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

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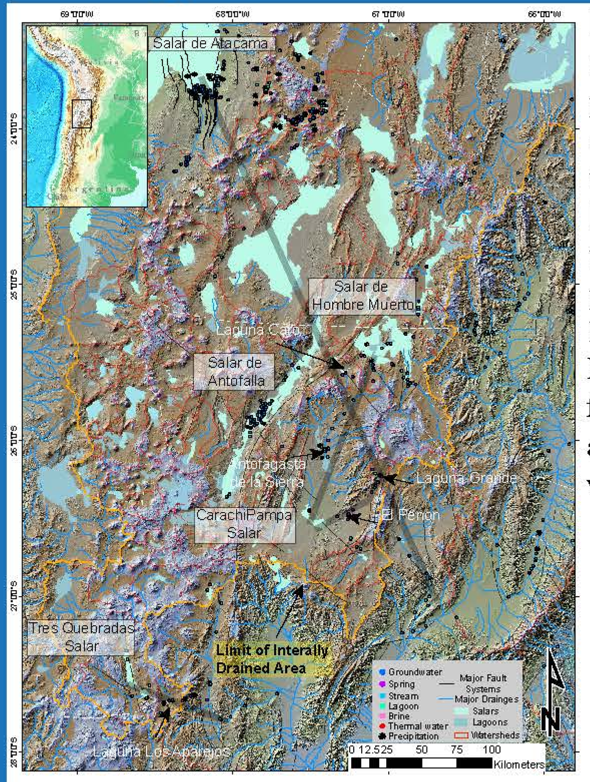
Motivation & Objective

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.

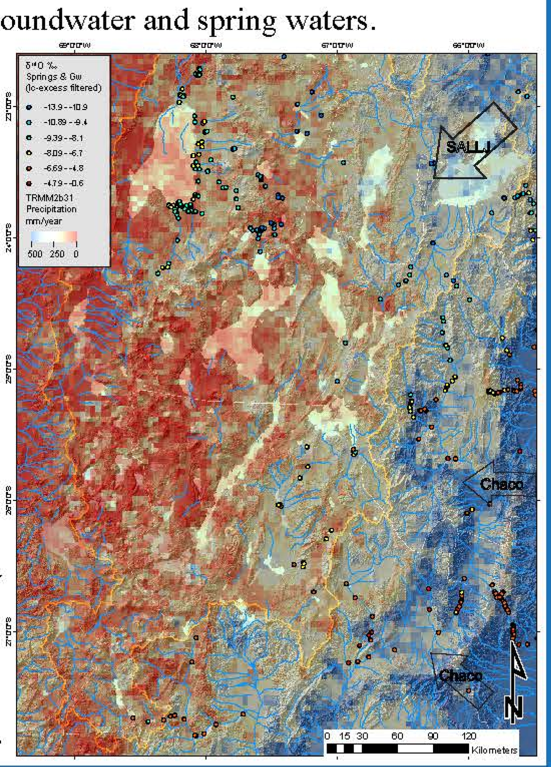
We seek to address the following questions:

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

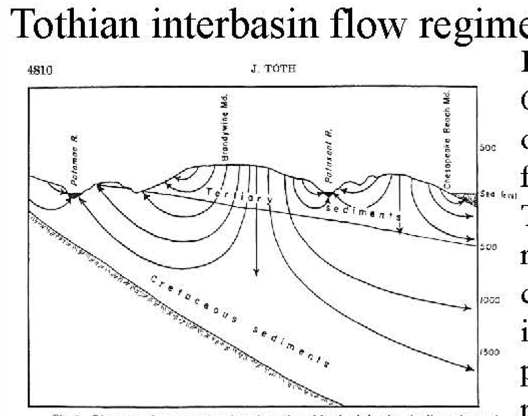


Left: Regional map of Altiplano Puna plateau, basins discussed in this work, sample locations in this work and location of profiles presented herein.



