Revealing Paleo-Groundwater and Interbasin Flow as Fundamental to Water and Mineral Resource Sustainability on the Arid Altiplano-Puna Plateau

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November 24, 2022

Abstract

Accelerating demand for energy storage has led to increasing development of brine resources in the "Lithium Triangle", estimated to hold about 75% of the planet's Li reserves but persistent and fundamental questions regarding the source and transit time of groundwater have confounded efforts to manage these resources effectively. The basins containing these brines lie within the massive Altiplano-Puna Plateau, home to people whose ancestors have inhabited this land for thousands of years and fragile ecosystems that exist nowhere else on Earth. This region is very dry, bordering Earth's driest non-polar desert and as such, groundwater is the predominant and, in many areas the only source of water. Fundamental questions about the spatiotemporal dimensions of these groundwater systems have only begun to be addressed. In much of this extreme and remote region, there is a severe lack of quality baseline understanding of the regional hydrological system and connections between surface and groundwater bodies. To address these questions, we utilize an exhaustive set (˜2,500 individual analyses) of environmental tracer data (δ18O, δ2H, 3H, 87Sr/86Sr), and dissolved major and minor elements in waters collected from over a dozen field campaigns in the Salar de Atacama and Altiplano of Chile and on the Puna Plateau of Argentina. Our integrated analysis pairs these data with rigorous geochemical modelling and physical hydrological measurements from the field and remote sensing products. 3H data show much of the groundwater currently discharging into these basins is non-modern (>60 yrs. old), stable isotope and geochemical data show strong connectivity but also a marked disconnect between some recharge and discharge areas. We show that "fossil" groundwater, 100-10,000 yrs. or older is widespread and fundamental to the system, sharp disconnects exist between the modern hydrological system, the water bodies it sustains, and those sustained by paleo-recharge water. By defining these connections in spatial detail and within a regional integrated framework, we greatly improve the fundamental mechanistic understanding of this and other groundwater-sustained systems. This will greatly improve the ability of communities, governments and industry to manage of these water resources in a way that is genuinely sustainable.

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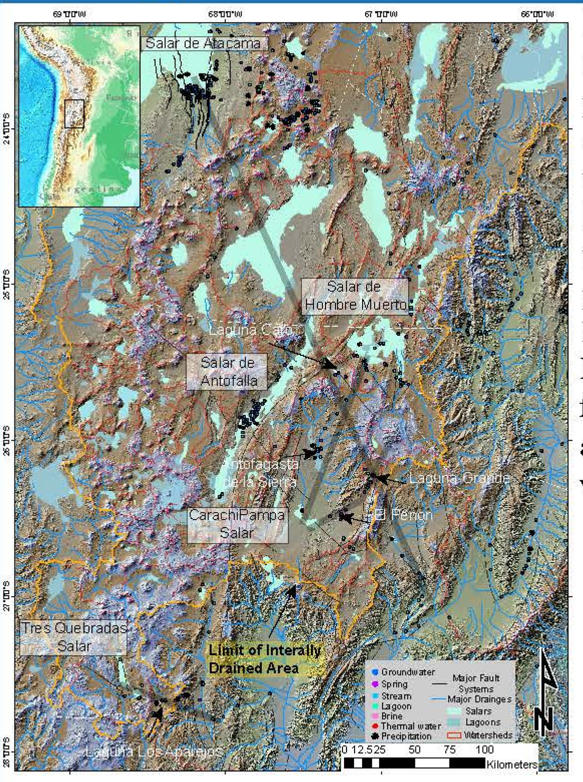
Motivation & Objective

Water resources on the arid high-Andean plateau are critical to sustaining both indigenous communities and fragile Ramsar World Heritage ecosystems yet accelerating demand for mineral resources and the effects of climate change have led to concerns about the sustainability of these resources. Persistent and fundamental questions regarding the source and movement of groundwaters, which sustain most surface waters here make managing these resources particularly difficult.

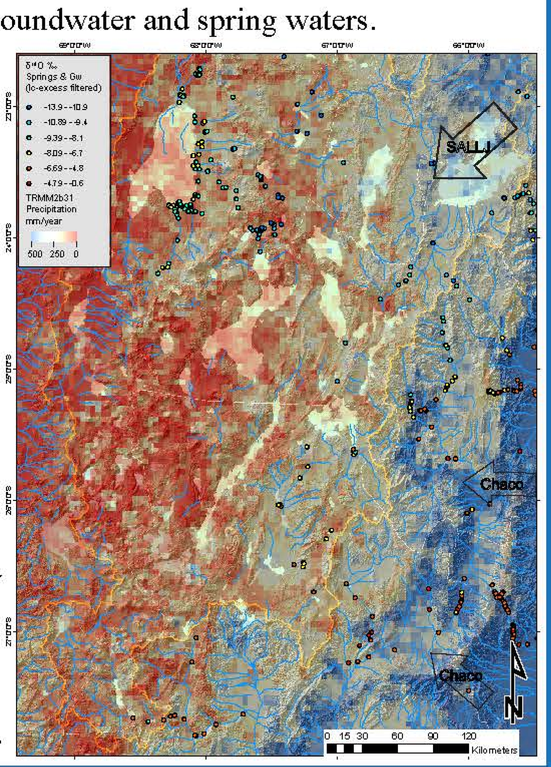
We seek to address the following questions:

