

Activity: **Modelación de agua de la subcuenca del río San Pedro en la comuna de San Pedro de Atacama.**

País: Chile

Fecha: Marzo 2015

Autor: Eric Sproles

ProEcoServ
San Pedro de Atacama
Proyecto para Servicios Ecosistémicos

Institución Ejecutora: CEAZA

Abstract

An analysis of the available water resource data in the Salar de Atacama suggests that groundwater is the primary component of available water in the region. Analysis of precipitation and runoff data show variability with regards to precipitation, but minimal variability with regards to runoff. This is evident visually and supported by statistical analysis. These data demonstrate that even in years of high or low precipitation, streamflow remains fairly consistent across years, strongly suggesting that groundwater is a major contributor to streamflow.

These data were also used in the development of a conceptual water balance model. Model results indicate inter- and intra-annual variability in groundwater storage remain fairly consistent. No groundwater data were available to validate the model, and results should be interpreted as conceptual in nature. However, the timing and amplitude of modeled groundwater are assumed to be representative of the timing and magnitude of actual variations.

Summary:

This technical report summarizes the analysis and modeling of water resources in the Salar de Atacama, Chile associated with the ProEcoserv project in the region. The content of this report provides an overview based upon the data that are available. These data were used in the development of a simple, direct water balance model that provides a conceptual understanding of the stores and fluxes of water in this hydrologically closed basin.

Analysis of precipitation and runoff data show variability with regards to precipitation, but minimal variability with regards to runoff. This is evident visually and supported by statistical analysis. These data demonstrate that even in years of high or low precipitation, streamflow remains fairly consistent across years, strongly suggesting that groundwater is a major contributor to streamflow. There were also no statistical trends associated with these data.

These data were also used in the development of a pilot water balance model for the San Pedro watershed for years 1992 – 2002. Initial model results indicate inter- and intra-annual variability in groundwater storage, but remain fairly consistent over the 13 years. No groundwater data were readily available to validate the model at the time of this report, but efforts to measure and include groundwater data have been implemented, and will be included in subsequent modeling efforts.

This same model structure was used to calculate a broad-scale water balance model based on monthly climatologies for 1950-2000. Climatology data represents the long-term mean of meteorological conditions. The original climatology data was perturbed to test for sensitivity with regards to variability in temperature and precipitation.

Introduction and study area

The Atacama Desert is one of the driest and oldest deserts on Earth (Houston, 2006), formed approximately 15 million years ago. The Salar de Atacama (Fig.1) is a closed basin (933 km^2) ranging in elevation from 2300 m in the salar to 5900 m on the volcanic peaks that create the border with Argentina and Bolivia. Temperature and precipitation closely follow this elevational gradient, with the salar receiving 8mm of average annual precipitation, and the upper elevations receiving roughly 200mm of precipitation each year. Hence, upper elevations above provide the primary source of water inputs for the region. Most of the precipitation arrives in the form of convective storms from December–March, originating to the east in Bolivia.

These convective bursts of precipitation fall as rain and snow, with snow primarily accumulating on the volcanic peaks. As a result the rain-driven storms create a quick response in river runoff. Despite the runoff peaks associated with isolated precipitation events, streamflow is consistent year round, even in the absence of precipitation for eight months of the year.

This consistent supply of water has led to the Salar de Atacama region to be occupied by humans for at least 10,000 years. The town of San Pedro exists as an oasis, and for millennium has served as the regional hub for commerce (Bowman, 1914).

Analysis, insights and trends from precipitation and runoff data

Monthly precipitation data for the El Tatio station (elev 4370 m, Fig 2) was downloaded from the Direccíon General de Aguas website for years 1978-2012. The El Tatio station is located just outside of the San Pedro watershed, but is located on the high altiplano in close proximity to an ambiguous watershed boundary. It was incorporated into this study as it is the only high elevation station for the San Pedro watershed, and it has temperature data (described in model section).

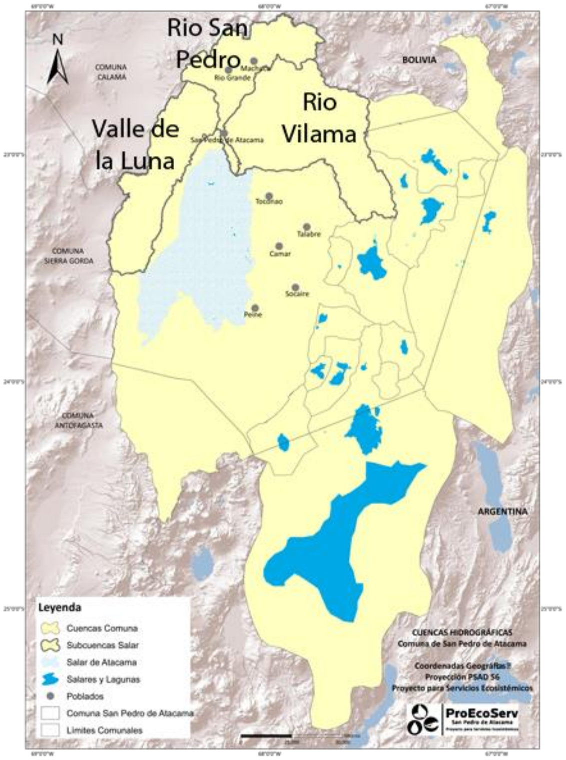


Fig 1. Context map of the Salar de Atacama

Inspection of the precipitation (*P*) data showed month long data gaps during the earlier period of record, but with a more consistent data record starting in 1978. The calendar year 2006 did not have precipitation data and was not used in this study.