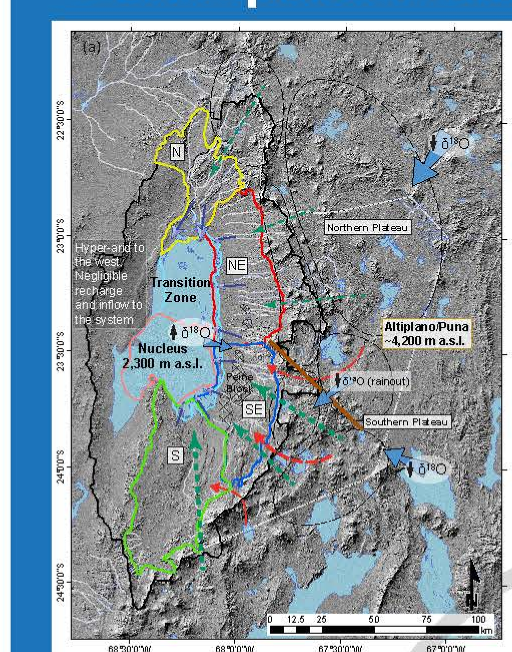
Below: Average precipitation region-wide 1998-2009 from the TRMM satellite, reanalyzed by Bookhagen at al., (in review). Data points are lc-excess filtered $\delta^{18}O$ values from groundwater and spring waters.

Tothian interbasin flow regime

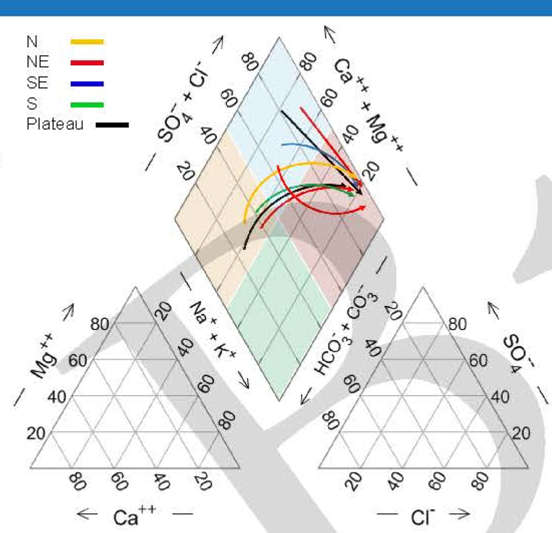


Left: Conceptualization of regional flow from Toth (1963). These flow regimes commonly develop long, interbasin flow paths in arid mountainous areas.

Conceptual Framework

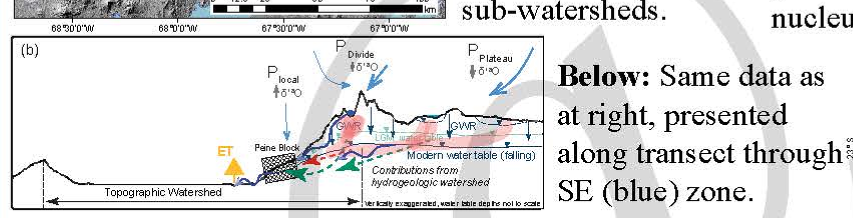


Left: Conceptual model of the hydrogeologic flow regime of the Salar de Atacama (SdA) basin from Moran et al., 2019; in profile view below. Watershed is solid black outline, sub-watersheds are colored.

