Fall November 2014

ENVIRONMENTAL CHANGE AND THE AGRO-PASTORALIST LIVELIHOOD IN THE ANDES OF PERU

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Recommended Citation

Mazzarino, Meagan M., "ENVIRONMENTAL CHANGE AND THE AGRO-PASTORALIST LIVELIHOOD IN THE ANDES OF PERU" (2014). *Doctoral Dissertations*. 276.
https://doi.org/10.7275/qzke-8r21 https://scholarworks.umass.edu/dissertations_2/276

ENVIRONMENTAL CHANGE AND THE AGRO-PASTORALIST LIVELIHOOD IN THE ANDES OF PERU

A Dissertation Presented

by

MEAGAN M. MAZZARINO

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

September 2014

Water, Wetlands, and Watersheds

ENVIRONMENTAL CHANGE AND THE AGRO-PASTORALIST LIVELIHOOD IN THE ANDES OF PERU

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DEDICATION

This dissertation is dedicated to the people in Nuñoa, Peru, particularly the alpaca herders. It is also dedicated to my family.

ACKNOWLEDGMENTS

Many people have provided their guidance and support along the long and winding road that has led to this dissertation. First I would like to thank my PhD committee and specifically my co-chairs Paul Barten and John Finn for having faith in this interdisciplinary project and in my abilities to see it through. I would also like to thank each committee member individually since such an interdisciplinary topic required more participation than usual from every member at one time or another. Furthermore, R. Brooke Thomas shared his enthusiasm, knowledge, and past faux pas of the Andean region with me. In doing so, he helped shape this research and ensured that I was properly prepared to take on the challenge of field work in a remote region at an elevation above 4,000 meters. Brooke's sincere support of me and this dissertation is so very valued. John (Jack) Finn has taught me much about statistics, GIS, and remote sensing. But more importantly, he has taught me much about statistics, GIS, and remote sensing in an atmosphere of patience, encouragement, and understanding. I will miss sitting at the table, eating chocolate, and erupting in laughter over various topics of conversation with both Jack and Maili Page. Over the years Maili's friendship and reality checks have been invaluable. Sarah Raposa, my wonderful friend since our undergraduate days as aspiring geologists, continually offered her support throughout my PhD years. Our various short, but laughter filled vacations always provided the re-energizing motivation that was needed to get me to the finish line. Suzanne Holt has been there for me and for our family on numerous occasions. If it were not for her help with logistics of child care then this dissertation would not have been possible. Thank you Suze!

There are several people in Peru who unselfishly provided their time, energy, and effort to help me achieve my research goals. The fieldwork component of this research was possible and successful because of their support. Uriel Alex Montúfar Condorena and Sra. Luz Marina

Antezana Velasquez dedicate so much of themselves to assist others that they have my utmost respect. I thank them for their help on many levels. Victor Hugo Gutierrez Morales and Jimmy Boza Monge helped with transportation and equipment installation. I thank all of the members of the herding community who were so gracias as to allow me and three other foreigners into their lives for a short time and share their thoughts and knowledge with us. I also thank the Cala/Caceres family for opening their home to me during each of my visits. It has been a pleasure getting to know them. Henry Lyle III, Alyse Wheelock, and Anna Culver made one of the research trips so enjoyable that I can't image Nuñoa without them and their music. I would also like to thank Professor Tom Leatherman for all of his guidance and for the times we've spent "talking Nuñoa" over coffee.

Finally, I would like to express my love and gratitude to my family not just for their support during the dissertation years but for their love through all of the years.

ABSTRACT

ENVIRONMENTAL CHANGE AND THE AGRO-PASTORALIST LIVELIHOOD IN THE ANDES OF PERU

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This dissertation research focuses on a high elevation Andean social-ecological system. It examines system linkages between climate, grazing pasture (wetlands), and agro-pastoralist livelihood strategies in an indigenous peasant community. Working within the conceptual framework of complex systems dynamics and sustainable livelihoods analysis, methods and concepts are synthesized from the disciplines of climatology, hydrology, remote sensing and political ecology, and results contribute to the transdisciplinary literature on vulnerability analysis within the context of environmental change.

In the Andes of southern Peru livelihoods are based on agro-pastoralist activities that rely on access to natural resources in the puna ecosystem. The majority of pastoralists in the study region are indigenous Quechua who in the higher elevations raise herds predominantly of alpaca and sheep. This region in Peru has the highest density of alpacas and is a national leader in the production of fiber. The people in the District of Nuñoa are extremely proud of their alpaca herding heritage and have recently declared the district to be the “World capital and patrimony of the Suri alpaca”. Alpaca are therefore both economically and culturally important. Together with other members in the camelidae family (llama, vicuña, and guanaco), alpaca are well suited to the high elevation puna ecosystem. Wetlands in the puna, known as *bofedales*, have hydrological and biological characteristics that make them a vital resource to the pastoralist livelihood.

Climatic and environmental perturbations may be more pronounced in mountain regions and the affects to local water balance, ecosystems, and humans may be more profound. The sensitivity, adaptive capacity, and hence vulnerability of individuals, groups, and livelihoods to perturbations is a complex function of social, political, and environmental factors. This research uses a hierarchy of spatial scales to understand climate variability in the region as well as spatial and temporal changes in the natural resource base. A case study of an agro-patoralist community allows for the characterization of two disturbance regimes (climate and land use and management) and the linkages between components in the herding system and climate system. The results indicate that there is periodicity in the regional hydroclimatology but a deterioration of the resource base in the watershed. Economic and political factors may be contributing to the overuse of natural pastures which increases the future vulnerability of alpaca herders to environmental change in the Nuñoa watershed.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This dissertation is an endeavor to characterize climate variability and environmental change together with contemporary agro-pastoralist livelihood strategies in an Andean watershed. A primary goal of this research was to quantify the changes in a natural resource base that is essential to the pastoralist system. This resource base includes natural pastures of the puna ecosystem as well as areas known as *bofedales*. *Bofedales* are high elevation wetlands, similar to fens that maintain saturated soils and dense vegetation throughout the year, including the dry season. As a result, *bofedales* are a critical grazing resource especially for alpaca. Vegetation vigor is highly correlated with precipitation and the Altiplano is a region known for year to year variability in climate. Thus, the interannual variability in precipitation and vegetation was investigated as well as were trends over time. Another facet of this dissertation involved understanding and where possible, decoupling local, regional, and global drivers of variability and change.

The objective of this research was to gather information across spatial scales to increase our understanding of the contemporary agro-pastoralist system in the Andes of Peru. As such, the research draws on several areas including the fields of remote sensing, hydrology, and climatology as well as from the international development field and the social sciences. The characterization of the human-environment system and each of the components is in no way complete nor is it as thorough compared to if the focus were limited to one field or component. However, the aim was to describe several key elements in the human-environment system with a focus on the physical environment and to illustrate how these elements are interrelated. In doing so it was understood that additional questions and future research areas would arise.