1. What is the nature of hydrogeologic connectivity within the plateau; between topographically closed basins and between modern infiltration (<60 yrs.) and the paleo-groundwater system?
2. How connected are surface water bodies (wetlands, lakes, salt lakes and salars) on the Puna to the groundwater (aquifers) and what is distribution and magnitude of these connections?
3. What are the dynamic response times of surface and groundwaters to perturbations from climate change and groundwater extractions?

Background

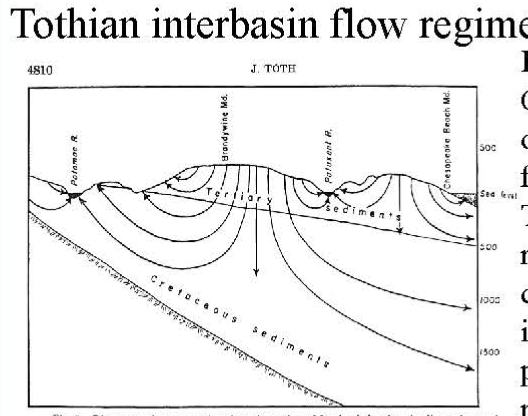


Left: Regional map of Altiplano Puna plateau, basins discussed in this work, sample locations in this work and location of profiles presented herein.



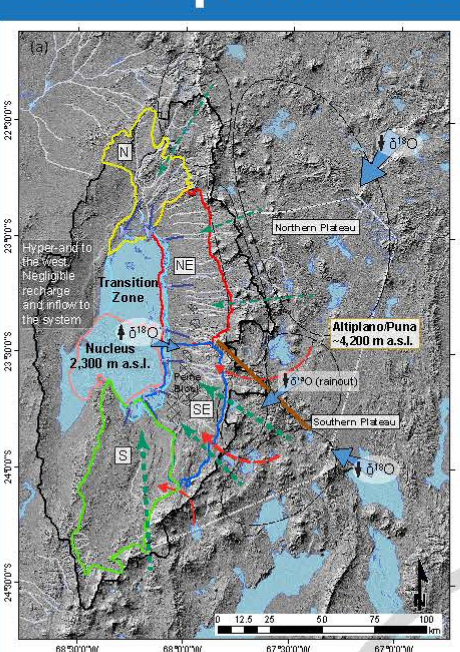
Below: Average precipitation region-wide 1998-2009 from the TRMM satellite, reanalyzed by Bookhagen at al., (in review). Data points are lc-excess filtered $\delta^{18}O$ values from groundwater and spring waters.

Tothian interbasin flow regime

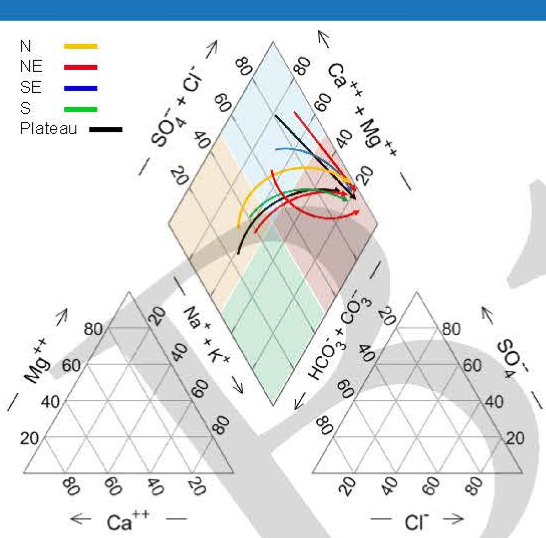


Left: Conceptualization of regional flow from Toth (1963). These flow regimes commonly develop long, interbasin flow paths in arid mountainous areas.