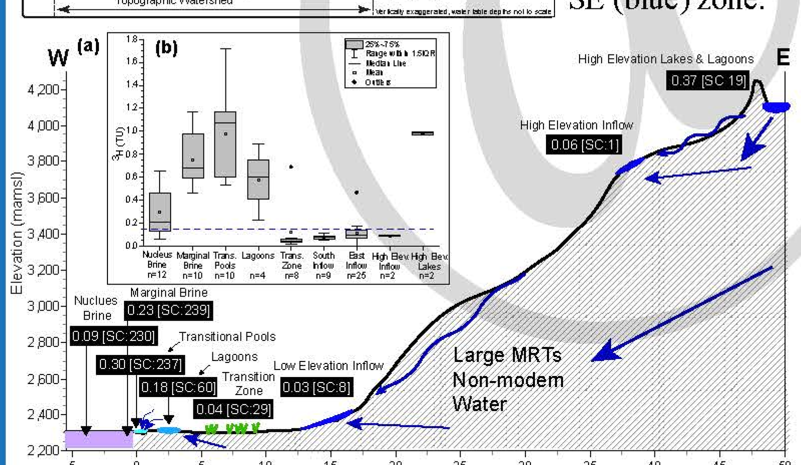


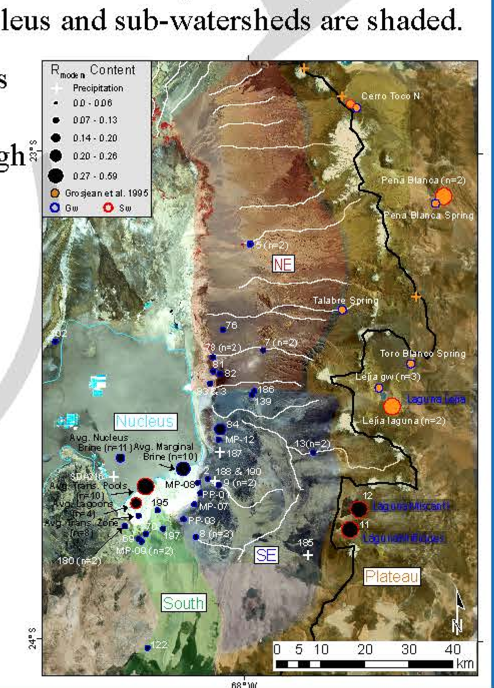
Above right: Major hydrochemical facies within SdA catchment. Colors correspond to major sub-watersheds.

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

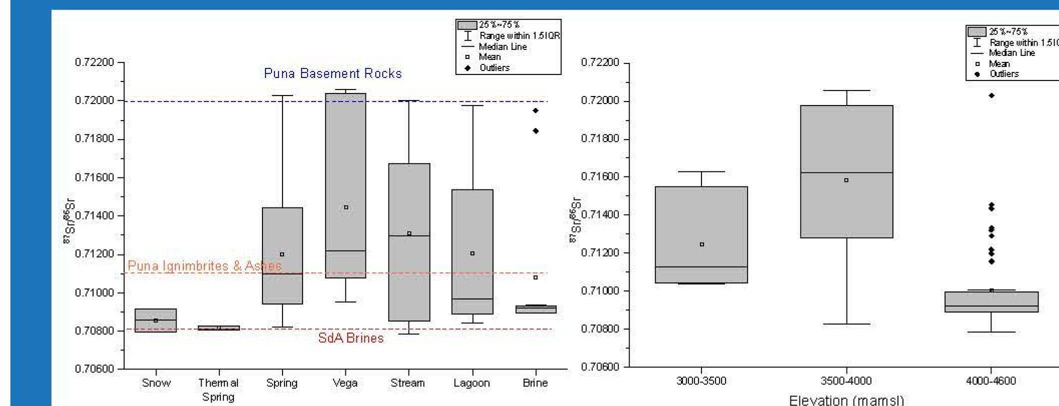


Below: Same data as at right, presented along transect through SE (blue) zone.



