Multitemporal remote sensing analysis of a playa lake groundwater system in northern Chile

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Introduction

Salar de Ascotán and Salar de Carcote are internally-drained, evaporative basins located in Region II of Chile. They are connected by a regional groundwater system, which is locally expressed as spring-fed surface water flows on the salar surface. The relative fresh surface water supports diverse flora and fauna, such as migratory flamingo, llama, huanaca, and vicuna and an endemic fish species, *Orestias ascotanensis*. Copper mining projects in the region also depend on the shallow groundwater system of the salars, and in particular pumping initiation in the mid-1990's at Salar de Ascotán raised concern about the preservation of the surface water flow for ecological conservation. Remote sensing provides an opportunity to assess anthropogenic and/or climatic impact over time for the regional groundwater system associated with the salars. Future water management in the region seeks to maintain ecological diversity as well as economic progress, and remote sensing can act as a tool for large-scale monitoring and can also inform pumping regimes for optimization.

Background

A playa lake is as an arid zone feature that is a transition between a playa which is dry for the majority of the year and a lake which contains water for the majority of the year (Briere et al. 2000). In general the term salar is interchangeable with playa lake, but more specifically for my study, a salar is an internally drained, intravolcanic, evaporative basin. The main differentiation between the salars of my study and the general playa lake definition is that there is perennial surface water, which is fed solely by a groundwater system as springs. The two salars I focus on are located at 4,000 meters above sea level in El Loa Province, Chile; about 100 kilometers from the Bolivian border (Figure 1). These salars are part of the hyper-arid Atacama desert, where average annual precipitation ranges from 50 to 300 millimeters, with potential evapotranspiration greatly exceeding that (Risacher et al, 2003). The majority of precipitation occurs as snowfall on the eastern peaks during the summer months of November to February, commonly referred to as the “Altiplanic Winter.”

Regional geology is controlled by active volcanism and N-S trending compressional faults from the oceanic-continental subduction margin (Hartley et al., 2000). The regional faulting plays a major role in governing the size and morphology of the intravolcanic salar basins, and in particular the springs at Ascotán are proposed to occur along a fault plane. Further, active volcanism in the region implies geothermal-driven groundwater flow, as opposed to the normal hydraulic gradient dependent on elevation and pressure. Local stratigraphy of the salars includes Ca-Mg salt crusts which overlie interbedded Cenozoic tuffs and sedimentary strata, with a deep carbonate sequence that could play host to the regional groundwater system (Stoertz and Ericksen, 1962).

Keller and Soto (1998) describe the regional groundwater system which serves as the basis for this study. The system initiates as recharge from thermally-enhanced snowmelt in the Pastos Grandes caldera, which infiltrates as recharge and follows the general NW fault-block tilting before it discharges locally at Salar de Ascotán (Figure 2). The spring-fed surface water flows in the same NW direction and either evaporates or reinfiltrates as a brine to the shallow water table. This shallow brine feeds the spring-flow at Carcote, and the groundwater system ultimately terminates in the regional topographic low of Salar de Uyuni. The evidence for hydrologic connection between the Pastos Grandes caldera and Ascotán and between the two salars is observational, and so remote sensing can be used to further assess hydrologic connections of this proposed system.