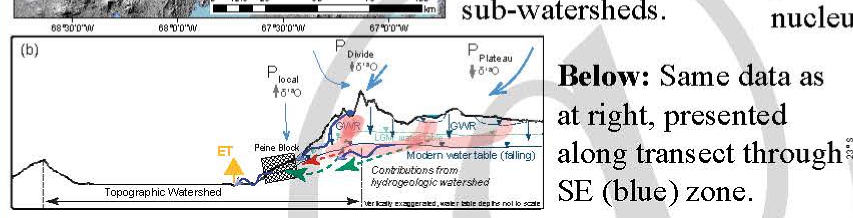
Conceptual Framework



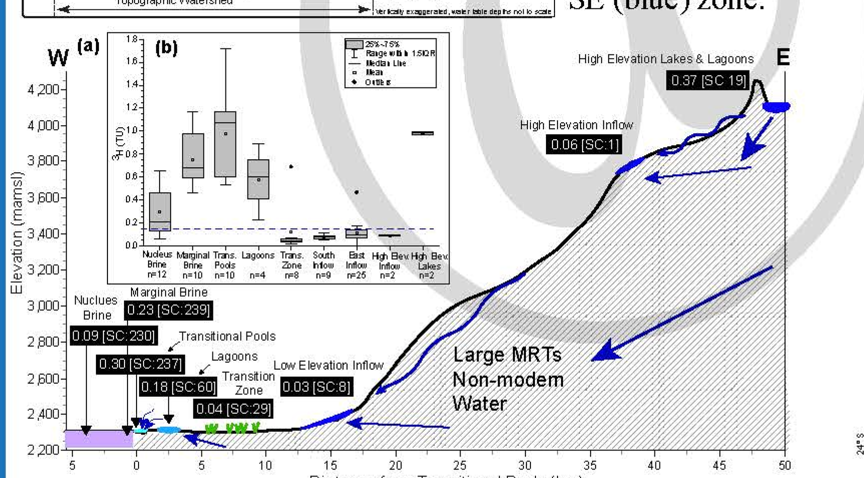
Left: Conceptual model of the hydrogeologic flow regime of the Salar de Atacama (SdA) basin from Moran et al., 2019; in profile view below. Watershed is solid black outline, sub-watersheds are colored.

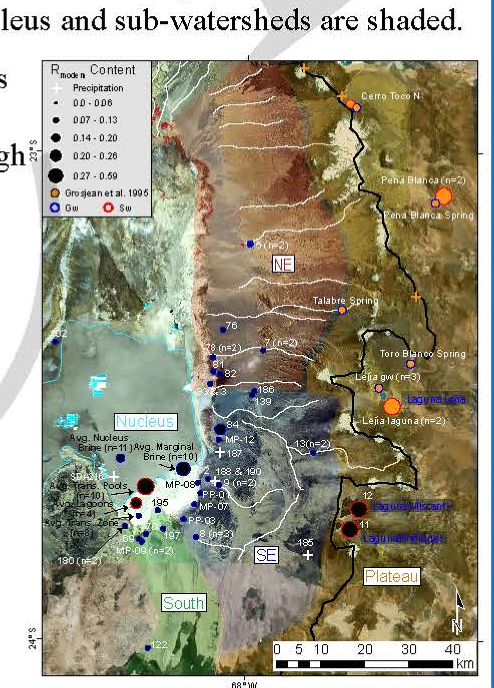


Above right: Major hydrochemical facies within SdA catchment. Colors correspond to sub-watersheds.



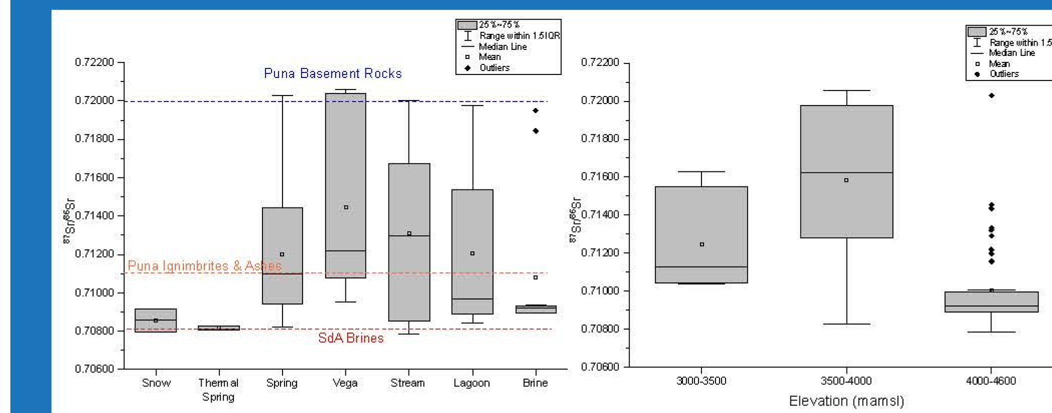
Below: Same data as at right, presented along transect through SE (blue) zone.