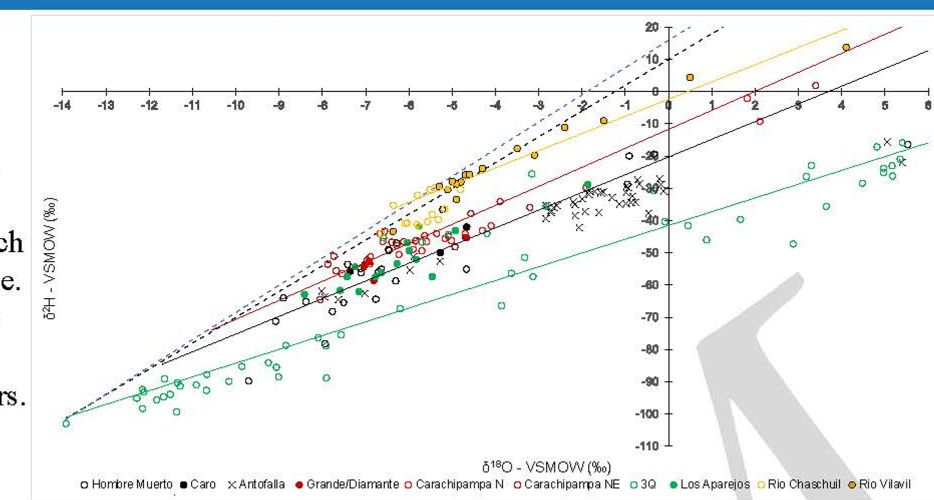


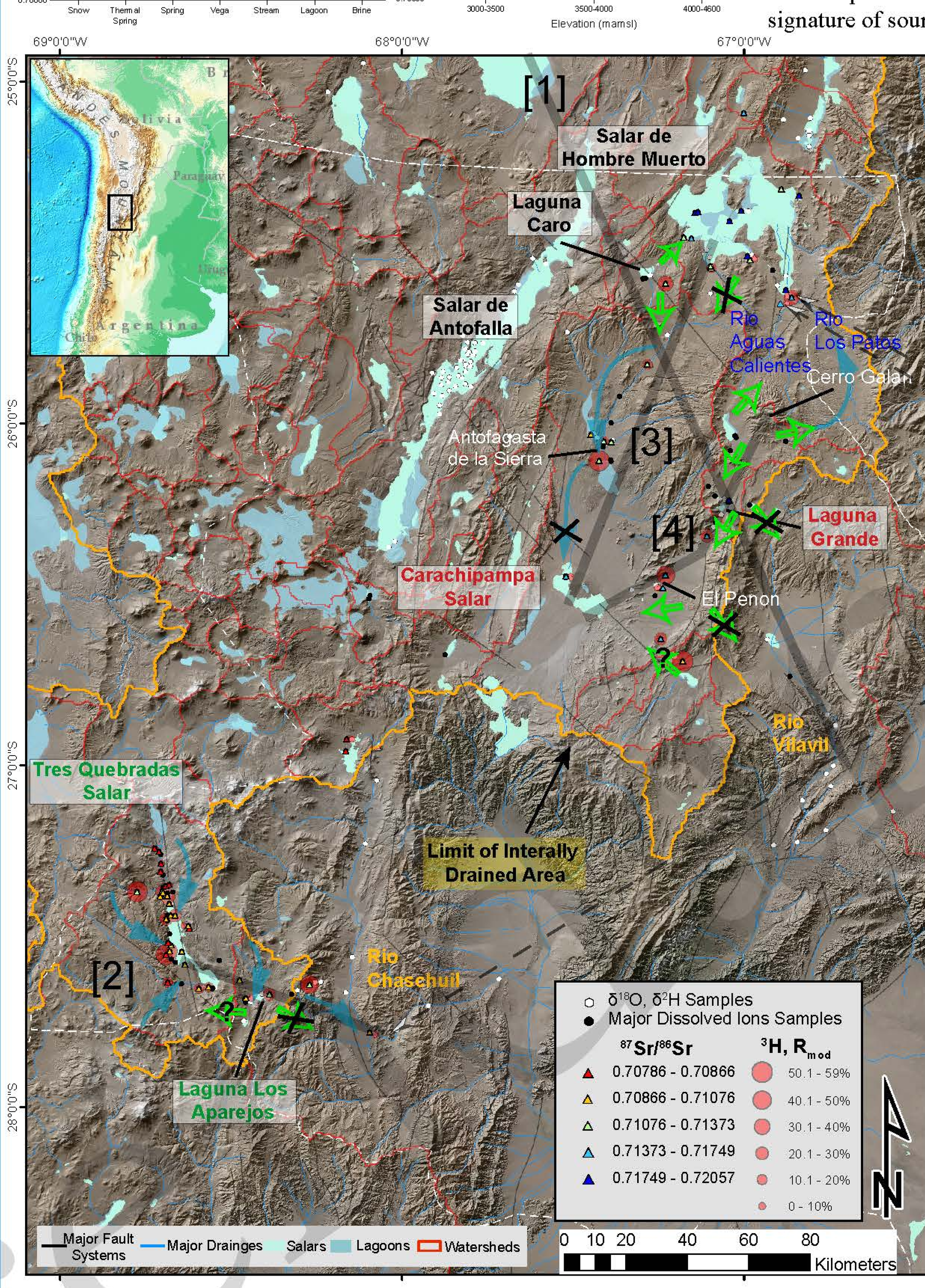
Results



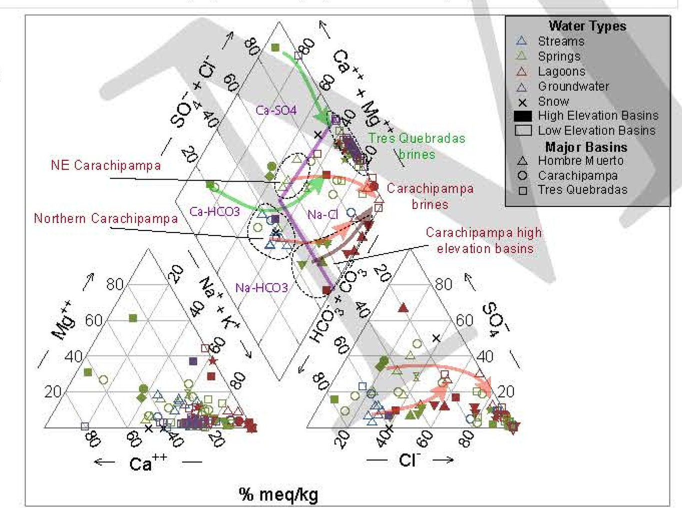
Left: $^{87}Sr/^{86}Sr$ data from this work. Potential end-member signatures indicted by dashed lines.