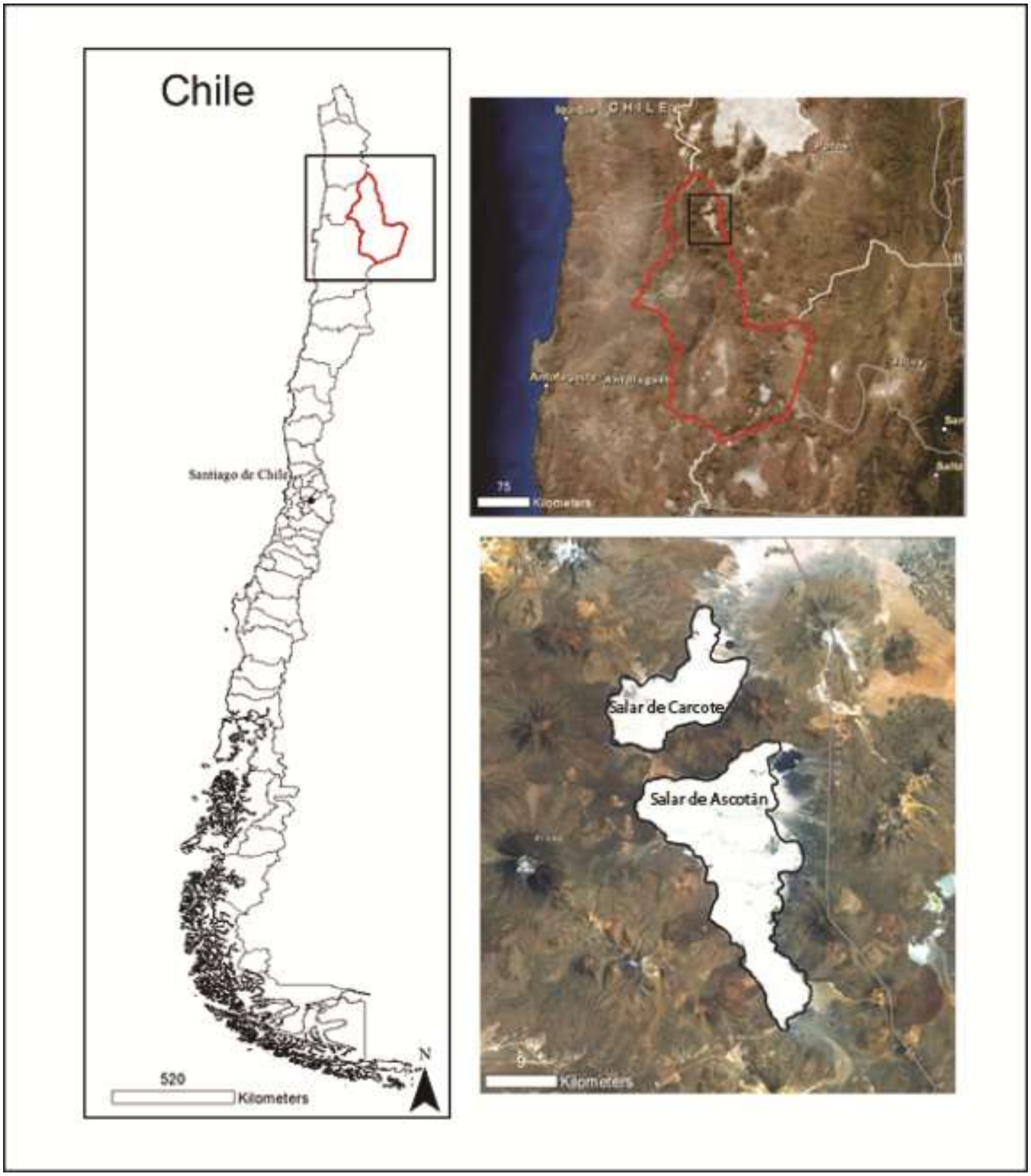

Figure 1. Map of El Loa Province in Chile, with regional and local inset satellite imagery of Salar de Ascotán and Salar de Carcote (source: ERSI ArcGIS 10 Base maps).