Daily streamflow data for the Rio San Pedro gage at Cuchabrachi was downloaded from the Direccíon General de Aguas website for years 1959-2012. Streamflow from 2002 is missing eight months of data and was not included in this study. These flow data (m^3/s) were converted to units of equivalent runoff (*Q*, mm/month) to keep units consistent and for integration into the water balance model.

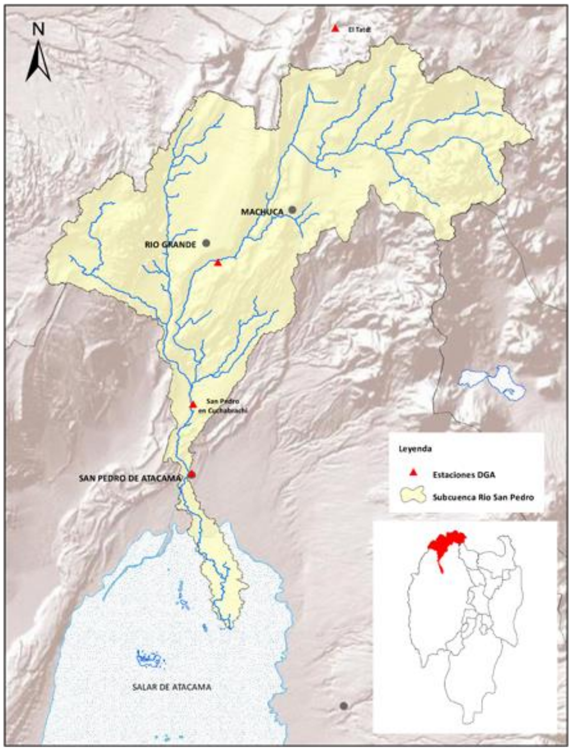


Figure 2: Context map of the San Pedro watershed. Note the location of the El Tatio meteorological station outside of the northern portion of the watershed, but still in the same topographic region.

This gage is well situated, and provides an relatively unaltered hydrologic signal that is representative of the catchment. It is positioned where the broad uplands of the Cuenca San Pedro become more constricted (Fig 2), making it geographically well suited to capture upstream contributions. This contributing area is minimally impacted by human activity, and is upstream of any major diversions and groundwater extractions.

Comparison of precipitation and runoff data

Monthly *P* and daily *Q* data were aggregated to annual time steps for comparison across years (Fig. 3). From 1978 – 2013 precipitation represented a high degree of variability, and streamflow remained relatively constant across all years (Table 1). The coefficient of variation (the standard deviation divided by the mean - a normalized measure of variation within a data set) for annual *P* (0.75 mm) was roughly 2.5 times greater than annual *Q* (0.32 mm). This is evident in Figure 3, where even though precipitation varies greatly from year to year, streamflow remains relatively consistent.

At monthly time steps, the impact of isolated summer precipitation events is demonstrated in the Río San Pedro hydrograph (Fig. 4a), with the spikes in discharge corresponding to large precipitation events during December - March. To better understand runoff without these large events data for December – March was filtered from the dataset (Fig. 4B).

The high degree of variability in annual P and a relatively consistent degree of variability of *Q* describe important characteristics of how the Río San Pedro functions as a hydrological system. There is a consistent level of baseflow during periods with little to no rain (April – November), which strongly suggests that groundwater plays a dominant role in sustaining baseflows during these periods.

Trends over the study period were calculated for annual precipitation and runoff, monthly runoff (all months), and monthly runoff (April – November) for 1978 – 2002 (Table 1). There was no statistically significant trend for any of these data.

Table 1: Statistical values for annual *P* y *Q* for 1978 - 2010. Neither time series is statistically significant.