As with most studies, the formulation of a research concept and its underlying tenets is largely based on the evolution of theory and results that have emerged from the work of predecessors. The research topic and choice of field site was largely influenced by Brooke Thomas, Professor Emeritus of Anthropology and a member of this dissertation committee. Professor Thomas has worked on human-environmental issues in the Nuñoa region for over 40 years. Much of the early literature on pastoralist systems in the Andean region stems from anthropological and ethnographic research (e.g., Murra 2002 and Mayer 2002). In the 1960s through the 1970s Nuñoa was the site of several long term anthropological studies spearheaded by Paul Baker (see Little, Thomas,and Garruto 2013 for a more detailed historical account). These studies focused on high altitude biology and adaptation research with an emphasis on the biological and behavioral components of the human system. Many of the concepts and theoretical frameworks put forth in these earlier works still apply and have become widely used in recent years, especially with respect to climate change. The concept of adaptation for example, as “the ability of an organism or population to respond to conditions in such a way as to maintain critical components or variables within their limits…” (Thomas 1979:140) remains relevant to this research. The works of Brush (1976, 1982) and Winterhalden and Thomas (1978) provide early descriptions of the ecosystem, environment, and modes of agricultural production by high elevation Andean communities. Schematic and simulation models by Thomas (1976) and McRae (1984) diagram several interrelated components in the Andean pastoralist subsistence system such as key resources, required inputs, resulting products, and the processes involved in the production and exchange of goods. In most of these studies and others on the Andean pastoralist system the interaction between climate and the production of agricultural goods is rather explicitly explored and discussed. In these pre-climate change years the focus is on seasonality and the year to year climate variability with a large interest in drought. Hence, natural climate variability is one important aspect of the human-environment system in the Andes. This includes intraannual variability (seasonality) as well as interannual variability.

Global climate change has become an issue of increasing concern since the 1980s. The latest International Panel of Climate Change (IPCC) defines climate change as “a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer” (IPCC 2014). Green house gases have increased over the last 200 years and land and sea surface temperatures have increased over the last 100 years. As a result, surface humidity is increasing. Increased moisture leads to more intense storms and precipitation events (Cubasch et al. 2013). Furthermore, El Niño-Southern Oscillation (ENSO) (the anomalous warming or cooling of the equatorial Pacific) influences global mean temperatures (Trenberth et al. 2007). There is some indication that there has been a trend toward more extreme ENSO events in the 20th century (Gergis and Fowler 2009). However, based on model results, there is no consensus on how the behavior of ENSO (frequency and amplitude) will change with climate change (Meehl et al. 2007). In the Altiplano region a good proportion of the variability in precipitation is attributed to ENSO (Garreaud and Aceituno 2001) with dry (wet) years often corresponding to the El Niño (La Niña) phase of ENSO. Thus, there is uncertainty in how the nature of droughts and floods will vary in the future. Additionally, consistent with documented decreases in snow cover, reductions in glaciers, sea ice and ice sheets (Cubasch et al. 2013) the world over, Andean tropical glaciers are receding at accelerating rates (Rabatel et al. 2013; Buffen et al. 2009; Silverio and Jaquet 2012) and some are disappearing.

As a result of the issues raised by climate change there has been a refocused attention on understanding coupled social-physical systems. Increasingly, vulnerability and adaptation analyses are used to characterized how human and natural systems respond to and interact with climate (e.g., Ford and Smit 2004; Mahdi et al. 2009). Specifically, there is a call for place-based research that couples vulnerability analysis with environmental change science and that includes analysis of linkages and feedbacks between the human and environmental dimensions (Eakin 2006; Turner et al. 2003). Vulnerability analysis has been deemed useful as a process to gain increased understanding of a system, as a means to address social injustice (Kasperson and Kasperson 2001), and to direct attention, planning and policy measures to improve adaptation (Adger 2000). It is increasingly being used to investigate how a livelihood is susceptible to climate and other changes (Turner II et al. 2003). Analysis of social vulnerability to climate change should include examination of resource use (Kelly and

Adger 2000) within the context of sustainability (Polsky et al. 2003). Finally, social and economic factors and related policy and interventions can either hinder or support the capacity of individuals and communities to cope and adapt (Adger and Kelly 1999; Kasperson and Kasperson 2001).

Simply put, a system (i.e., individual, community, or livelihood) is vulnerable to an event or perturbation (or suite of events) if the effects to the system are outside the range of what the current configuration of the system can handle. Vulnerability can be viewed as a function of exposure, sensitivity, and adaptive capacity (McCarthy et al. 2001; Turner II et al. 2003). Exposure relates to the nature of the phenomena or events of interest as well as who is exposed to what. Sensitivity is determined by the resulting multitude of changes in the system. Adaptive capacity is the degree to which a community or social unit can handle a stress (via avoidance, mitigation, preparation, or recovery) and is a function of social, economic, and natural capital (assets, goods, and services) as discussed by Sen (1990). Increasingly, individuals and communities are seen as active agents capable of building adaptive capacity through the processes of learning, experimenting, and generating innovative solutions (Armitage 2005; Acosta-Michlik and Espaldon 2008).

Many of the earlier studies that focused on Andean herders were in fact forms of vulnerability analyses. With the goal of understanding and characterizing the Andean herding communities some studies sought explicitly to understand the behavioral and biological systems that buffer stresses (Thomas 1976). Others aimed to describe how illness and seasonality act as additional stresses in the system (Leatherman 2005;

Leatherman et al. 1988) or the capacity of specific herding systems to cope with drought (McRae 1984). While many social, political, and economic changes have occurred since in the Andean region, some fundamentals have remained the same. Agriculture and related activities are still the predominant livelihood strategies for many if not the majority of households. As a result, there continues to be reliance on the natural resource base to maintain food security and well-being. The following salient points from previous studies provide context for this dissertation: the field site is representative of a tropical mountain ecosystem with specific geologic, climatic, and biotic conditions that govern specific human-environmental interactions and relationships. This is what Brush and Guillet (1985) describe as the “adaptationist model”. Agro-pastoralist activities, including herding of alpaca and cultivation of tubers and cereals and importantly, related products, maximize the efficiency of this system which is considered “energy-limited” (Thomas 1982). Husbandry of camelids (alpaca and llama) and cultivation of traditional Andean crops are thus considered sustainable and critical adaptations (Thomas 1976; Flores de Ochoa 1977). Seasonality, drought, and frost are well-known climate phenomena with the potential to disturb food production and decrease well-being. Land management practices, particularly a rotation system for crops and herds and access to and management of natural resources in a variety of micro-environments are adaptation strategies that reduce these risks (Murra 1984; Thomas 1979; Sperling et al. 2008).

Due to the complexity of climate change and the timescales involved it is difficult to document indicators of change at the local level. As a result, aside from hydrological studies and glacier studies (Mark et al. 2010; Bury et al. 2008), most research on local change in the Andes includes observations by herders. Recent observations suggest that the timing and intensity of precipitation events may be changing. Warmer daily temperatures and more intense frost events have also been cited (Valdivia et al. 2013; McDowell and Hess 2012; Young and Lipton 2006). However, there is uncertainty in how the regional climate system will change in the future with respect to droughts and floods. Climate models can be downscaled but there is still extreme uncertainty at regional levels especially with respect to changes in precipitation. The study area does contain a few small glaciers but their contribution to the water balance in the watershed is small compared to other glacierized catchments in the Andes, such as the Cordillera Blanca. Therefore, changes in the regional hydrological balance will most likely be dominated by precipitation/evaporation processes. Despite these uncertainties, an understanding of the climate regime together with changes in key resources together and livelihood strategies are one step toward understanding potential trajectories of future change. With this in mind, the current research set out to examine the links between the pastoral livelihood strategies, hydroclimatology, and vegetation.