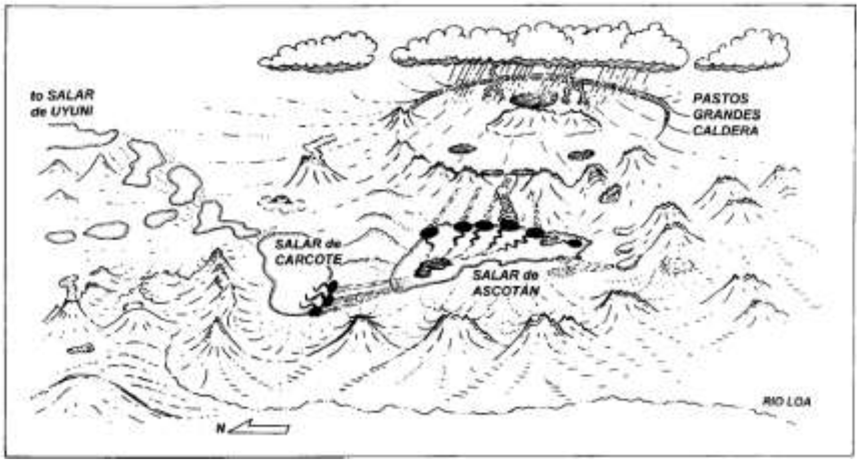

Figure 2. Conceptual diagram of the proposed regional groundwater system (Keller and Soto, 1998).

The water budget for a playa lake can be described by Equation 1, but the hydrologic regime and climate of these salars allows for several assumptions and simplifications to the budget. First, the basins are internally drained and the only source of water is from the springs, thus the surface water input and output term can be eliminated. Further, direct precipitation to the surface is negligible and snow accumulation on the surrounding peaks sublimates before reaching the surface, and so the precipitation term can be eliminated to result in Equation 2 (Figure 3). Finally, we can assume that evaporation and infiltration rates are not changing significantly over time, and so a change in volume of water is indicative of changes to the groundwater system over time. Remote sensing of water extent is useful then because it can be used to quantify a change in area, and since the salars possess relatively low topographic relief, this can be used as a rough analog to the groundwater system.

$$\Delta V = (P + I_{GW} + I_{SW}) - (ET + O_{GW} + O_{SW}) \quad (1)$$

$$\Delta V = (I_{GW}) - (ET + O_{GW}) \quad (2)$$

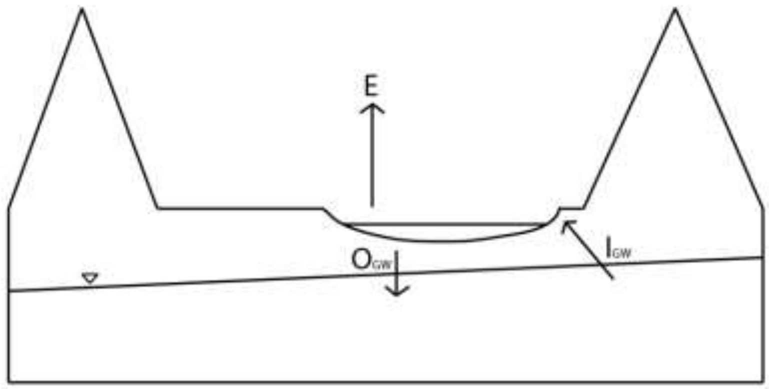

Figure 3. Conceptual diagram of the salar water budget.

Objective

1. To develop a methodology for quantifying water extent on the salars over time as an analog to the groundwater system.
2. To validate/refute the Pastos Grandes Caldera as a recharge zone.
3. To assess change over time for the salars with respect to climate and anthropogenic activity.

Methods

For the remote sensing analysis, I chose to use Landsat (5 TM and 7 ETM+) orthoimagery because it is the most temporally comprehensive dataset available, with relatively continuous global coverage from 1972 to the present and a 30 meter pixel resolution, which is reasonable given the size of my field area. In total, 13 scenes over the time period of 1985-2011 were downloaded from the USGS Landsat Archive, which provides cloud-free, georeferenced, and orthorectified images in a GeoTIFF format (Figure 4). 5 of the scenes were chosen over the course of 2009 to establish seasonal response to wet/dry periods, as well as to determine the best window of which to assess long-term changes. The scenes were then imported to ESRI ArcGIS 10 where I performed a "Layer Stack" to combine each of the spectral bands, projected the stack using the WGS 1984 Datum and UTM Zone 19S projection, and clipped the raster to the salar and caldera extent.