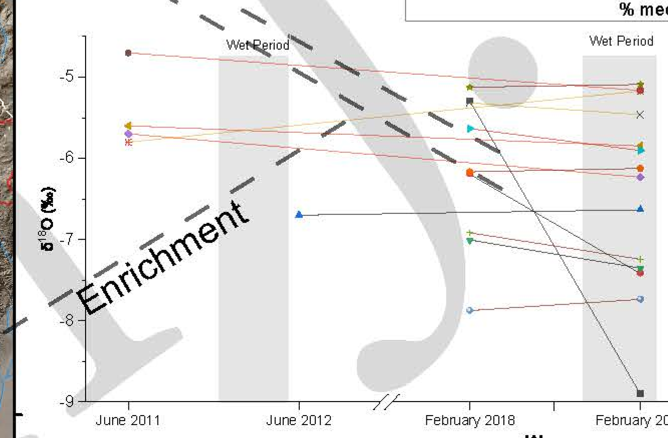
Right: O and H isotope data from each basin, each with different color/shape. Local Evaporation Lines indicate predicted signature of source waters.





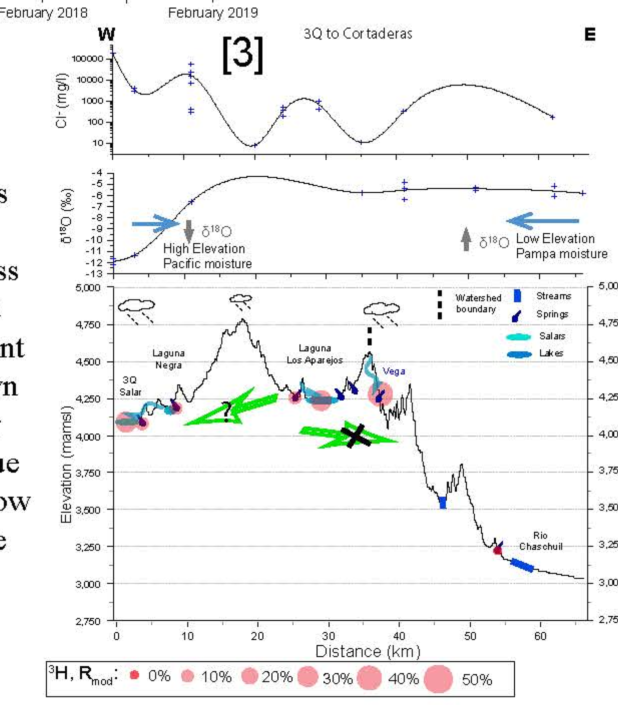
Right: Piper diagram of data collected in this study and available published data. Data shapes identify basin, colors are water type. Important water group and evolutionary pathways are labeled and colored by basin.