1.2 Research Approach and Objectives

Various aspects of the coupled human-environment system have been addressed using three spatial scales. The first analysis is at the regional watershed scale, the second analysis at the sub-watershed level, and the third at the level of a herding community within the sub-watershed. Thus the study area for this research consists of community herding land in the 2,770 km^2 Nuñoa subwatershed, which is itself within the larger Ramis watershed (14,706 km^2) in Southern Peru. This region is considered the Central Andes and is at the northern edge of the Altiplano. These scales of analysis, like the corresponding objectives are nested. While the first two objectives (Chapters 2 and 3) could stand alone, the third objective (Chapter 4) integrates information gained from these earlier analyses together with information learned in the field.

Chapter 2 (Objective 1) characterizes the prevailing hydroclimatology in the Ramis Watershed over the last 40 years in order to understand the broader climatological regime as the context in which changes to the human-camelid-pasture system have taken place. This chapter seeks to answer three questions: What is the relationship between ENSO and precipitation and streamflow in the region in the past five decades? Are other modes of climate variability significant? And generally, is this information useful for predictive purposes? Precipitation and streamflow data for the years 1964 through 2007 were used for analyses in this chapter.

Chapter 3 (Objective 2) investigates changes to a key natural resource for the pastoralist livelihood: grazing land. Here, I focus on spatial and temporal changes in vegetation, specifically in wetlands (*bofedales*), in the Nuñoa subwatershed from 1985 through 2010 using remote sensing and the Normalized Difference Vegetation Index (NDVI). Access to wetlands is a critical variable in herder vulnerability to environmental extremes since wetlands provide essential forage for herds. Wetlands vary in time in response to climate variables and land management practices. For this objective annual dry season (July and August) NDVI for 20 of the 26 years from 1985 to 2010 was calculated and the mean used to delineate wetlands in the watershed. I then review the spatial nature of NDVI trends in the wetlands and elsewhere by applying a multiple regression model to every 30m cell in the watershed. A second multiple regression model was applied to investigate the trend in watershed-averaged NDVI and the relationship between spatially averaged NDVI and precipitation and temperature from 1985 through 2010. These analyses allowed for a quantification of vegetation change in the Nuñoa watershed and an understanding of where and why NDVI trends were occurring.

Chapter 4 (Objective 3) uses a sustainable livelihoods framework (Chambers and Conway 1991) to characterize the human-environment system and some of the multiple stressors that challenge high elevation herders in the Andes of Peru. It describes the major geo-physical stresses on a herding community and the resulting impacts to livestock and crops. In this chapter, I synthesized information from objectives one and two and compiled a description of the links and feedbacks between climate variability, natural resources, and the agro-pastoralist production system. This objective is from the perspective of a herding community in the Nuñoa watershed. *Comunidades campesinas*, or peasant communities, in the Altiplano are rural and socially marginalized indigenous (Quechua and Aymara) populations. Locally in the field study area the pastoralists predominately speak Quechua. Bebbington et al. (2007:15) noted “the community marks an institutional link to a far longer local history of territorially based governance that itself is part of a longstanding cultural identity and patrimony.” Although Peruvian Constitution article 89 recognizes peasant communities as “social institutions, governed by legally established rules of collective and individual access to land" (Franco, 2006: 91.), these communities are subject to discrimination and lack the economic, political, and social services afforded to others. Chapter 4 provides a qualitative vulnerability analysis of a *comunidad campesina* to environmental change.

Chapter 5 summarizes the findings of the three main chapters. I discuss the contributions of this research and I conclude with thoughts on new questions and potential future research objectives.

CHAPTER 2

MODES OF PRECIPITATION AND STREAMFLOW VARIABILITY FROM 1964 TO 2006

2.1 Introduction

The research presented here was part of a larger transdisciplinary study on the vulnerability of indigenous herders in the Peruvian Altiplano to climate variability and environmental change. Several previous studies focused on climate and climate variability in the Altiplano and, on the physical mechanisms associated with climate variability (Aceituno 1989; Vuille 1999; Garreaud and Aceituno 2001; Garreaud et al. 2003). It is well established that a large portion of interannual variability in precipitation in the Altiplano is attributed to the influence of El Niño Southern Oscillation (ENSO) (Aceituno 1989; Vuille 1999; Garreaud and Aceituno 2001). One aspect of this relationship is the oceanic component. Sea surface temperatures in the equatorial Pacific correlate with temperature and precipitation data in the Altiplano of Peru (Garreaud and Aceituno 2001; Garreaud et al. 2003; Vuille et al. 2000). Warm El Niño years often correspond to dry conditions while La Niña years are associated with wet conditions. El Niño events occur with a periodicity of two to seven years and can last anywhere between one and three years (18 months is the typical duration) (Garreaud and Aceituno 2001).

Agriculture and fisheries are two important economic sectors in Peru. Given the association between ENSO events and negative impacts to these sectors, there is interest by the government in the ability to forecast ENSO to mitigate associated risks.

Consequently, the government of Peru monitors conditions in the equatorial Pacific (e.g., sea surface temperatures and wind conditions) and issues monthly bulletins that describe the expected resulting conditions in various geographic regions and on various sectors. The release of these bulletins began after the severe drought of 1982 (the most pronounced on record) that was associated with a strong El Niño event. Local traditions exist in the Andes whereby herders in Peru and Bolivia look to the Austral winter sky to predict ENSO events and summer season precipitation based on cloud conditions (Orlove et al. 2002; this study). However, ENSO events do not always produce the expected associated wet/dry extreme conditions and there is known spatial variability in the strength of the correlation. For example, for reasons related to the location of the moisture source, the western Altiplano exhibits a stronger ENSO signal than the eastern region (Vuille et al. 2000). Many of the baseline studies on ENSO teleconnections in the Altiplano region were completed in the early 1990s. It remains unclear how strongly precipitation and streamflow at the scale of an Andean watershed correlate with ENSO events and if this relationship still holds.