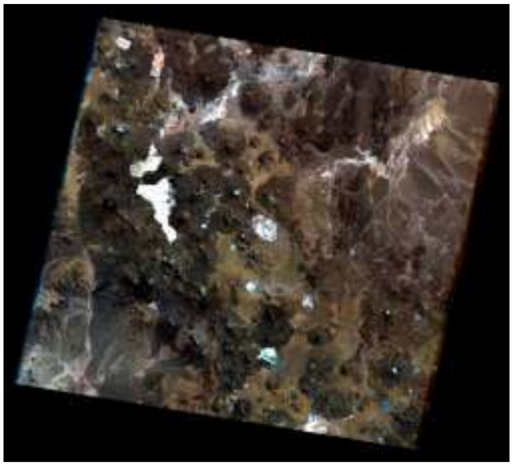

Figure 4. Example of a stacked Landsat scene (Row: 75/Path: 233).

Following the pre-processing in ArcGIS, I performed the various remote sensing analyses using ERDAS Imagine 2011: Optical Analysis of single band and “false” composite images, Normalized Difference Water Index (Xu, 2006), unsupervised classification (Casteneda et al., 2005), and supervised classification (Lillesand and Kieffer, 1987). Finally, to quantify the total and compartmentalized water extent, I imported the classified water pixels as a layer in ArcGIS and clipped the layer to correspond with North Ascotán, South Ascotán, and Carcote (Figure 5). I did not acquire the pumping and meteorological data in time for this term project, and so precipitation data was taken from the NASA TRMM dataset, which provides monthly average rain rates for the region from 1998-present.

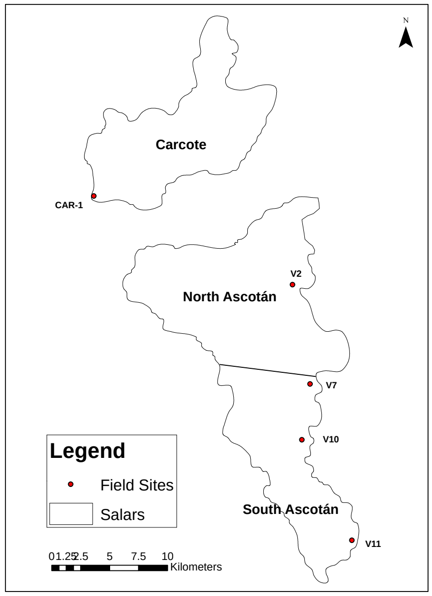

Figure 5. Map showing the spatial division utilized in the remote sensing analysis.

Results and Discussion

The first objective was to develop a remote sensing methodology for classifying and quantifying surface water extent (Figure 6). Different band combinations can be performed to create a 'false' image, which enhances absorbance of water bodies and maximizes surface reflectance of the salt crusts (Lillesand and Kieffer, 1987). This method is good for optical analysis, and while it does not allow for a quantification of water pixels, it works as an error reference for other classification methods. The first method I applied to the salars was the Normalized Difference Water Index (NDWI) developed by Xu (2006). This method is similar to the NDVI, in that it utilizes band differencing to extract water pixels, shown by Equation 3. This method overestimated the water extent, and also resulted in incorrect classification of water pixels in the surrounding mountainous areas. I hypothesize that the error is result of this algorithm's dependency on atmospheric and geometric correction of the data.

$$\text{NDWI} = (\text{Green} - \text{NIR}) / (\text{Green} + \text{NIR}) \qquad (3)$$

The next remote sensing method I utilized was an unsupervised classification, where I generated 50 classes with a convergence of .975 and 100 iterations. This method has previously been applied to classifying water-related facies in salars, and it relies on the inherent spectral and spatial autocorrelation of the pixels (Castaneda et al., 2005). Of the resulting classes, I found two that correlated best with the water extent on the false composite, but there was still a significant overestimation of water extent on the salar and the surrounding area. I hypothesize that this error is a function of geometric and atmospheric effects, but also a function of the spectral variability depending on water depth and salinity. The final method I tested was a supervised classification of the salar water extent. This method requires a user to define the classes by creating 'training polygons' which the computer program can then use to classify the remaining pixels in the image. The results showed the best agreement with the false composite image, and also leave hope for a possible quantification of volume based on my field measurements of water depth at various locations throughout the salars.