	P	***Q***
Coef Var (mm)	0.75	0.32
Median (mm)	123.6	20.0
STD (mm)	104	6.4
P-value	0.59	0.68

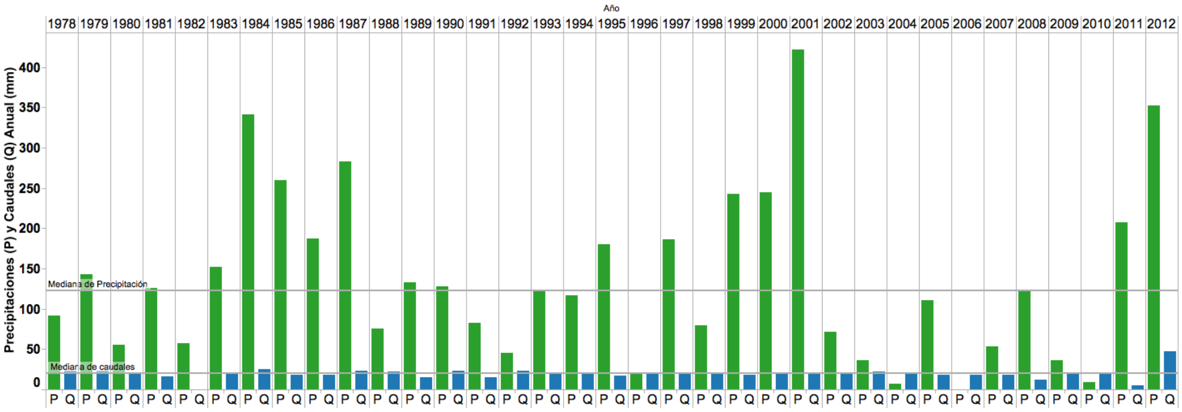
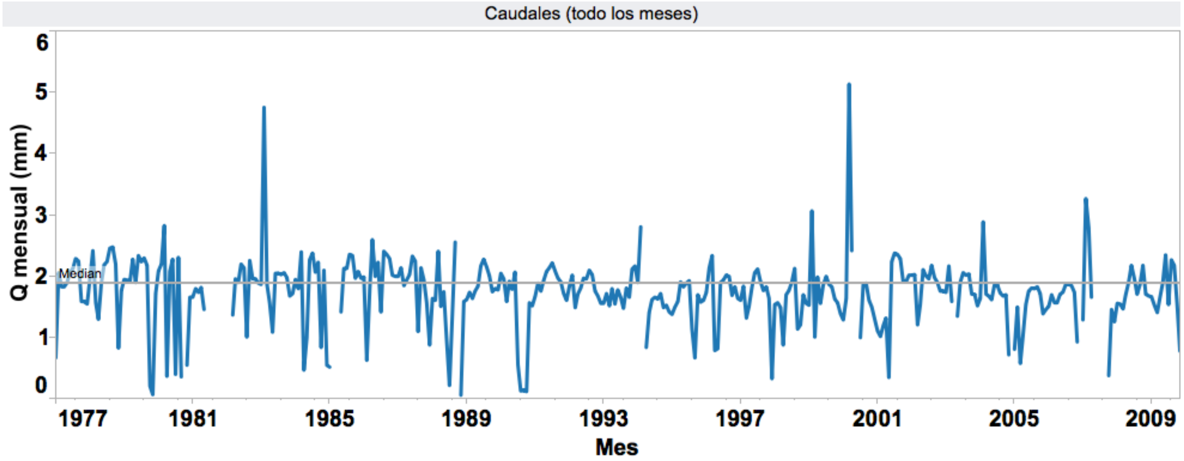
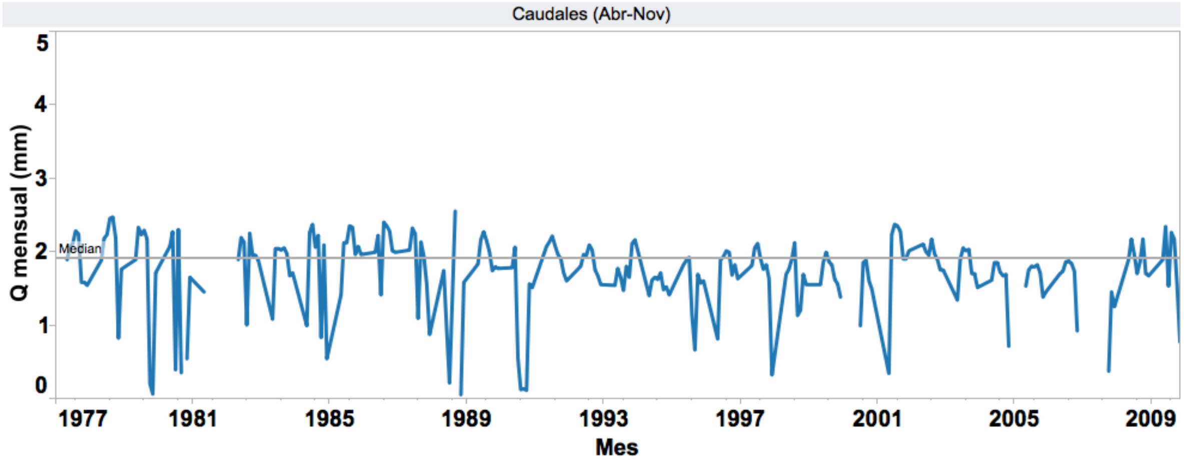


Fig. 3: Total annual precipitation at El Tatio meteorological station and streamflow at Cuchabrachi. The grey line represents the median of total annual precipitation value.





