resources if we take out our stream monitoring equipment. Tomás communicated the sentiments of the municipality, the water users, the community, and himself, “We are infinitely grateful for your support.” He went on to say “It is the supportive and caring spirit [of the GWB group] that perhaps we will never be able to return to you, but for which you should feel a great sense of satisfaction.”

Figure 14: Photos of project participants, clockwise from upper left: group shot at the home of Tomás and Gladis, June 2019; Peruvian and American geologists and engineers, June 2019; student presentations at AGU, December 2019; student presentation at AGU, December 2018; Wyeth Wunderlich exploring the geology of the URW, June 2018; students exploring outcrop in lower Ramuschaka, June 2018; Tomás assisting in seismic refraction surveys, June 2019; Wilnder Bandera and Vidal Antoni Barrientos Cruz with the Anta Plain below, June 2019.

Student Impact

Over two years, 9 graduate students and 19 undergraduate students traveled to Zurite and participated in our program. These students represented 7 different disciplines from physics to film, and came from 8 different institutions across the United States, and from Lima and Cusco. Students applied knowledge specific to their discipline and expanded their knowledge through collaborative field work. Students from the United States lived with host families in a remote, rural Peruvian village and, for a month, experienced life fundamentally different from the one they had known. Peruvian students gained an opportunity to teach U.S. students, to practice English and experience parts of our culture, and to gain experience using a suite of traditional and sophisticated hydrogeologic and geophysical equipment. Two of the Cusco based students were paid by the grant to conduct field work, providing each with steady income and fantastic experience. One student, Wilner Bandera, borrowed equipment purchased by the GWB grant and used what he had learned working with us to produce his senior thesis, titled "Estudio hidrogeógico para el diseño de métodos de recarga en acuíferos en la microcuenca de Unuhuayco, Distrito Oropesa, Provincia Quispicanchi – Cusco 2019." For all, the experience cultivated patience, understanding, motivation to improve our planet, and ultimately peace. Students left our program empowered to pursue education and careers that embodied the spirit of HSU's graduation pledge: "*I pledge to explore and take into account the social and environmental consequences of any job I consider and will try to improve these aspects of any organizations for which I work."*

United States students sent us the following comments after participating in our program:

- "This trip made me rethink what approach I want to take to grad school (location, concentration), and made me think more about pursuing a career in water resources"
- "When I think of my time at Humboldt State there are three life-changing opportunities that stand out and working with Jasper [in Zurite] was one of them."
- "I truly believe that [this program's] approach has prepared us to excel and stand out in hydrologic sciences as geologists, and to think critically about the interconnected nature of the systems in which we work."
- "This trip broadened my horizons immensely. It made me realize that I can do meaningful work in almost any part of the world while still doing something I enjoy"

Wilner Bandera wrote the following (translated from Spanish):

- "to be part of this investigation was not only a great honor, but I also gained such knowledge… for me, it was a great experience for the sharing of knowledge and excellent friendships it brought me. I want to continue being a part of this project and cultivate my knowledge through all of you."

PI Impact

As lead PI, I am satisfied we completed the objectives of the project. The themes of the project (community benefit, student empowerment, and fundamental hydrology research) are three of my passions. I seek to integrate these themes in the work that I do. It is wonderful to see the growth in our students and the inspiration they feel through this work. I am inspired to continue student-led water development projects in Zurite, the Cusco region, or perhaps beyond. I have made professional connections with Cusco based hydrologists (Sr. Pumayalli) and Andean water resource organizations (AguaAndes). We need to and will publish our scientific results as well as an outline of our education model. We will be pursuing funding from GWB and elsewhere to continue this work.

Lessons Learned

Whereas the community was generally welcoming, appreciative, and supportive of our project, we could have done a better job communicating the need for this project, our objectives and early results in town hall type meetings. We were successful in presenting at two meetings, but should have done more to cultivate a collaborative spirit between our group and Zurite. Some members of the community were envious of the position of Tomás and Gladis hosting our group. Living conditions in Zurite are basic, and as trip leader it is my responsibility to keep students safe. Still, we think we should have spread the benefits of our presence in Zurite more equitably throughout the community. We learned to be patient working with the authorities, given there was a change in leadership in Zurite in December 2018. We should have sooner established a direct connection with the new authorities instead of communicating through Tomás.

This type of experience only works with a pre-field experience preparatory class and a post-field experience research seminar. Taking students to rural highland Perú is challenging, and the preparations we covered prior to departure were essential in a successful field campaign. Students must be sturdy, self-directed, responsible, open-minded, respectful and most of all be excited to learn and contribute to the work. We hope to lead similar trips again, and now have an idea of which students will succeed in this type of program. For future trips, we would like to include at least 2 full time master's students to take on more responsibility over a two-year program.