The next step towards a mutlitemporal remote sensing analysis was season selection, and I did this by plotting the water area over the course of a wet and dry season for the year of 2009 (Figure 7). The results show a lagged response to the rainy season, followed by a recession for the rest of the year. This lagged response is a expected for a regional groundwater system, because the recharge must travel over a distance before it is expressed as increased springflow to the salar surface. From this initial multitemporal analysis, I found a general average water extent between March and August, and thus used that as a window for scene selection over the entire time period of 1985-2011.

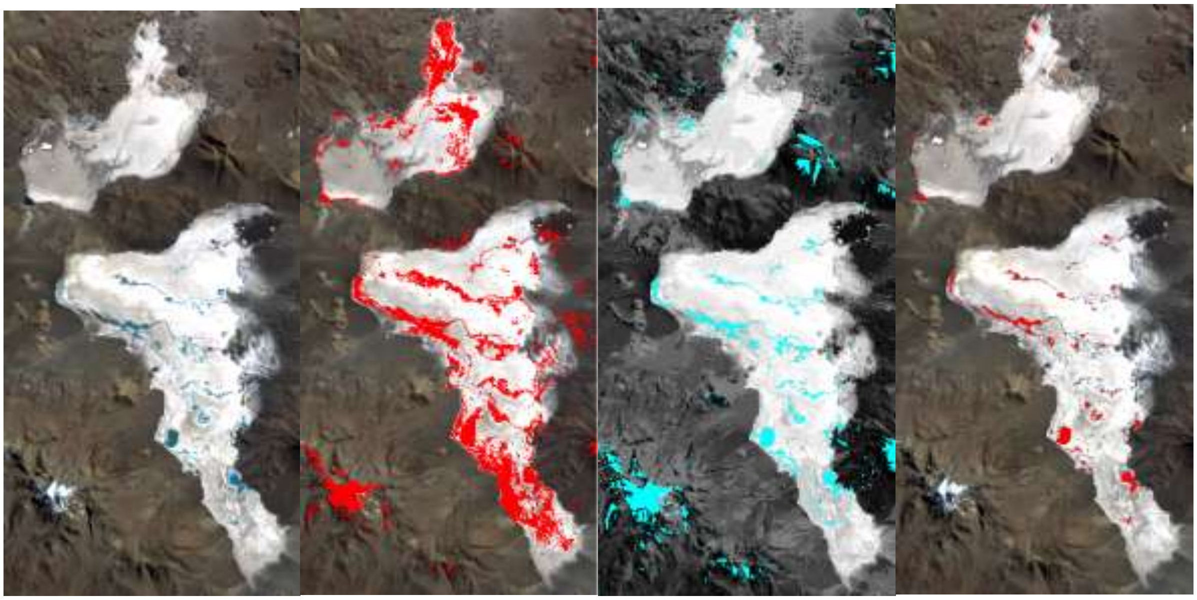

Figure 6. Screen captures of the methods utilized to attempt to classify water extent. From left to right, Optical Analysis, NDWI, Unsupervised Classification, and Supervised Classification.