There is evidence that ENSO dynamics in the 20th Century has changed in at least two major ways. First, the proportion of extreme episodes has increased (Gergis and Fowler 2009). Second, the spatial development of El Niño events changed circa 1976 and this is related to a shift in Pacific circulation (Trenberth et al. 2001). While events in more recent years tend to begin in the Central Pacific and then spread east toward the coast of northern Peru (the Niño 1 + 2 region) (Wang 1995), events prior to 1976 evolved in the opposite direction. Furthermore ENSO activity displays decadal variability in both the intensity of events and the recurrence interval of El Niño and La Niña episodes (Diaz et al. 2001). It is unclear if the recent changes in ENSO dynamics are a part of natural variability in the system or a consequence of anthropogenic forcing. Regardless, a non-stationary ENSO regime has direct implications for precipitation and streamflow variability and seasonal prediction. If there is non-stationarity in the signal then predictions based on teleconnections at one time may not be reliable over other time periods. For example, predictions may be accurate for 1977 through 1997 (an active ENSO period) but not before or after. To this point, Camberlin et al. (2001) in a study on the relationships between African rainfall and ENSO from 1951 through 1997 found stronger correlations between Sahel precipitation and ENSO beginning in the 1970s. In India the strength of the relationship between ENSO and monsoon rainfall has decreased in recent decades (Kumar et al. 1999; Mokhov 2011). And if the ENSO regime is not linear with respect to El Niño and La Niña episodes, then predictions for flood and drought should be separated. Furthermore, other modes of variation, such as the tropical Atlantic, may act as an independent driver of variability (and modulate the ENSO effect) as in the case of Northeast Brazil (Nobre and Shukra 1996), the Amazon basin (Yoon and Zeng 2010), Central America (Enfield and Mestas-Nunez 2000) and West Africa (Camberlin et al. 2001; Lamb and Peppler 1992).

Additionally, mountain regions are particularly sensitive to changes in climate (Diaz et al. 2003). Temperature in the Andean region, similar to the global average, has increased by approximately 0.1°C per decade for nearly 70 years (Vuille et al. 2008a). Various studies have focused on glacier retreat throughout the Andes (Rabatel et al.

2013; Buffen et al. 2009; Pouyaud et al. 2005; Silverio and Jaquet 2005, Silverio and Jaquet 2012), and on modeling future changes in hydroclimate (Minvielle and Garreaud 2011; Lavado et al. 2011; Urrutia and Vuille 2009; Thibeault et al. 2010). Results from global climate model (GCM) projections (Bradley et al. 2006; Thibeault et al. 2010) and regional climate model studies (Urrutia and Vuille 2009) are in agreement and project continued increased surface temperatures in the 21st Century for the Central Andean region. Projections regarding precipitation are less consistent and this may be due in part to the fact that studies vary slightly in geographic region covered and time period analyzed. Based on GCM multi-model results, Thibeault et al. (2010) predict a significant increase in Austral summer precipitation for the 2020-2049 time period in the Bolivian Altiplano. In contrast, results of a downscaled model by Urrutia and Vuille (2009) demonstrate the opposite trend for the Central Andean region south of 12°S for the years 2071-2100. Based on the relationship between upper-level winds and summer season precipitation, Minvielle and Garreaud (2011) use GCM projections of zonal winds together with multiple regression analysis to show that a future increase in westerly winds will shorten and weaken the rainy season in the region. The authors suggest that this effect will be greater in the western and southern Altiplano. Lavado et al. (2011) modeled future changes in evapotranspiration and annual and seasonal discharge in several watersheds in the Peruvian Amazon-Andes basin showing that trends vary by watershed and for the watershed just to the northwest of the one used in this study, results are sensitive to the model scenario choice. Thus, with respect to future hydrological changes in the Central Andean region (and the Altiplano), modeling results suggest that there will most likely be a shift in seasonality but the direction of trends is still unsettled.

However, herders have expressed concerns regarding observed changes in the precipitation cycle, temperature, winds, frosts, and water availability and the resulting impacts to pasture vegetation and animal and human health (Orlove 2009; Young and Lipton 2006; Postigo et al. 2008). In light of climate change, the aspect of increased unpredictability in an already highly variable system is particularly concerning. This research investigates the possibility that a high elevation watershed in a region known to be impacted by ENSO can benefit from a better characterization of the regional hydroclimate-ENSO relationship for use in forecasting.

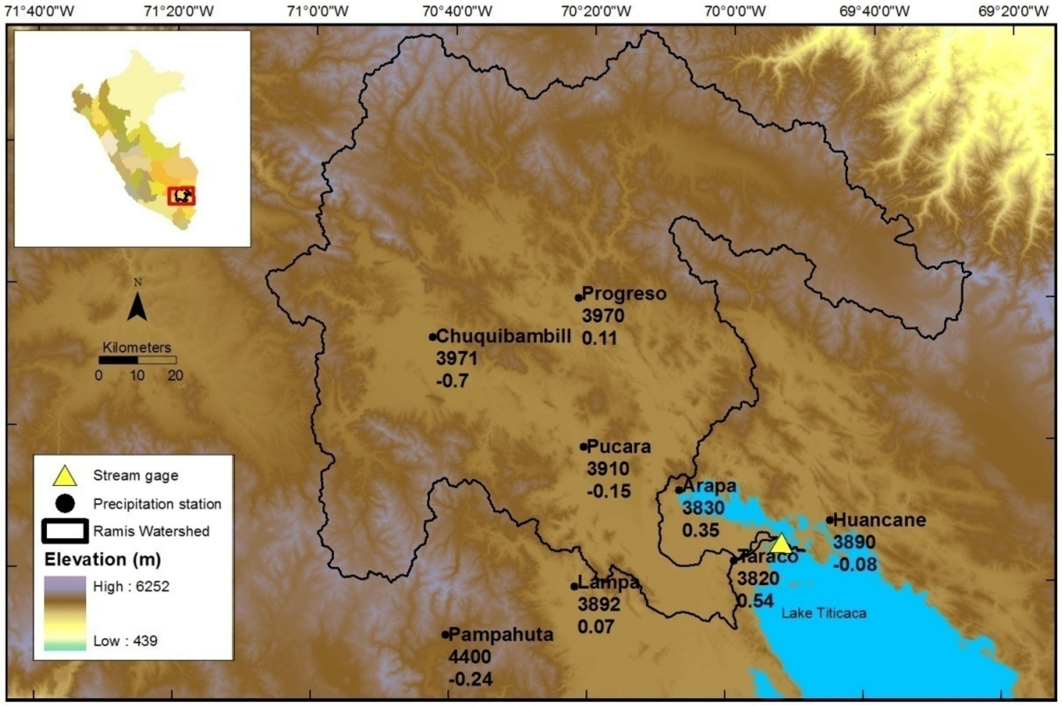
2.1.1 Objective

The objective of this study is to characterize the prevailing hydroclimatology in the Ramis watershed since 1964 based on meteorological and stream gage data with respect to sea surface temperatures. With the benefit of over a decade's worth of additional precipitation data compared to previous studies in the region (e.g., Aceituno 1989; Vuille 1999; Garreaud and Aceituno 2001), this analysis returns to the question of teleconnections in the Altiplano. The goal of this analysis is to assess whether the well-established ENSO teleconnections to regional precipitation (and streamflow) can provide locally relevant information at the scale of an Andean watershed. We focus on the summer season (December through March) when, based on our data, approximately 71% of precipitation falls. The study was conducted using correlation analysis and regression analysis to address the following questions, 1) how do SST anomalies in the equatorial Pacific and Atlantic basins affect precipitation and streamflow in the watershed? 2) Are significant modes of variation such as ENSO changing over time (i.e., are they stationary) and thus degrading their potential utility in prediction?