Figs 4a-b. *Q* at El Tatio for all months and for low flow months. The median values are almost identical, 1.88mm for all months and 1.90 mm for Apr-Nov.

Water balance model

Model development

Water balance models provide an accounting-based approach to understand the inflows and outflows of water through a hydrological system. The basic structure of a water balance model is straightforward:

$$Precipitation = Runoff - Evapotranspiration \pm \Delta Storage$$

In the Salar de Atacama, precipitation and streamflow data suggest that groundwater storage is the primary component of the water balance, and can be isolated by:

$$\Delta Storage = Precipitation - Runoff - Evapotranspiration$$

Water balance models can vary in complexity, but the structure of the model should match the available data inputs (Zhang, Walker, & Dawes, 2002). Thus in regions with minimal data available such as the San Pedro watershed in the Salar de Atacama, the model should be developed in as straightforward manner possible.

Using simplicity as its strength, our water balance model requires minimal data inputs and can be calculated in a spreadsheet program like Microsoft Excel. It also allows for the model to be run on hourly, daily, or monthly time steps.

The model used in this study was run at monthly time steps for 1992 -2002 based upon available temperature data (described subsequently). The measurements of precipitation and runoff previously provided measured model inputs.

The climate of the Atacama Desert provides distinct challenges in calculating evapotranspiration. Here potential evapotranspiration (*PET*) will almost always be greater than the amount of water available. The Hargreaves method calculates actual evapotranspiration (ET_o) in data limited environments using an empirically-based approach using mean, minimum, and maximum temperatures and latitude (Hargreaves & Allen, 2003):

$$ET_o = 0.0023(T_{med} + 17.8)(T_{max} - T_{min})^{0.5} R_a$$

Where ET_o is estimated actual monthly evapotranspiration, T_{med} is mean monthly temperature, T_{max} is mean monthly maximum temperature, T_{min} is mean monthly minimum temperature, and R_a is extraterrestrial radiation (calculated from latitude). The availability of T_{max} and T_{min} was the limiting factor for period of study.

While this approach reduced estimated potential evapotranspiration, calculations of ET_o still exceeded available water. Applying calculated rates for ET_o resulted in water deficits for the study period, which did not match physical measurements of streamflow. An explanation for this mismatch between calculated ET_o and measured runoff is explained by the hyper-arid climate of the Atacama. Precipitation that does not infiltrate past 20-40 cm into the soil column is effectively evaporated (Houston, 2006; Johnson, Yáñez, Ortiz, &

Muñoz, 2010). This limits evapotranspiration to immediately following precipitation events. Conceptually, this represents little to no water losses from evapotranspiration for eight months of the year.

To account for the overestimation of calculated ET_o, a prescribed value for monthly scaler for ET_o was developed using a model fitting approach with values described in Table 2. This approach constrains ET_o to better match physical realities—more ET_o during the wetter portions of the year and almost no ET_o during the drier portions of the year.

Table 2: Scalers applied to calculate ET_o by month

Month	**Scaler**
Oct	0.02
Nov	0.05
Dec	0.1
Jan	0.1
Feb	0.15
Mar	0.15
Apr	0.05
May	0.03
Jun	0.03
Jul	0.03
Aug	0.03
Sep	0.02

Model results – San Pedro watershed

The model results provide a conceptual understanding of the inter- and intra-annual relationship between P, Q, ET_o, and Storage (S) in the Rio San Pedro watershed (Fig 5). During years 1993 – 1995, nine individual months with more than 12 mm of precipitation occur. These inputs are not expressed in Q, but are likely responsible for considerable increases in S. The following year, 1996, is markedly drier. However, Q remains consistent, but S decreases. This suggests that the nine precipitation events in 1993 – 1995 increased groundwater stores that then sustained base flows during the subsequent drier year. Years 1997-2000 each have one month with precipitation over 25 mm, and groundwater recharge fluctuates on an annual cycle.

There are a few important considerations in using this model and interpreting these results. The model is not validated, as it is impossible to do so without groundwater data. All values are in mm, it is important to note that while the P, ET_o, and Q are absolute terms, values for S are relative. It is not possible to anchor the S calculations to a fixed datum without groundwater data or aquifer characteristics. However, the timing and amplitude of the S model outputs are assumed to be representative of the timing and magnitude of actual groundwater variations. Despite its limitations, these results demonstrate that this modeling framework functions well describe and quantify the ranges of groundwater recharge and drawdown each year.