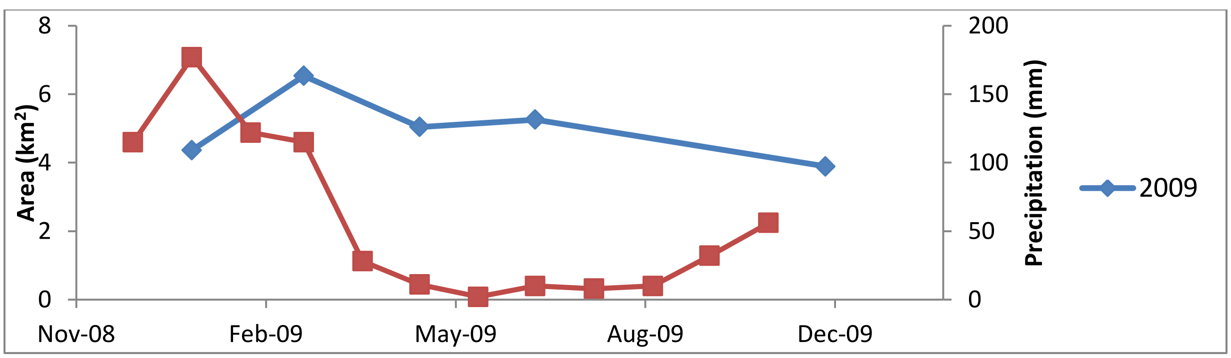

Figure 7. Initial multitemporal analysis for season selection.

The second objective of this study was to validate or refute the Pastos Grandes caldera as a recharge zone for the regional groundwater system. From looking at false composite images, my initial observations show a clear relationship between water presence in the caldera and water presence on the salars (Figure 8). To further test this hypothesis, I performed a supervised classification of the water extent for the caldera and plotted the resulting area versus total water area on the salars (Figure 9). The graph shows a fairly positive correlation, with the exception of a major outlier, which results in a statistically poor regression (R^2=.23). I plotted the same results without the outlier point, and the resulting regression shows a really good correlation (R^2=.85) between caldera and salar water extent (Figure 10). While I cannot ignore the outlier point, I hypothesize that the image was taken following a large precipitation event but preceding the salar response. This is supported by a clear time lag demonstrated from the 2009 analysis, and I plan to test this hypothesis by adding an image from a few months later to see if the salars do in fact respond.

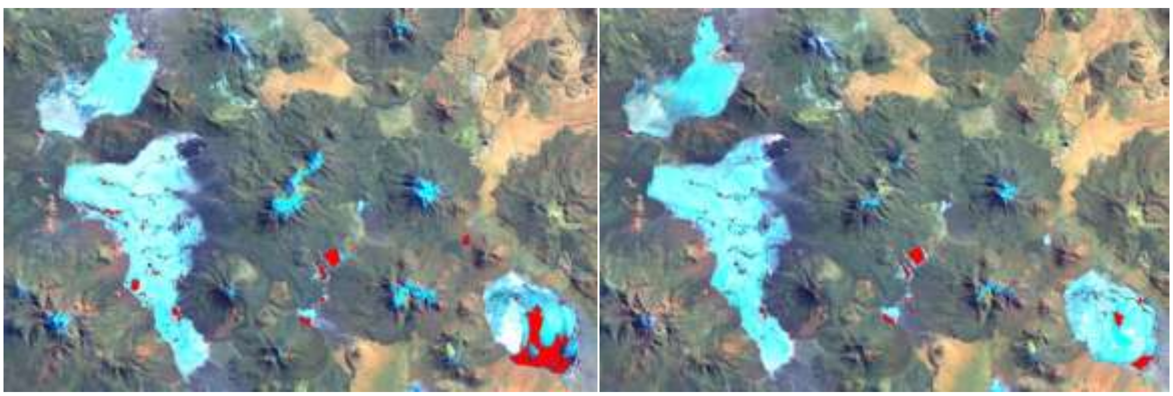

Figure 8. False composite showing the change in water extent in the salars with respect to the caldera from August, 1985 to August, 1990.