2.1.2 Study Area

This research focused on the 14,706 km^2 Ramis watershed in the Department of Puno in Southern Peru between 14°03’26.6” and 15°27’33.7” South and 69°25’26.4” and 71°07’4.7” West (Figure 2.1). This is the central Andean region at the northern extent of the Altiplano. The elevation of the watershed ranges from 3,810-m to 5,750-masl and in the remote, upper elevations, predominately Quechua herders live in an environmentally harsh and energy limited system (Thomas 1976). Since herding of llama and alpaca is possible at elevations up to approximately 4,600 meters it is the primary livelihood for most residents. High altitude (up to approximately 4,200 meters) crops such as quinoa, cañihua, and several varieties of sweet and bitter potatoes are grown mainly for subsistence. This region has the densest populations of camelids in the Andes, and is Peru’s largest producer of alpaca fiber.

Figure 2.1 Location of the Ramis watershed in Peru (insert) and the eight precipitation stations and one stream gage used in the study. Elevation of the precipitation stations (in meters) appears directly below station name. The loadings of the stations on the second principal component resulting from the PCA analysis appear below the elevation data.



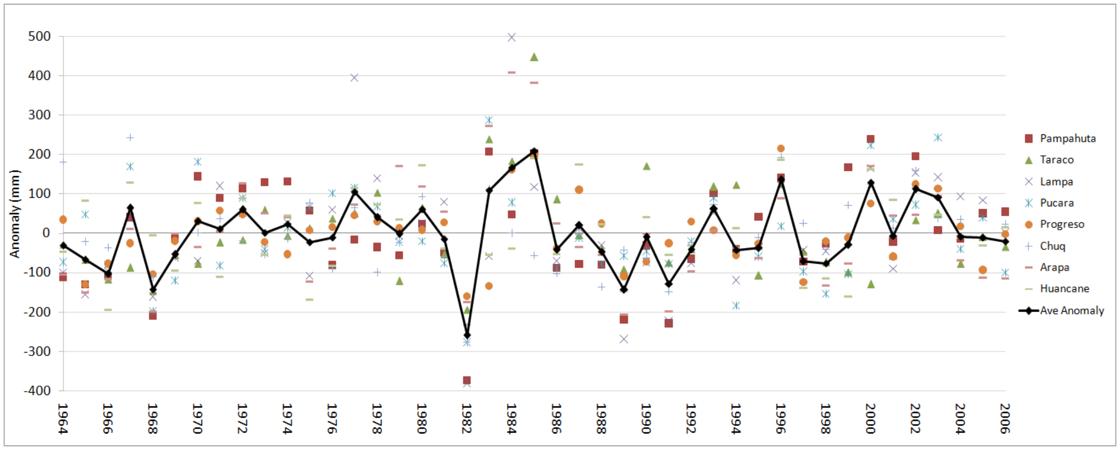
The region has a semi-arid climate with yearly precipitation averaging 760 mm. The seasonal cycle of precipitation is characterized by dry months (June through August) when there is often no precipitation, and wet months (December through March) when precipitation may be 200 mm per month. Temperature during the dry season averages 4˚C while the wet season months of November through February are warmer with monthly averages of 10˚C (ATDR-Ramis, 2008). However, there is greater variation in diurnal temperatures than in annual temperatures and this is most pronounced in the dry season when the daily temperature often ranges between -12˚C and 12˚C. In drought years, the dry season may be prolonged resulting in a lack of precipitation during the planting season months of September and October. Anomalously low precipitation during the usual rainy season (December-March) impacts harvest. Prolonged drought in any season negatively impacts herd and human health. Alternatively, floods (often associated with La Niña events and typical in the months of January through March) also negatively impact crop production and herd and human health.

2.2 Data and Methods

This research utilizes monthly precipitation data from eight meteorological stations, average monthly discharge data from one stream gage station in the watershed, sea surface temperature datasets for the Tropical Pacific and Tropical northern Atlantic, and both a Pacific decadal oscillation (PDO) index and a North Atlantic Oscillation (NAO) index. Each dataset and the applied methods are described below.

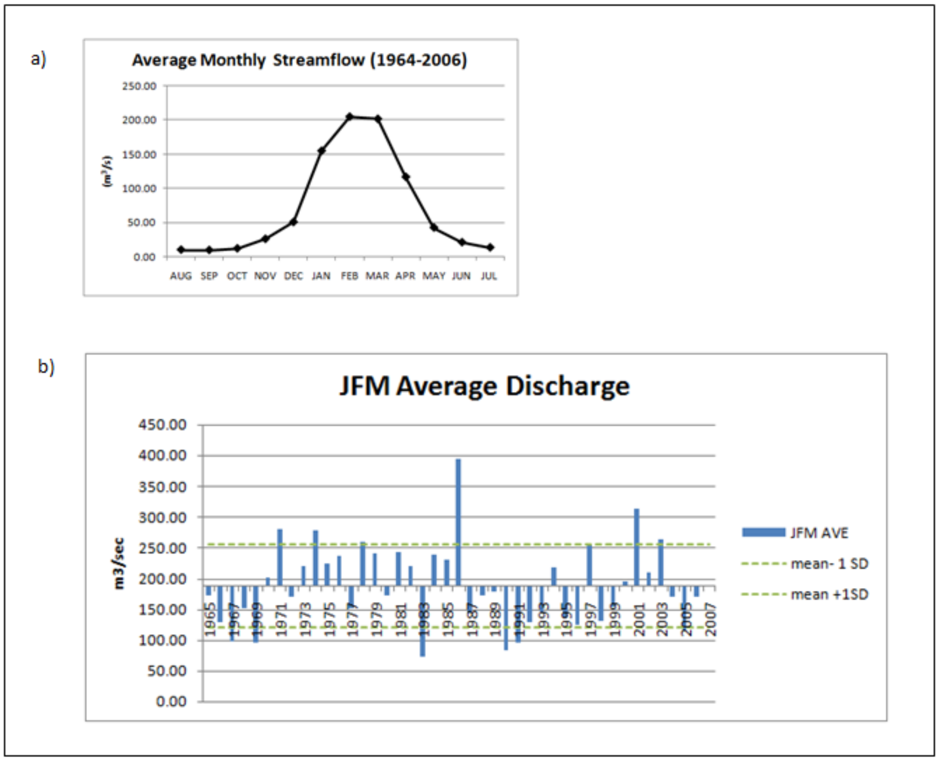
Monthly precipitation values were obtained from eight meteorological stations currently maintained and operated by Servicio Nacional de Meteorologia e Hidrologia del Peru (SENAMHI-Peru) in the Department of Puno, southern Peru (Figure 2.1) (Appendix A). The stations are located at the northern extent of the Altiplano from 14˚41’ to 15˚29’ south and 69˚45’ to 70˚42’ west. Four of the meteorological stations are located in the watershed of interest and four stations are located in adjacent watersheds. Elevation for seven of the eight stations ranges from 3820 meters to 3970 meters. One station is located at an elevation of 4400 meters. Concurrent years of data are 1964 through 2007. Wet season precipitation totals for each of eight stations were calculated using the 4-monthly sums of December, January, February and, March. A given wet season year is based on the month of December so that the 1964 wet season consists of December (1964) and January through March (1965). A total of twelve monthly values were missing from five stations and corresponding to six wet seasons. Therefore, approximately 2% of the rainy season totals across all eight stations for the 43-year record were completed using backward stepwise regression using Akaike information criterion (AIC). The consistency of station records was reviewed with double mass analysis (Searcy and Hardison 1960). Wet season anomalies for the years 1964-2006 were then calculated (Figure 2.2) resulting in a matrix consisting of 43 rows (years) and 8 columns (stations). Principal Component Analysis (PCA) was performed on non-transformed data using the correlation matrix.