We would like to cultivate the inroads made in relationship building with authorities in Zurite and expand to other communities. There are fantastic opportunities to work in neighboring communities, to leverage local expertise, and to go deeper – for example in groundwater harvesting tunnels – to expand to reach of our impact and guide sound water management decisions.

Conclusion

In summary, this project has had impacts in three areas. First, a contribution from GWB, engineering expertise, and agreements with local leaders produced 1.3 km of irrigation canals. This project directly benefits over 100 families, who own land along the length of the canal. Student participants leave our program inspired and empowered to pursue careers that bridge the gaps between science and community. Early scientific results of our study have been presented at international meetings by students and the PI. We expect to publish our scientific results and educational model in the coming year. We are sincerely grateful to Geoscientists Without Borders for supporting our project. Thank you very much.

References

Bonhomme, M. G., Fornari, M., Laubacher, G., Sébrier, M., & Vivier, G. (1988). New Cenozoic K- Ar ages on volcanic rocks from the eastern High Andes, southern Peru. *Journal of South American earth sciences*, *1*(2), 179-183.

Buytaert, W., & De Bièvre, B. (2012). Water for cities: The impact of climate change and demographic growth in the tropical Andes. *Water Resources Research*, *48*(8).

Carlier, G & Carlotto, V. (1990) Evidence for the origin of a shoshonitic suite by mixing of peraluminous and ultrapotassic magmas: the oroscocha and quimsachata quaternary volcanoes, Sicuani province, southern Peru. ISAG. 353-356.

Carlier, G & Carlotto, V. (1990) Evidence for the origin of a shoshonitic suite by mixing of peraluminous and ultrapotassic magmas: the oroscocha and quimsachata quaternary volcanoes, Sicuani province, southern Peru. ISAG. 353-356.

Carlotto, V., Carlier, G., Jaillard, E., Sempéré, T., & Mascle, G. (1999). Sedimentary and structural evolution of the Eocene-Oligocene Capas Rojas basin: evidence for a late Eocene lithospheric delamination event in the southern Peruvian Altiplano. Andean geodynamics : extended abstracts; ISAG99: Symposium International sur la Géodynamique Andine, 4., Göttingen (DEU). p. 141-146.

Carlotto Caillaux, V. S., de Guzmán, C. N., Fernando, R., Cárdenas Roque, J. D., García Fernández Baca, B., & Villafuerte, C. (2010). Geología y geodinámica en la quebrada Qenqo: aluviones que afectaron Zurite-Cusco (2010).

Célleri, R., Feyen, J., 2009. The hydrology of tropical Andean ecosystems: importance, knowledge status, and perspectives. Mt. Res. Dev. 29, 350–355.

Davis, E., Murray, H., Schmidt, L., Oshun, J., Keating, K., Lang, M. M., & Wunderlich, W. (2019). A Geophysical Investigation to Image the Critical Zone Architecture in a High Andean Puna Grassland. *AGUFM*, *2019*, NS21C-0829.

Helprin, O., Keating, K., Oshun, J., & Lang, M. M. (2018). High Andean Geophysical Investigation of the Puna Grassland Critical Zone. *AGUFM*, *2018*, NS41B-0825.

Oshun, J., Lang, M. M., & Keating, K. (2018, December). Applied interdisciplinary Critical Zone research and water development in the Andean Puna. In *AGU Fall Meeting Abstracts*.

Oshun, J., Lang, M., Keating, K., Helprin, O., & Wunderlich, W. (2019, August). Student-led water development in the Andean Puna. In *SEG International Exposition and Annual Meeting*. Society of Exploration Geophysicists.

Oshun, J., Lang, M., Keating, K., Wunderlich, W., Schmidt, L., Murray, H., ... & Smith, L. (2019). Identification, explanation and quantification of the hydrologically important components of an Andean Watershed. *AGUFM*, *2019*, H52F-04.

Rempe, D.M, and Dietrich, W.E. (2014) A bottom-up control on fresh-bedrock topography under landscapes. *Proc Nat. Acad. Sci. Early Ed.*

Wunderlich, W., Oshun, J., Keating, K., Lang, M. M., Saloma, R. P., Schmidt, L., ... & Murray, H. (2019). Quantifying water storage capacity in, and dry season water yield from Bofedales, Andean Wetlands. *AGUFM*, *2019*, A21U-2668.