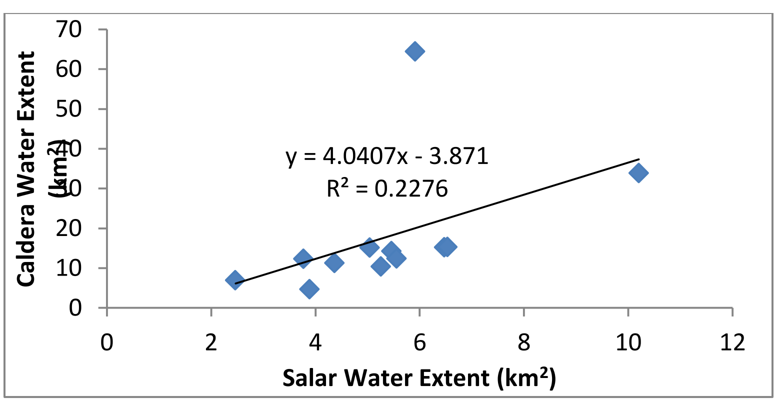

Figure 9. Plot of water extent on salars versus the Pastos Grandes caldera, including the outlier point.

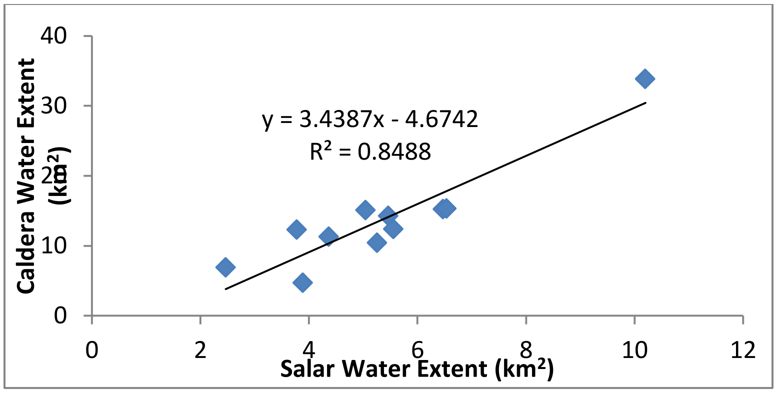

Figure 10. Plot of water extent on salars versus the Pastos Grandes caldera, excluding the outlier point.

The final objective of this study was to assess the change over time of salar water extent with respect to climate and anthropogenic activity. The full multitemporal water extent results reveal a dynamic system (poor R^2 value of .41) that, in general, has diminished over time (Figure 11). Pumping for the mining project initiated in 1997, which corresponds with a sharp decrease in water presence, but further analysis of precipitation data for the region also shows a steady decline in the rainfall peaks from 1998 to the present (Figure 12). Future work is needed to obtain and analyze pre-pumping precipitation data, because the sharp decline may also correspond with a period of lower precipitation over the Pastos Grandes caldera. Furthermore, since pumping is only currently taking place in the southern portion of Salar de Ascotán, I wanted to see if remote sensing could be used to establish a hydrologic connection within the Ascotán basin, as well as between the Ascotán and Carcote basins. The results of this show a minor cross-over between north and south Ascotán that occurs around 1985, and a second cross-over that occurs around the time of pumping initiation (Figure 11). The second cross-over is expected, because pumping decreased spring flow in the southern portion, but the first cross-over suggests a hydrologic disconnect in that the springs at the north end of the basin may be fed by a different flow system than the south end. Further hydrochemical analysis of conservative ions, temperature, and stable isotopes will be utilized to possibly decouple the two flow systems. Carcote, however, shows a muted response to the changes occurring in the Ascotán basin, which validates the proposed connection between the two salars. Additionally, the water extent does not appear to be diminishing over time at Carcote, which suggests that the magnitude of pumping has not significantly affected the groundwater system beyond the southern springs of Ascotán.