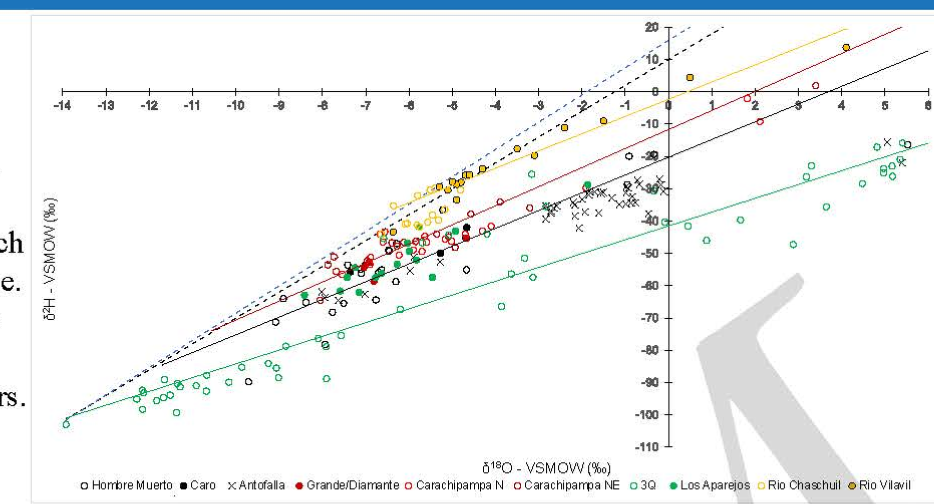


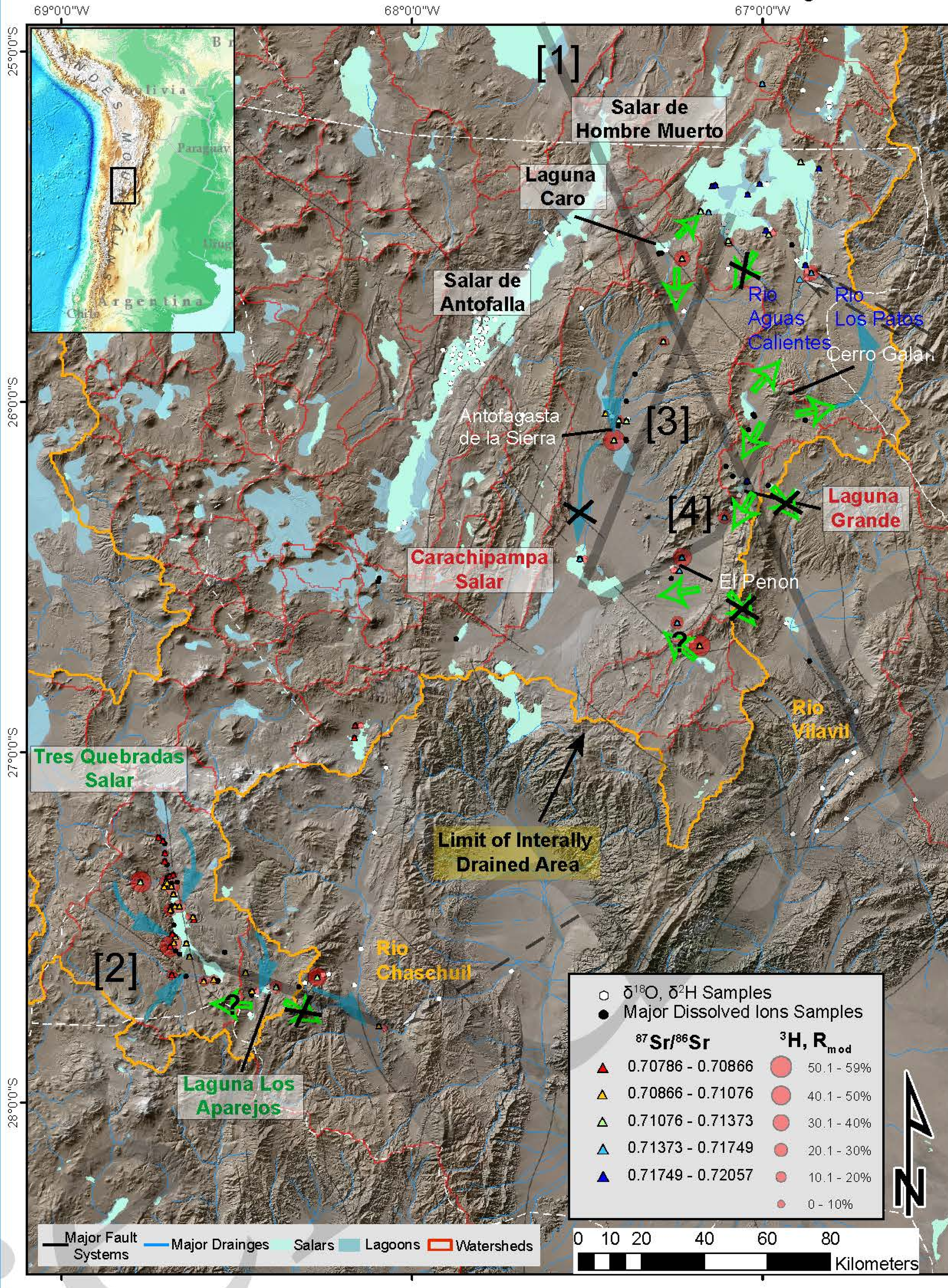
Below: Percent modern water in 86 samples determined by ^{3}H decay. The salar nucleus and sub-watersheds are shaded.