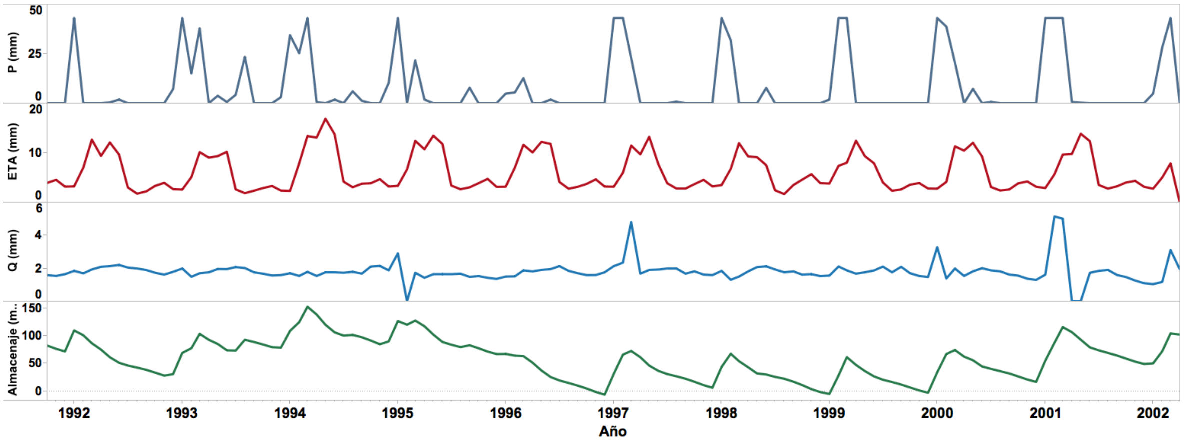


Fig. 5: Model results for the Rió San Pedro watershed.

Model results – comparison to satellite-based measurements of changes in water storage

While there are no direct measurements of groundwater variability in the region, NASA's Gravity Recovery and Climate Experiment (GRACE) satellites provide broad-scale measurements of changes in the monthly amount of water stored across and through the Earth (Tapley, Bettadpur, Ries, Thompson, & Watkins, 2004). Since 2002, GRACE measures monthly changes in the Earth's gravitational field that are proportional to regional changes in total water storage (Wahr et al., 2006). While GRACE data are coarse they provide insights that incorporate all components of the hydrological cycle. They are independent of on-the ground data, making them especially useful in data poor regions. In hyper-arid regions such as the Atacama with negligible soil moisture, the GRACE signal is assumed to represent changes in groundwater storage.

Unfortunately there is no overlap between the model study period and the GRACE data record, but there are similarities regarding the timing and magnitude of total water storage and model outputs. GRACE data shows peak storage during February – April with an annual range of approximately 100 mm in the region around the Salar de Atacama (Fig 6). Model results for the model outputs show the same timing with regards to storage and a range of approximately 60 mm. These similarities do not validate the model, but rather support that the model results are realistic with regards to timing and magnitude.

GRACE data was also applied spatially using 127 months of GRACE data from January 2003 until October 2012. The Sen's-slope (Sen, 1968) was calculated at 1° resolution (same as GRACE inputs) for the Altiplano. A Sen's-slope reflects the median slope of the overall data series and is not over-influenced by outlying data points. In this case an extremely wet or dry year would not skew results. The resulting map shows increases in Terrestrial Water Storage over the southern portion of the Altiplano, which corresponds to an above normal precipitation in 2012 and 2013 (Fig 7).

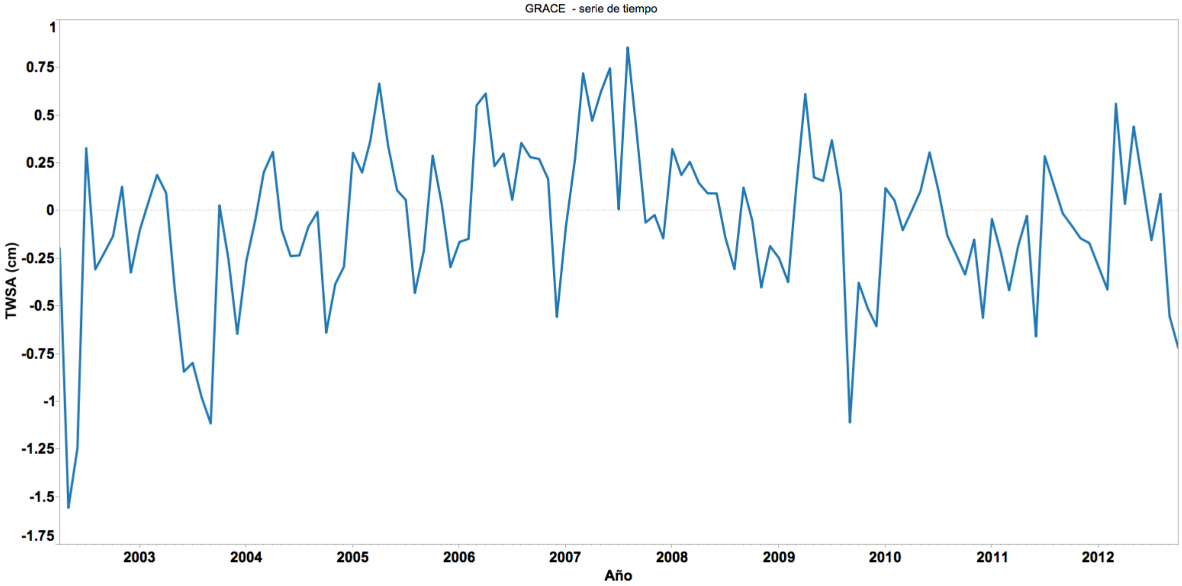


Fig. 6: GRACE data in the area around the Salar de Atacama have the same timing as the results of the conceptual water balance model, and a similar magnitude. The positive and negative values represent anomalies from the long-term mean value. These changes should be thought of as a water depth distributed across the region.