Figure 2.2 Precipitation Anomalies for the eight stations used in the PCA. The solid black line is the 8-station austral summer (DJFM) average.



Monthly average discharge data is available from one gage station located at an altitude of 3,820 m.a.s.l at the mouth of the Ramis River as it enters Lake Titicaca (Figure 2.1) (Appendix B). The station is maintained and operated by SENAMHI-Peru and years of data for this study are 1964 through 2007. The data have been quality checked, corrected, and completed (28 missing values across all months and 43 years totaling 5.4% were filled using a multiple regression model) by Instituto Nacional de Recursos Naturales (INRENA 2008). Average monthly discharge for the 1964 through 2006 water years (August-July) is displayed in Figure 2.3a. Peak flows occur in February and March during and following months of high precipitation (December through March). Streamflow analyses for this study were performed using the average January, February, and March discharge for each water year from 1964-2006 (note that the water year runs from August to July so that the water year 1964 corresponds to January, February, and March of 1965). These are the months with average streamflow greater than the 95th percentile and collectively they represent 65% of the total annual streamflow. A graph of JFM discharge and deviations from the mean from 1964-2006 appears in Figure 2.3b.

Figure 2.3 Streamflow data for the Ramis River. a) Average monthly discharge for the 1964 through 2006 water years (August-July). b) JFM averaged discharge in the Ramis from 1965-2007 as displayed from mean JFM discharge (187 m^3/sec) over that period. Date is based on calendar year of January –March.



We use sea surface temperature indices for three ENSO regions and the Tropical North Atlantic (TNA). Sea surface temperature anomalies (SSTAs) are averaged over two seasons, a “predictive” season which includes September, October, and November and a contemporaneous season which includes the months of December through March. The three ENSO regions analyzed are the Niño 1+2, Niño 2, and Niño 3.4 regions. Monthly sea surface temperature data and anomalies for the Niño 1+2 (0-10° S and 90° - 80° W) and Niño 3.4 (5° N-5° S and 170-120° W) regions were obtained from NOAA Climate Prediction Center. The data are from the ERSST.V3B data set (Smith et al. 2008). Niño 2 SST data are from the NCEP Reanalysis data set (Kalnay et al. 1996) for 1° N to

4.8° S and approximately 80-85° W. The data were obtained from the NOAA/OAR/ESRL Physical Sciences Division.

The Tropical North Atlantic (TNA) index (Enfield et al. 1999) was obtained from NOAA Physical Science Division. The database contains anomalies of monthly SSTs averaged over the Tropical North Atlantic Region between 5.5 – 23.5° N and 15- 57.5° W for the years 1948-2011 using the reference period 1951-2000.

Additionally, for some analyses we use both a Pacific Decadal Oscillation (PDO) index and a North Atlantic Oscillation (NAO) index. The PDO index was obtained from NOAA Physical Science Division. Values are not anomalies but instead the leading principal component scores from average monthly SSTs north of 20° N in the Pacific. The North Atlantic Oscillation (NAO) index is from the NOAA Climate Prediction Center and represents the northern hemisphere winter pressure gradient over Greenland and 35-40° North in the Atlantic Ocean. For both of these indices the four month average of November through February is used.

Linear correlation analyses were performed between a precipitation index, seasonal discharge, and the following regional climatic indices: SSTAs in the tropical Pacific; detrended SSTAs in the Atlantic (TNA); the PDO index and; the NAO index. Correlation analysis was performed using the entire length of recorded station data (1964-2006) as well as for three distinct time periods: 1964-1976, 1977-1997 and, 1998-2006. The PC1 scores were further divided into terciles and correlation analysis was performed between upper and lower precipitation terciles and averaged SST anomalies. Composite images for years in each tercile were created using the SST NCEP Reanalysis data set (Kalnay et al. 1996).

We perform an analysis similar in concept to a path analysis (Wright 1960; Li 1975) to determine the independent relationships between key variables. Path analysis involves specifying relationships between variables based on a theoretical basis. These relationships are often detailed in a path diagram. The postulated relationships are then tested through a series of structured linear regression models. Since both dependent and independent variables are standardized (z-scores) prior to modeling, the resulting beta coefficients (or path coefficients or standardized partial regression coefficient as they are then termed) can be compared and analyzed. Here, we construct a path diagram that specifies key variables and the relationships between variables based on literature and our results of the correlation analyses. We then perform a series of regression models that account for direct and indirect effects of the variables.

In order to reveal oscillations in the time series and detect non-stationarity, wavelet analysis was performed on both the first principal component resulting from the PCA on precipitation and on discharge data using the Morlet wavelet transform with white noise background. The analyses and figures presented here were performed with the Interactive Wavelets website (http://ion.researchsystems.com/IONScript/wavelet/) and therefore incorporate the method of Torrence and Campo (1998).

2.3 Results

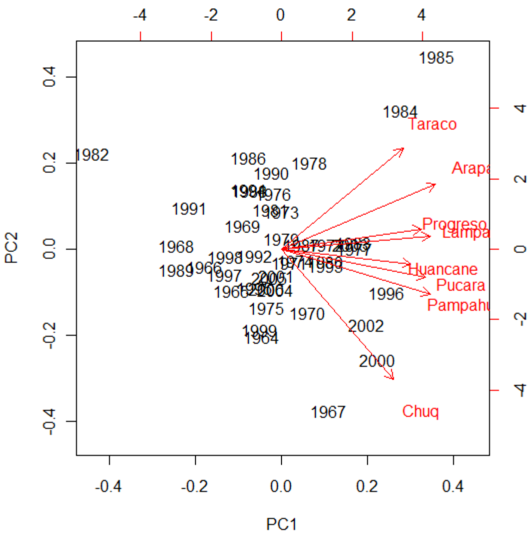
2.3.1 PCA Results

Results from the PCA of precipitation data are shown in Table 2.1. While the first three principal components explain 77% of the variance, only the first principal component (PC1) has an eigenvalue above the expected random broken stick value (see Jackson (1993) for a description of the broken stick method and discussion of the stopping rule). The focus of the analyses is therefore on PC1. The eigenvalue for PC2, however, while not above the broken stick value, is just above one. Therefore, some attention is paid to this component. PC1 explains approximately 56% of the total variance with similar loadings across the eight stations (Figure 2.4). PC2 explains an additional approximately 13% of the variance with two stations exhibiting strong loading (opposite in sign) and the other six stations loading along a positive/negative loading gradient. The biplot of PC1 and PC2 (Figure 2.4) demonstrates that sample 19, the year 1982, is an extreme data point on PC1 and, that samples 21 and 22 (years 1984 and 1985, respectively) load with the highest positive values on the first and second principal components.