Results

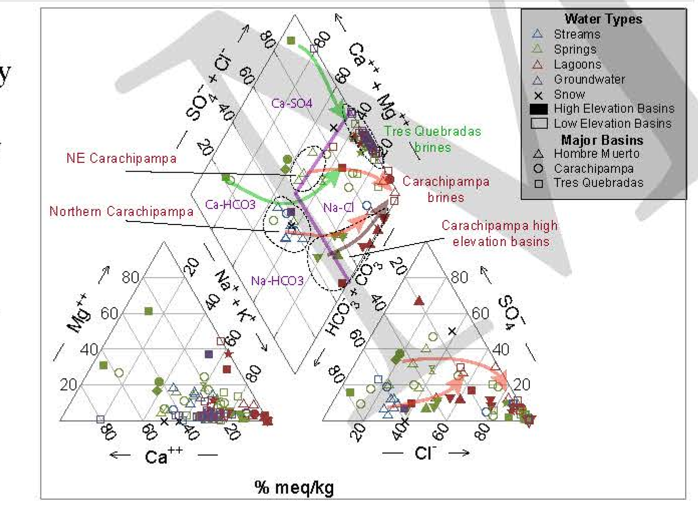


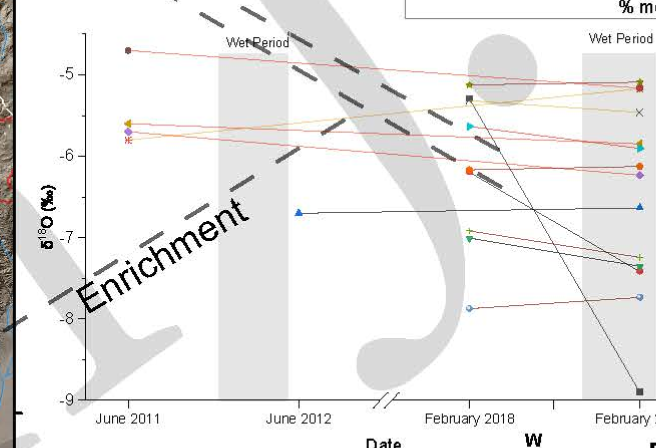
Left: $^{87}Sr/^{86}Sr$ data from this work. Potential end-member signatures indicted by dashed lines. **Right:** O and H isotope data from each basin, each with different color/shape. Local Evaporation Lines indicate predicted signature of source waters.





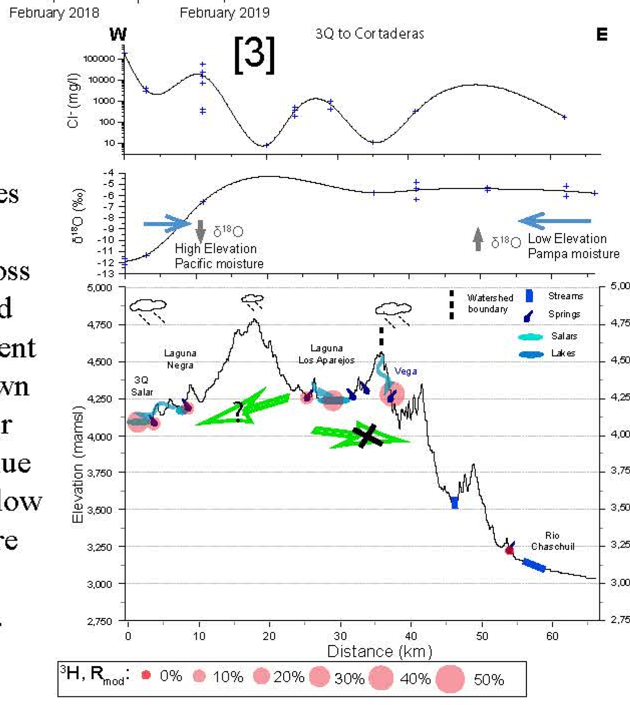
Right: Piper diagram of data collected in this study and available published data. Data shapes identify basin, colors are water type. Important water group and evolutionary pathways are labeled and colored by basin.