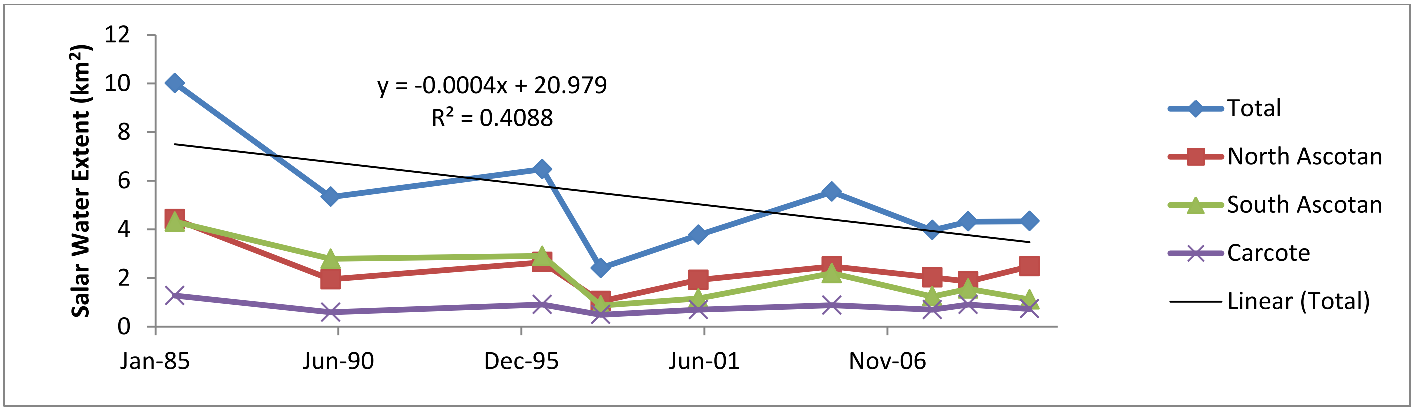

Figure 11. Multitemporal plot showing total salar water extent, as well as Carcote, and north and south Ascotán .

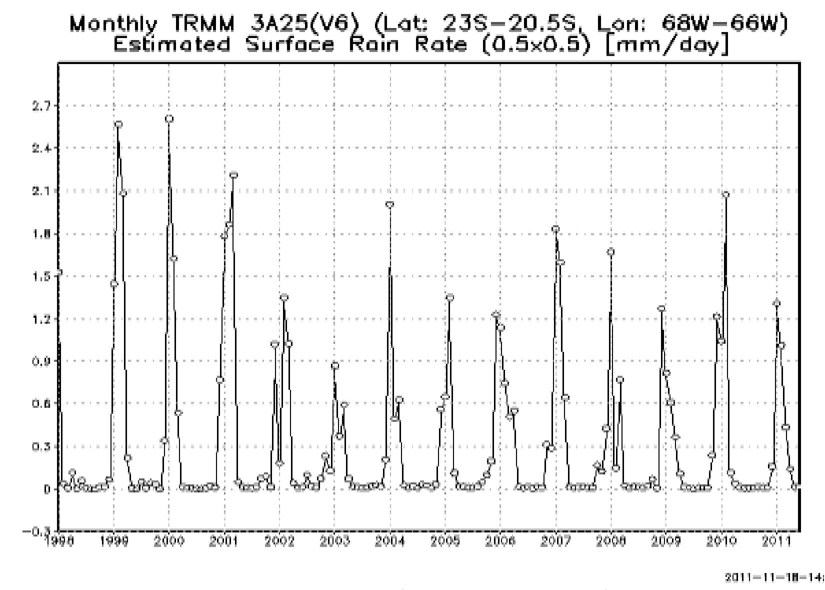

Figure 12. Regional monthly precipitation from 1998-present (NASA).

Conclusions

This study found that remote sensing can be used as a tool to assess the groundwater system associated with Salar de Ascotan and Salar de Carcote. I developed a methodology to quantify surface water extent using false composite images and a supervised classification method. I found a positive correlation between the Pastos Grandes caldera and water extent on the salars, while future work remains in addressing the outlier point. The multitemporal analysis revealed that total surface water extent has decreased since 1985, but it is not certain whether the cause is predominantly anthropic or climatic. Finally, Carcote shows a muted response to the changes at Ascotán, but the hydrologic relationship between North and South Ascotán remains a question. Future work remains in integrating hydrochemical analysis to further assess the decoupling and/or connectivity within and between the salars.

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