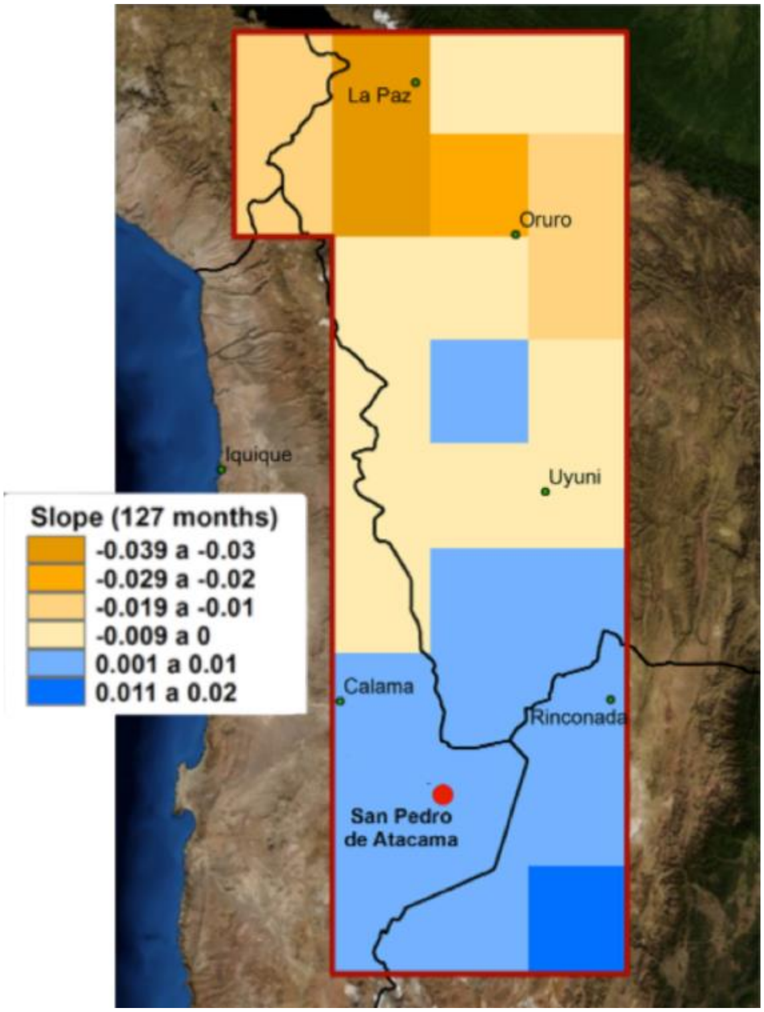


Fig 7: The Sen's slope calculated across the Altiplano from 2002 – 2013. Results show a general increase in the amount of water in the southern portion of the region, and a decrease in the northern portion.

Model results – sensitivity analysis

This same modeling framework was applied to climate data to test the sensitivity of three sub-watersheds in the study area to changes in precipitation and temperature. The study watersheds are Rio San Pedro, Valle de la Luna, and Rio Vilama, and are identified in Figure 1. The input data sets are derived from individual climate stations from 1950 – 2000 and distributed at 1 km spatial resolution (Pliscoff, Luebert, Hilger, & Guisan, 2014). The monthly input climatology forcings of P, T_{med}, T_{max}, and T_{min} were used to calculate ET_o for each grid cell. The ET_o values were then adjusted using the same scalars as described in Table 2.

The same basic water balance model framework (P - $ET_o = S$) was applied at each cell in the raster. Values for S were summed at each monthly time step in three demonstration watersheds (Rio San Pedro, Rio Vilama, and Valle de la Luna; Fig. 1).

This approach provides an overview of S the timing and magnitude of water fluxes. However the model results have a very strong relationship with the mean of the GRACE signal (Figs: 8 – 9a-b). The temporal match with GRACE data does not provide a fully validated model, but it does strongly suggest that the model that was developed conceptually represents measured fluxes of water in the study area.

We next tested the sensitivity to increases or decreases in P and T. Using the same modeling framework, the P and ET_o inputs were then perturbed by ±10% in order simulate climate variability. Each perturbation was run individually for five total model iterations for 12 months.

The results show that the Rio San Pedro and Rio Vilama are most sensitive to variability in P, and less sensitive to variability in PET (Figs. 9a-b). However, the Valle de la Luna is insensitive to fluctuations in P or PET, as this sub-watershed simply does not have any water to gain or lose (Fig. 9c).

The results of this section demonstrate that climate variability are not expressed equally across the region. The results provide a conceptual analysis and numerical values should be interpreted with caution.