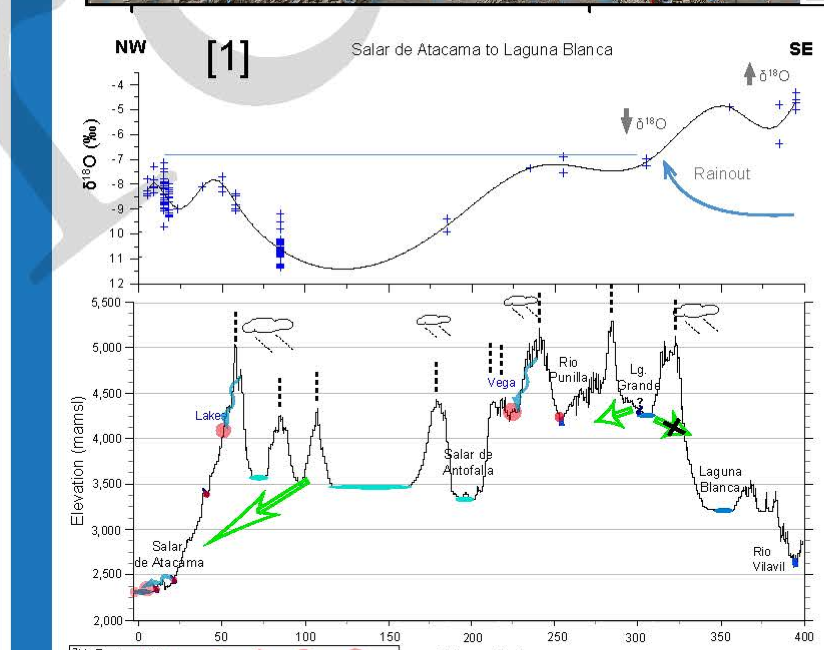


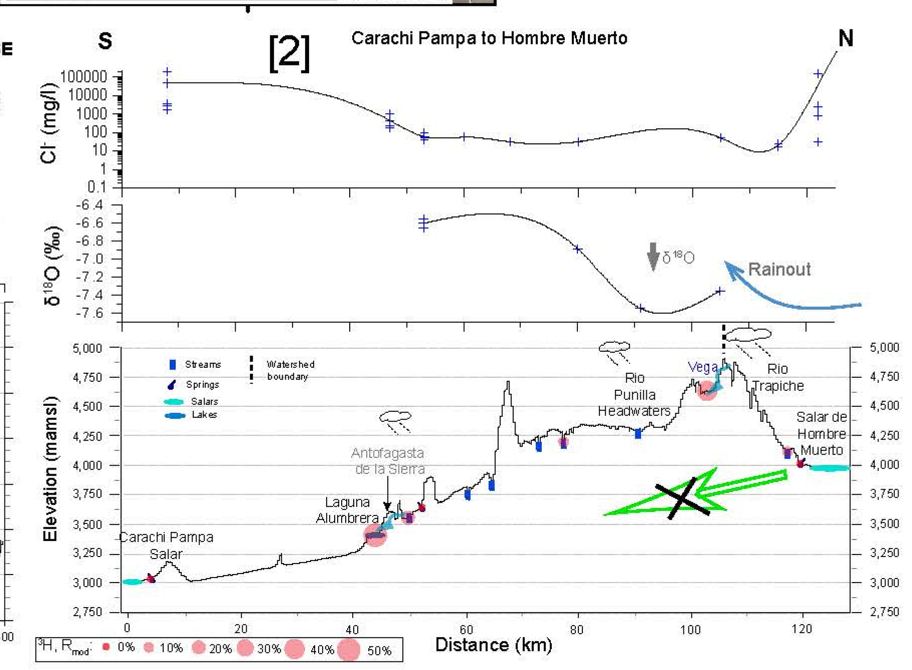


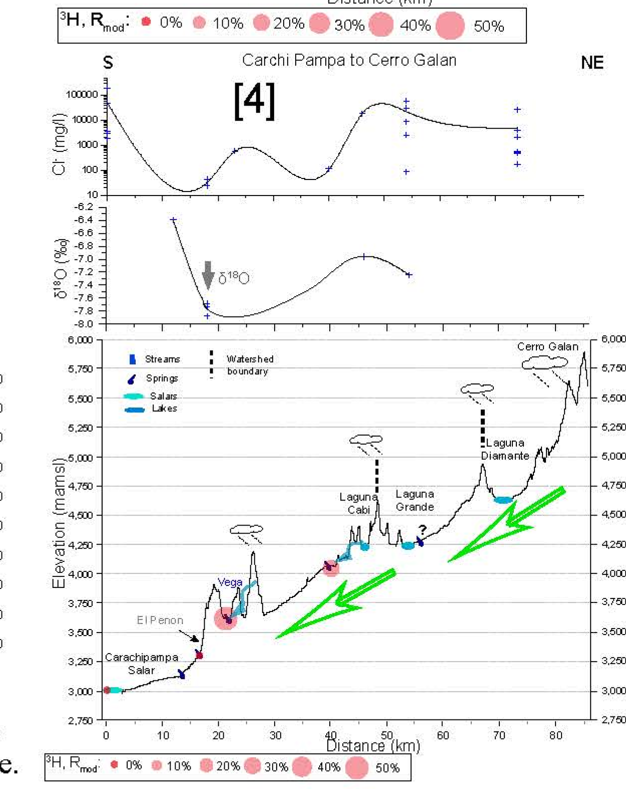
Left: Time series of $\delta^{18}O$ in spring and stream waters. Color of line corresponds to basin (same as plot above) and arrows to map indicate location of notable stream sites.

Left: Site map of study area. Topographic watersheds are outlined in red. Important basins, rivers and communities are labeled; colors of basin labels correspond to data across this work. Transects presented below are numbered. ^{3}H percent modern content of water shown as relative circle size; $^{87}Sr/^{86}Sr$ data shown on color scale. Blue arrows show major modern flow paths, green hollow arrows are major interbasin or paleo-groundwater flow path.