Table 2.1 Results from the PCA performed on mean summer (DJFM) precipitation anomalies for eight meteorological stations (1964-2006).

Principal Component	Standard Deviation	Eigenvalues	Broken Stick Values	Variance Explained (%)	Cumulative Variance (%)
PC1	2.11	4.45	2.7	55.6	55.6
PC2	1.01	1.02	1.7	12.7	68.3
PC3	0.85	0.73	1.2	9.1	77.4

Figure 2.4 Biplot of PC1 and PC2. Station loadings are displayed as red vectors.

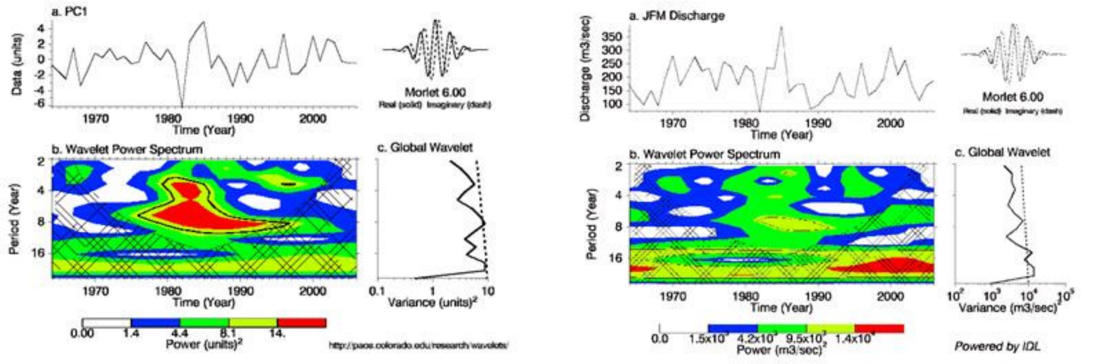


The first principal component is interpreted as representing a regional climate signal. Positive PC1 scores represent positive precipitation anomalies and vice versa. The second principal component (PC2) represents maximum variability in precipitation anomalies between stations located along a northwest-southeast transect. Station loadings appear in Figure 2.1. The two stations furthest west and at higher elevations have the strongest negative loadings while two stations located to the east and on the north end of Lake Titicaca have the strongest positive loadings. This implies a generalized east-west pattern together with localized effects of Lake Titicaca which modulates precipitation. We focus our analyses on PC1 and discharge because they represent a regional climate signal.

2.3.2 Wavelet Results

Wavelet is analysis is a useful tool for analyzing time series when there may be multiple dominant frequencies and large variation in, or even nonstationary, oscillations. Wavelet analysis decomposes a time series into time-frequency space without the constraints of choosing a predetermined scale or window as in Fourier analysis. Here, a complex, nonorthogonal wavelet function (Morlet) is passed over the time series to reveal information about the amplitude and phase of oscillations. The wavelet decomposition and power spectrums for PC1 scores and discharge in the watershed appear in Figure 2.5. For the precipitation data the wavelet spectrum reveals a general region of high power oscillations in the 3-5 years and 6-10 years frequencies, centered approximately at the middle of the record (1983). Lower power oscillations occur with shorter periods (3 years) at the limits of the cone of influence on either end of the data record. The greatest variance in the power spectrum is at the decadal level (8-9 years) and is significant at the 10% level. The wavelet power spectrum reveals a picture of variability that is generally consistent with ENSO variability (3-7 year oscillations) that is, however, only exhibited in the mid 1970’s to the mid 1990’s.

Figure 2.5 Results of wavelet analysis of PC1 Scores and Ramis discharge. Left panel: (a) Time series of PC1; (b) Wavelet power spectrum for PC1 scores. Black line is the 10% significance level with a white noise background. Other contours are at the 75%, 50%, 25%, and 5% level. Cross-hatched area is the cone of influence and; (c) global wavelet power spectrum for PC1. Dashed line is the 10% significance level with a white noise background. Right panel: same as left panel but for JFM average discharge. Torrence and Compo (1998).

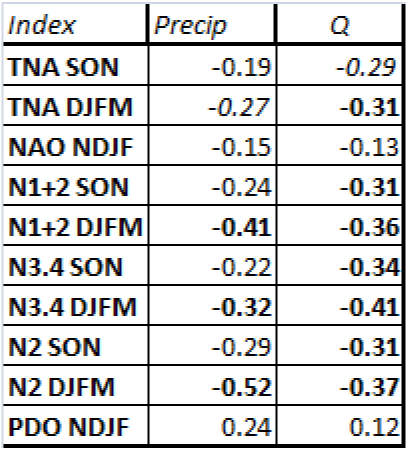


The results for streamflow are similar. In general, there is evidence of periodic behavior in the mid range of record at wave lengths of generally around 5-7 years but with weaker power. The center of the 6-10 year oscillations is shifted to a slightly shorter period.

2.3.3 Correlations among PC1, Streamflow, and Modes of Variation for 1964-2006

The results of the linear correlation analysis between PC1 scores and streamflow and all indices appear in Table 2.2. The correlation between DJFM average SSTAs in the TNA region and PC1 is significant at the 90% confidence level but significant at the 95% confidence level with streamflow. Correlations with PC1 and each of the DJFM ENSO regions are significant ($p<0.05$) but highest with the Niño 2 region so that 27% of the variance in PC1 is explained by SST variability in this region of the Pacific. The only significant ($p < 0.1$) association between predictive SSTs and PC1 is with the Niño 2 region. Streamflow correlation analysis yields significant correlations ($p < 0.05$) across all ENSO indices and the correlations are relatively consistent. Neither the NAO index nor the PDO index was found to have a significant relationship with PC1 or streamflow.

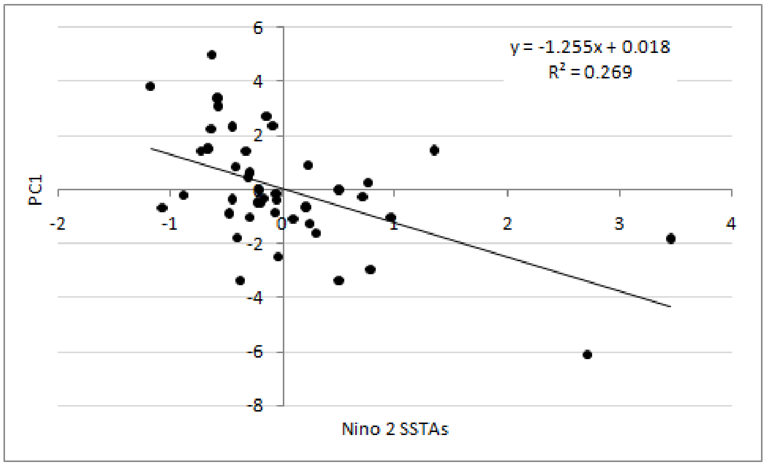
Table 2.2. Correlation coefficients (r) between PC1 scores (precip) and streamflow (Q) and the Tropical Northern Atlantic (TNA), Niño 3.4, Niño 1+2, and Niño 2 regions for SON and DJFM averaged SSTA values and the PDO and NAO Indices averaged for months November through February. Significant values in bold ($p < .05$) and italicized ($p < 0.1$).