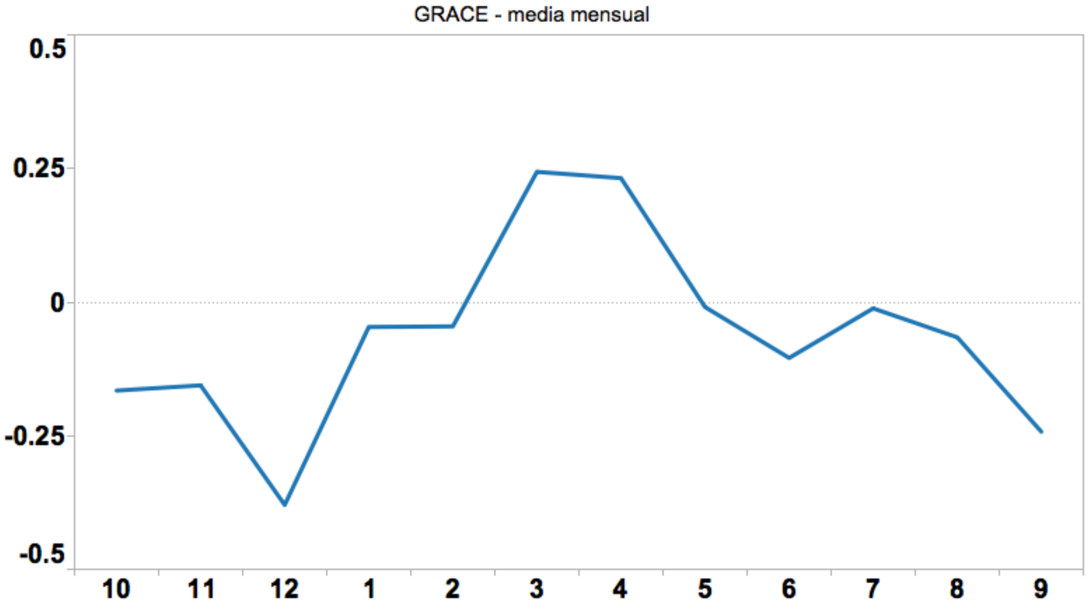
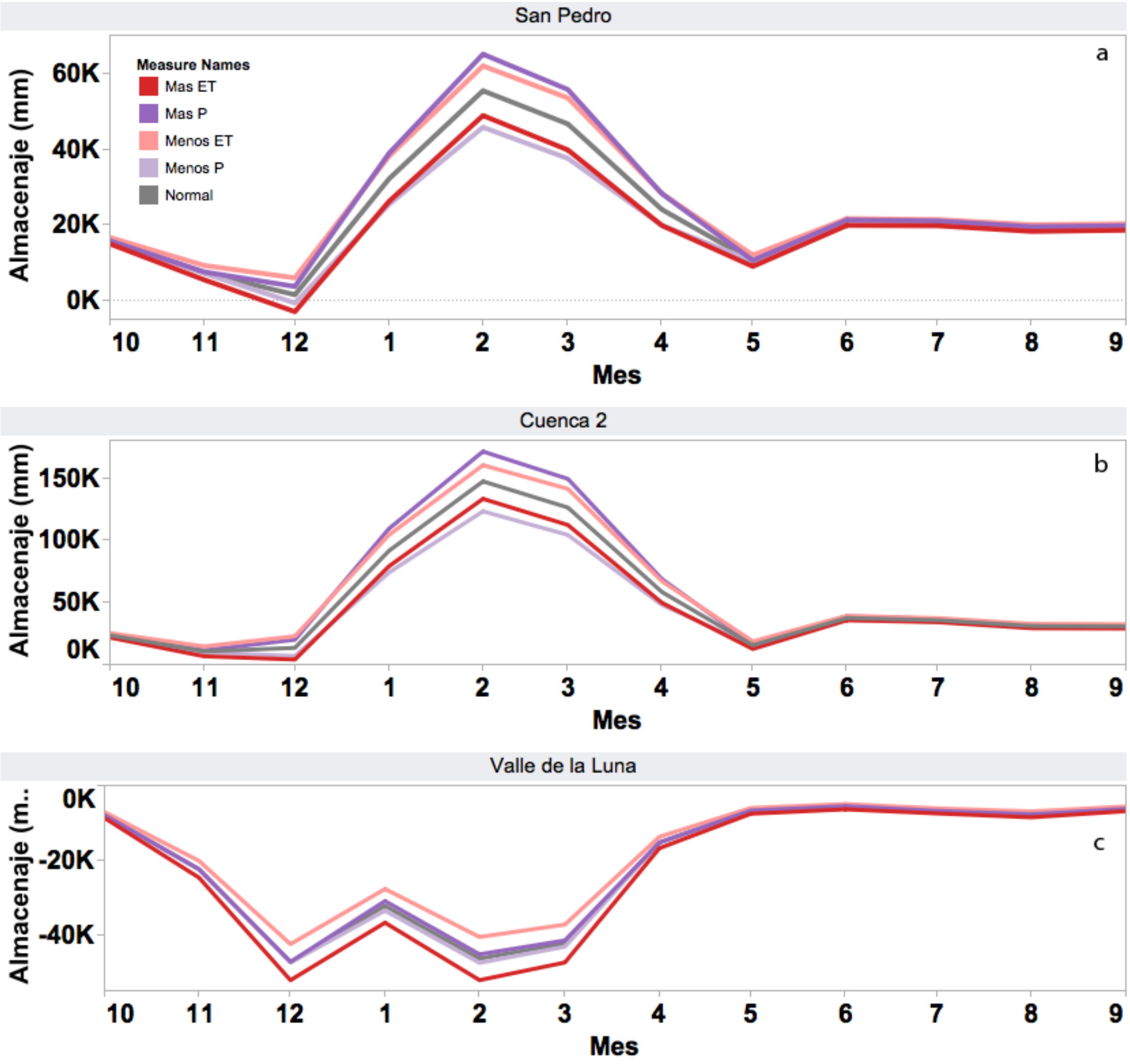