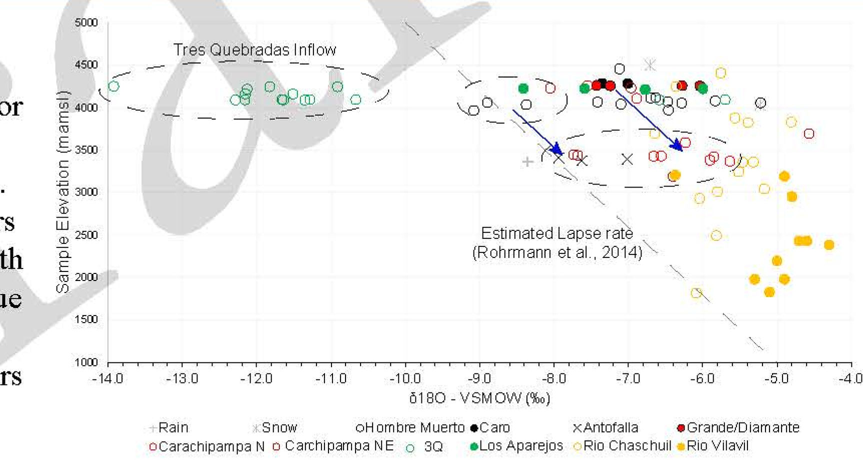


Above & Right: Cross-sections through study region, labeled 1-4 and on map. Red circle size relative to R_{mod} content in waters. Blue arrows indicate modern water transport, green arrows indicate interbasin flow. $\delta^{18}O$ and Cl^{-} along transect are plotted above.

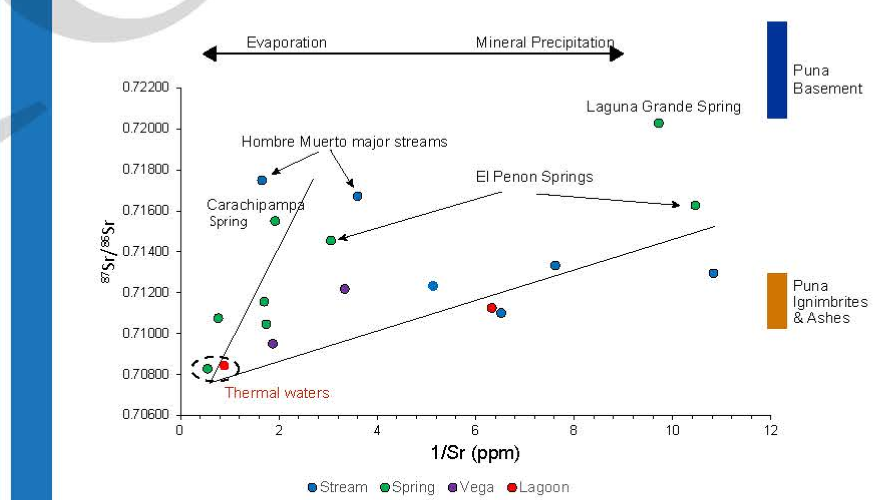
Conclusions

1. An exhaustive set (~350) of environmental tracer data ($\delta^{18}O$, $\delta^{2}H$, ^{3}H, $^{87}Sr/^{86}Sr$), and dissolved major ions in waters across this integrated system reveals substantial spatial heterogeneity in both interbasin and modern, shallow flow regimes; controlled by geologic structure and topographic features.
2. Pre-modern 'fossil' groundwater is fundamental in this system, most of the water discharging to large basin floors is composed of fossil water. The modern and fossil flow systems have very distinct transit time distributions and therefore sharp disconnects over short distances exists between them.
3. Our conceptual model of this integrated hydrologic system characterizes spatiotemporal connections. Using this understanding, potential impacts on critical and threatened wetland ecosystems and water resources from development or climate change scenarios can be greatly improved