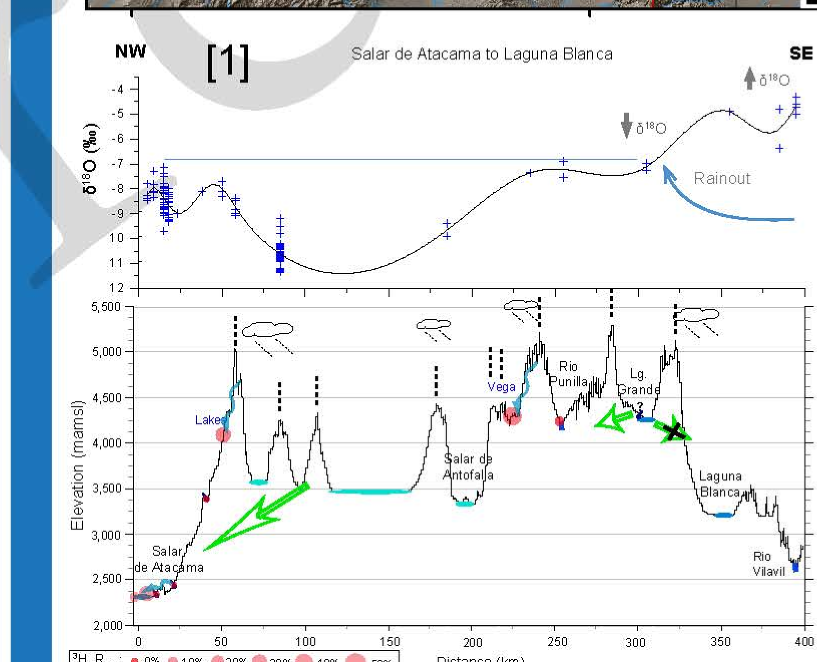


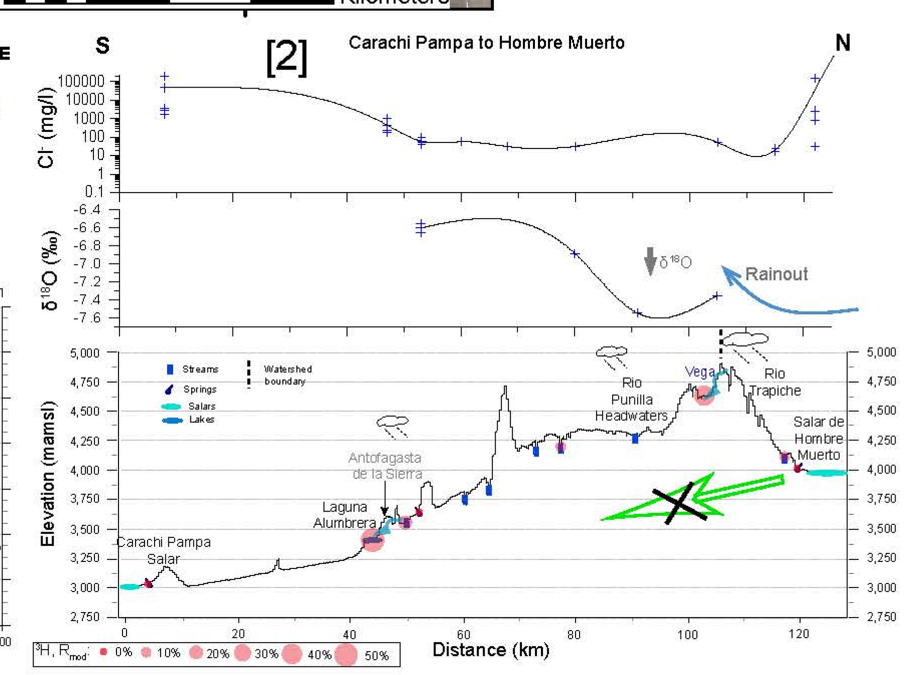


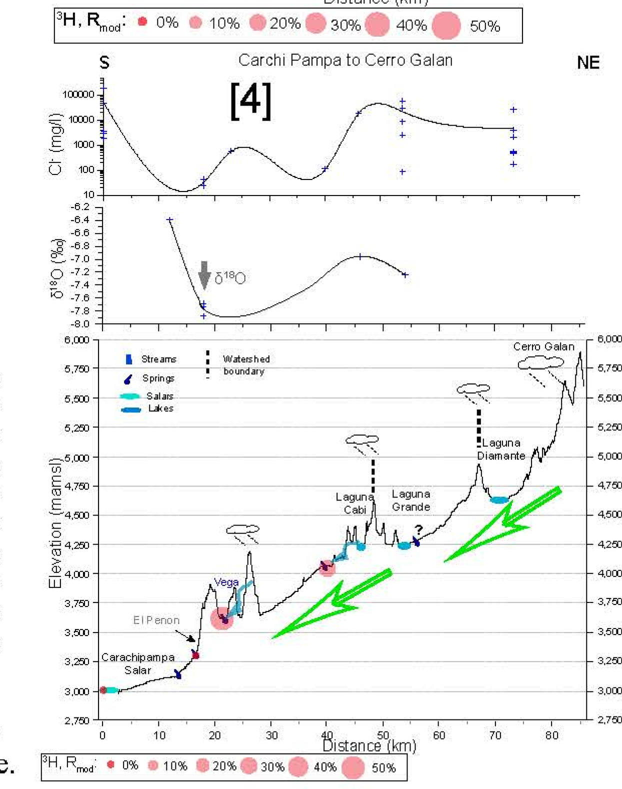
Left: Time series of $\delta^{18}O$ in spring and stream waters. Color of line corresponds to basin (same as plot above) and arrows to map indicate location of notable stream sites.