Fig. 8: GRACE data in the area around the Salar de Atacama and are averaged by month. These GRACE data show the same temporal pattern as the modeled results using the climatologies for years 1950 – 2000 shown in figures 9a-c.



Figs 9a-c: Sensitivity analysis of each of the three pilot watersheds Each of the three test watersheds. Almacenaje is the Spanish word for storage.

Future work

Model improvements

The straightforward modeling effort provided a positive first step into modeling the water resources of the Salar de Atacama. Potential improvements to the model will be incorporated in the next version that incorporates physical process (Controls on the amount of runoff and recharge, rate of groundwater runoff, and improved estimations of ET_o).

Extending the data series would provide the opportunity for direct comparison to the GRACE satellite record. However, currently published T_{max} and T_{min} data extends only to 2002 for the El Tatio meteorological station.

Extending the model

These model improvements will be applied to the spatially based model for the entire Salar de Atacama region.

Scenarios for the sensitivity analysis of the model will also be increased to show consecutive years of drought or increased precipitation, and applied to the entire Salar de Atacama region.

Data and research needs:

- *Hydro-climatic monitoring network in real time* – presently the region has a very sparse monitoring network. These minimal hydro-climatic data are typically available months to years later, preventing management based on current conditions. A network would have direct value for water management, scientific research, and for the public.
- *Continuous measurements of ground water in monitoring wells* – Pressure transducers will allow calculating aquifer characteristics and monitoring of wells. These data will greatly improve the capabilities validate a model and management of groundwater resources.
- *Continuous measurements of water levels in bofedales and salares* – Pressure transducer in these surface bodies of water provide a cost-effective means to monitor the amount of terrestrial water stored in the region. These data will be key in applying understanding the relative amount of water that exists in the region. Additionally, these will provide the first step in using GRACE data for longer-term water management.

Table 3: Description of variables and units of measure

Measurement	**Units**
Runoff (Q)	mm/time step
Precipitation (P)	mm/time step
Evapotranspiration Actual (ET_o)	mm/month
Storage (S)	mm/month
GRACE Terrestrial Water Storage Anomalies (TWSA)	Anomaly from mean (cm)

Works cited:

Bowman, I. (1914). Results of an Expedition to the Central Andes. *Bulletin of the American Geographical Society*, 161-183.

Hargreaves, G. H., & Allen, R. G. (2003). History and evaluation of Hargreaves evapotranspiration equation. *Journal of Irrigation and Drainage Engineering*, *129*(1), 53–63.

Houston, J. (2006). Evaporation in the Atacama Desert: An empirical study of spatio-temporal variations and their causes. *Journal of Hydrology*, *330*(3), 402–412.

Johnson, E., Yáñez, J., Ortiz, C., & Muñoz, J. (2010). Evaporation from shallow groundwater in closed basins in the Chilean Altiplano. *Hydrological Sciences Journal–Journal Des Sciences Hydrologiques*, *55*(4), 624–635.

Pliscoff, P., Luebert, F., Hilger, H. H., & Guisan, A. (2014). Effects of alternative sets of climatic predictors on species distribution models and associated estimates of extinction risk: A test with plants in an arid environment. *Ecological Modelling*, *288*, 166–177.

Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association*, *63*(324), 1379–1389.

Tapley, B. D., Bettadpur, S., Ries, J. C., Thompson, P. F., & Watkins, M. M. (2004). GRACE measurements of mass variability in the Earth system. *Science*, *305*(5683), 503–505.

Wahr, J., Swenson, S., & Velicogna, I. (2006). Accuracy of GRACE mass estimates. *Geophys. Res. Lett.*, *33*(6), L06401. doi:10.1029/2005gl025305

Zhang, L., Walker, G. R., & Dawes, W. R. (2002). Water balance modelling: concepts and applications. *ACIAR MONOGRAPH SERIES*, *84*, 31–47.