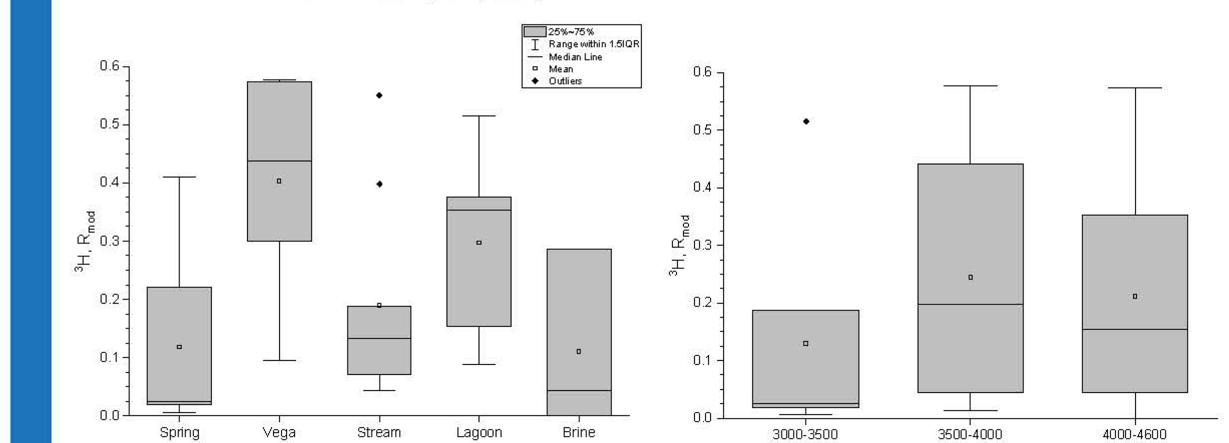
Discussion

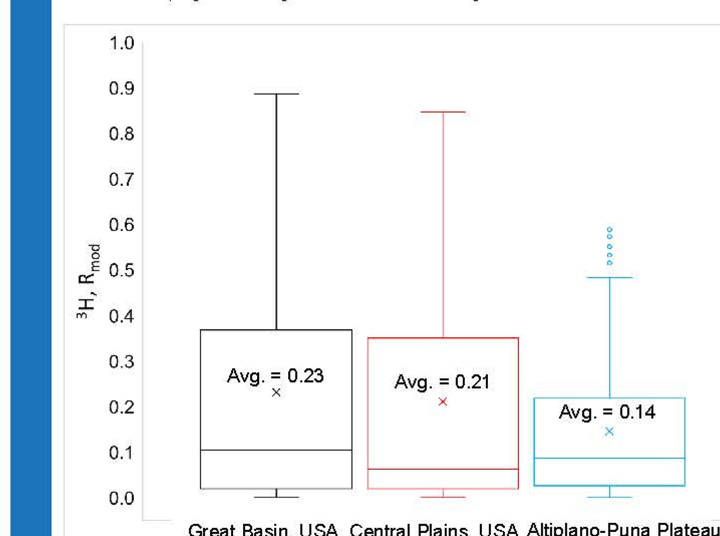


Right: $\delta^{18}O$ data vs elevation of sampling. Lapse rate estimated for this region from Rohrmann et al., 2014. Ellipses indicate waters at similar elevation with distinct signatures. Blue arrows are potential connections with waters down-gradient.

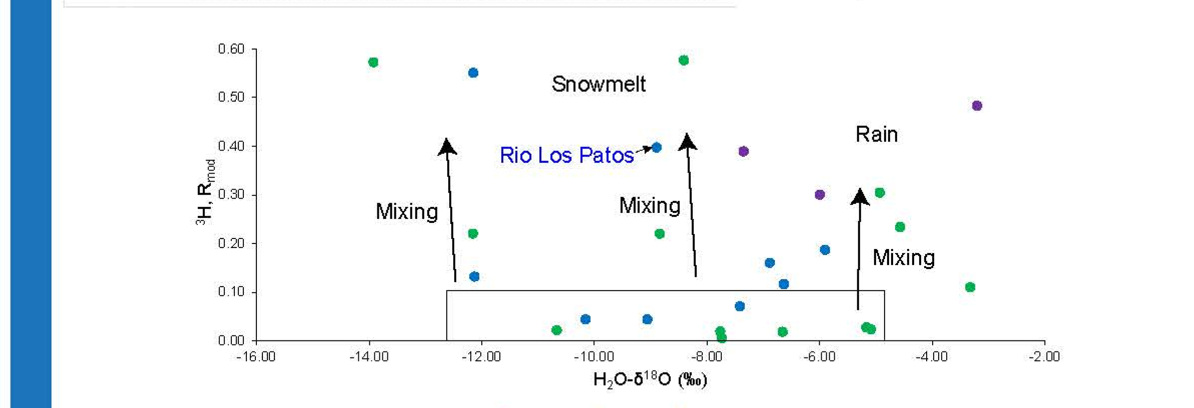


Left: $^{87}Sr/^{86}Sr$ v. 1/Sr from water across the study area. Signature from major rock types (Meixner et al, 2019) in this region and general end-member mixing lines noted. Major distinctions in water-rock interactions along flow paths are identifiable here.





Above: R_{mod} statistics from this study by water type grouping and elevation of sampling.
Left: R_{mod} in waters calculated from ^{3}H. Statistics are from three regions of comparable size. The Great Basin and Central Plains data are groundwaters. Data extracted from NWIS dataset and this study (including Salar de Atacama region) from Moran et al., 2019. R_{mod} in precipitation value used is from Lindsey et al., 2014



Above: Predominately fossil waters (values below ~10% R_{mod}) are related to their $\delta^{18}O$ signatures. Waters with high percentage of modern water and relatively low $\delta^{18}O$ values indicate a high elevation source (likely snow-melt) while rainwater has higher $\delta^{18}O$ values. Potential mixing between these waters can be identified.

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