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. ^3H 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.









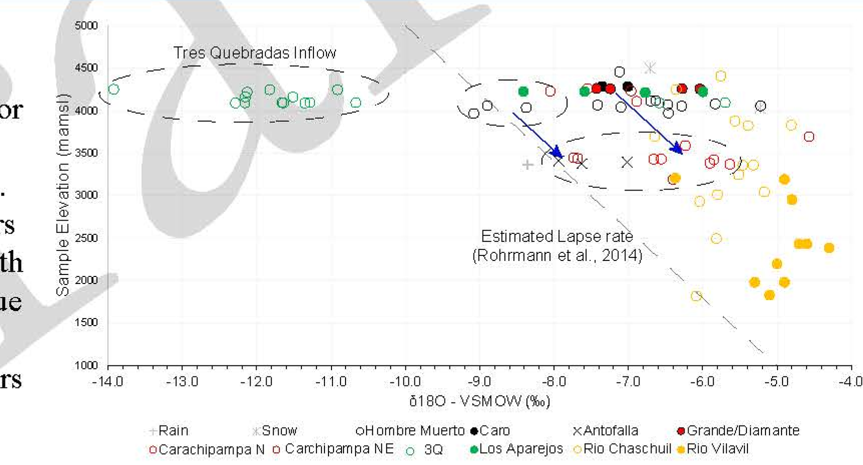
Above & Right: Cross-sections through study region, labeled 1-4 and on map. Red circle size relative to R_{mod} content in waters. Blue arrows indicate modern water transport, green arrows indicate interbasin flow. $\delta^{18}O$ and Cl^- along transect are plotted above.

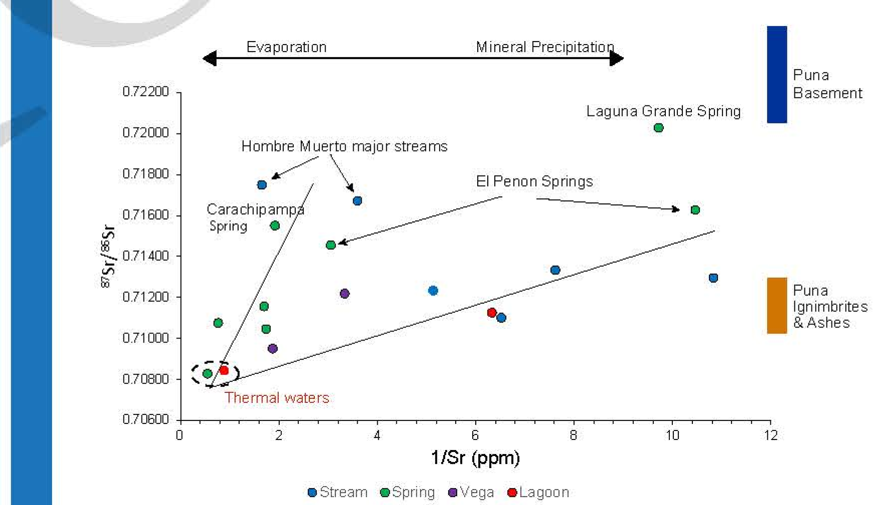
Conclusions

1. An exhaustive set (~350) of environmental tracer data ($\delta^{18}O$, δ^2H, ^3H, $^{87}Sr/^{86}Sr$), 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

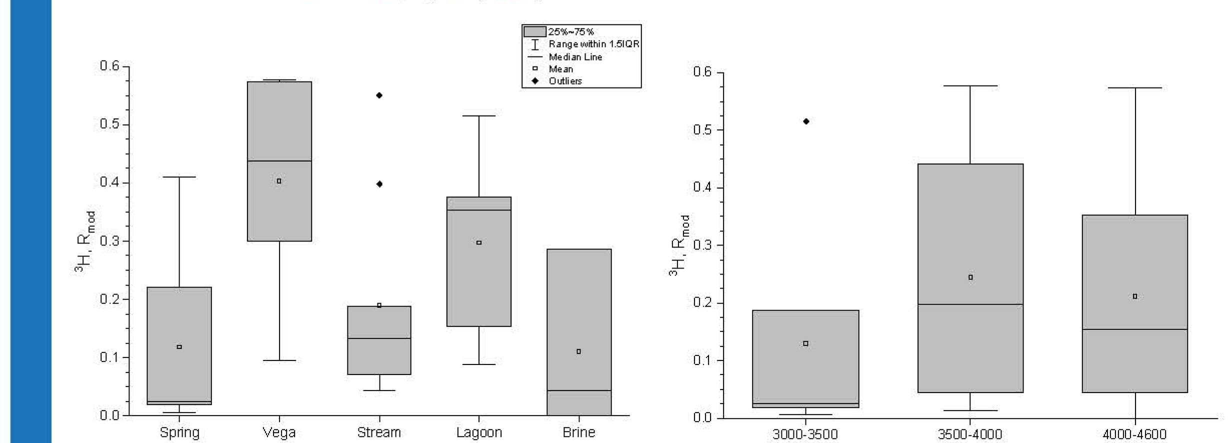
Discussion

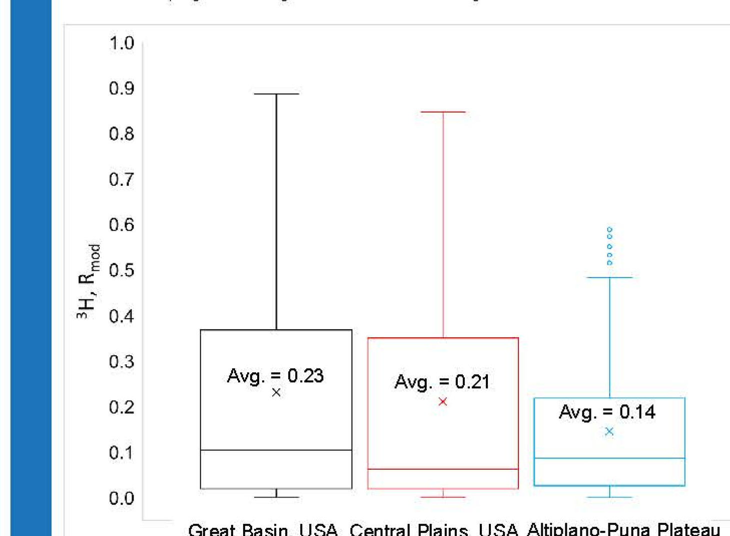
Right: $\delta^{18}O$ data vs elevation of sampling. Lapse rate estimated for this region from Rohrmann et al., 2014. Ellipses indicate waters at similar elevation with distinct signatures. Blue arrows are potential connections with waters down-gradient.





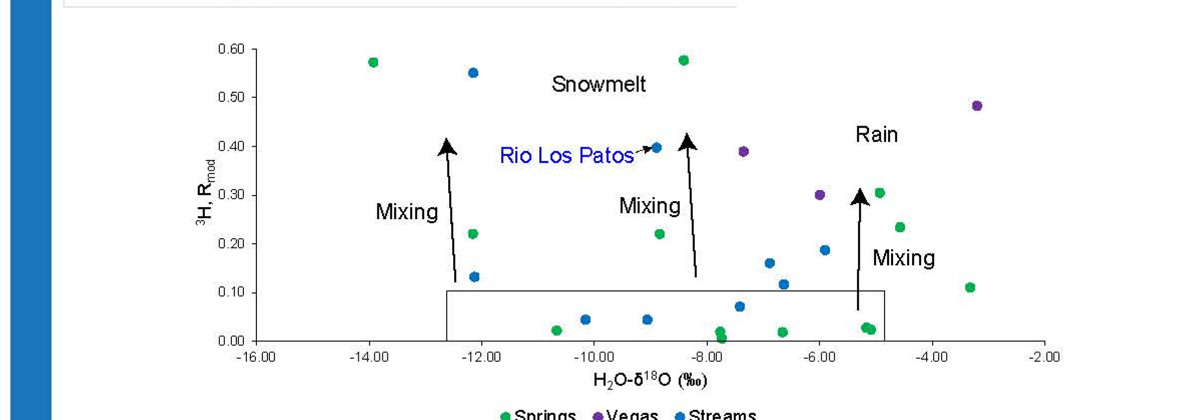
Left: $^{87}Sr/^{86}Sr$ v. 1/Sr from water across the study area. Signature from major rock types (Meixner et al, 2019) in this region and general end-member mixing lines noted. Major distinctions in water-rock interactions along flow paths are identifiable here.





Above: R_{mod} statistics from this study by water type grouping and elevation of sampling.

Left: R_{mod} in waters calculated from ^3H. 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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