Index	*Precip*	Q
TNA SON	-0.19	*-0.29*
TNA DJFM	*-0.27*	**-0.31**
NAO NDJF	-0.15	-0.13
N1+2 SON	-0.24	**-0.31**
N1+2 DJFM	**-0.41**	**-0.36**
N3.4 SON	-0.22	**-0.34**
N3.4 DJFM	**-0.32**	**-0.41**
N2 SON	-0.29	**-0.31**
N2 DJFM	**-0.52**	**-0.37**
PDO NDJF	0.24	0.12

Owing to the previously established relationship between ENSO and interannual variability in precipitation in the Altiplano (Aceituno 1989; Vuille 1999; Garreaud and Aceituno 2001), the correlation results with the Pacific SSTs are not surprising. Again, the expected relationship is that an increase in sea surface temperature anomalies in the Pacific correlates to negative precipitation anomalies, and vice versa. However, one can see that while a significant relationship exists between Niño 2 SSTs and precipitation in the region, there is still noise predominately in the quadrant where both SSTAs and PC1 values are negative (Figure 2.6). For example the 1966/67, 1989/1990, and 1999/2000 austral summer seasons had anomalously low precipitation but SSTAs in the Niño 2 region were negative to neutral (1999/2000 was a La Niña year). Other discrepancies in the expected relationship between ENSO region SSTAs and PC1 scores occur in 1972/73 (an El Niño year) and 2000/01, when positive Niño 2 SSTAs correspond to positive precipitation anomalies. There are also several anomalous Niño 2 SST years that do not correspond to years of anomalous precipitation in the region.

Figure 2.6 Scatterplot of Niño 2 (DJFM) vs PC1 scores for 1964-2006.



Several hypotheses have been put forth to explain the apparent temporary breakdowns in the ENSO teleconnections in the Altiplano (Garreaud and Aceituno 2001; Vuille et al. 2008b). These include spatial variability in the exact location of ENSO development and positioning of the upper tropospheric zonal winds aloft the Altiplano. A shift in ENSO behavior has been observed circa 1976 related to the climate shift in the Pacific circulation (Trenberth et al. 2001). Vuille et al. (2000) document decadal scale variability in precipitation represented by clusters of wet (late 60s to mid 70s) and dry (late 70s and early 80s) years. The authors hypothesize the shift may be attributed to the well documented climate shift in the tropical Pacific. And while they find significant correlations between austral summer precipitation in the Altiplano and lagged SSTs off the coast of Northwest Africa, they do not suggest that any mode of variation, other than ENSO might be related to these shifts. Thus, the significant correlations between

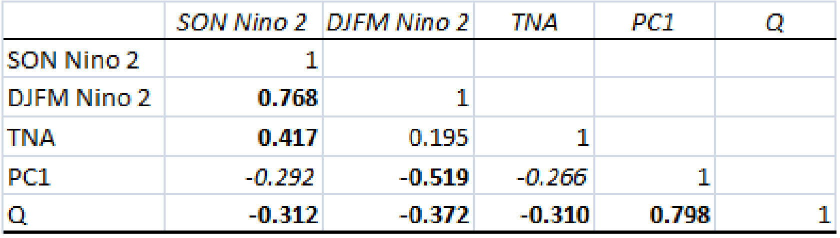
Atlantic SSTs and streamflow and PC1 in this study were not a given. If indeed there is an Atlantic signal in the watershed in question then characterization of this relationship may help explain inconsistencies in the ENSO teleconnection and may be useful in the forecasting of anomalously wet and dry summer seasons. The relationship between northern Tropical Atlantic SSTs and precipitation and streamflow is further investigated below.

2.4 Path Analysis

Understanding the strength of associations between precipitation, streamflow, and the indices as was done in Section 3.2 is insightful but limited in that many of the indices are highly correlated. Path analysis serves to isolate the key relationships between wet season precipitation, streamflow, and three explanatory variables (SON Niño 2, DJFM Niño 2, and DJFM TNA). Furthermore, we wanted to explicitly test the hypothesis that a significant linear relationship between precipitation and TNA and streamflow and TNA exists after accounting for the effects of Niño 2 SSTs on TNA, precipitation, and streamflow since it has been demonstrated that ENSO dynamics cause an associated positive response in SSTs in the TNA as a result of ocean-atmosphere interactions. During positive ENSO events (El Niño's), warming of the tropical atmosphere reduces the strength of the north-easterly trade winds and surface heat flux in the region, thereby increasing SSTs (Enfield and Mayer 1997) in the Atlantic. However, this warming is time-dependent based on the onset of an El Niño event. Furthermore, variability in SSTs in the TNA is not entirely ENSO dependent. For example, the NAO, via changes in the northeast trade winds also influences SSTs in the northern tropical Atlantic. However, there is also evidence that local fluctuations in tropical Atlantic SSTs at the decadal timescale force changes in the NAO (Wainer et al. 2008; Rajagopalan et al. 1998). In this section we review the relationships between SSTs and the precipitation and streamflow indices. The atmospheric connections (PDO and NAO) with regional hydrology are discussed in a later section.

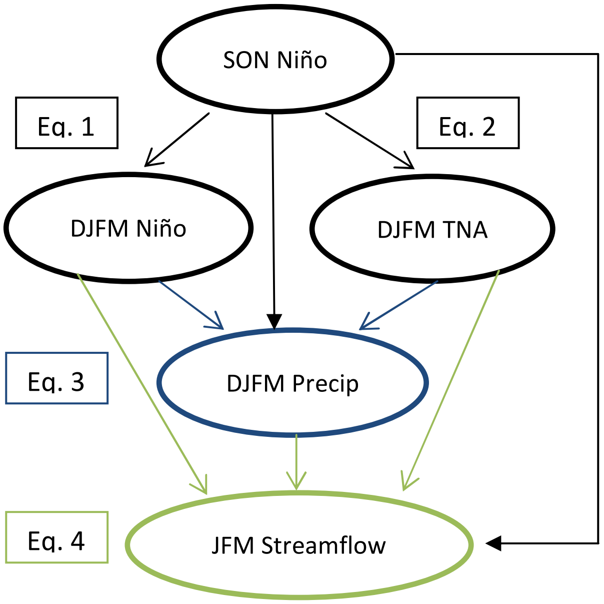
The correlation coefficients for the bivariate relationships in the path diagram appear in Table 2.3. All associations except that between TNA and DJFM Niño 2 are significant at p <0.1. Therefore, the path diagram (Figure 2.7) and series of regression models (Equations 1-4) must account for these relationships.

Table 2.3. Correlation matrix displaying the correlation coefficient for variables in the path diagram. Relationships that are significant at p<0.1 (DF = 41) are in italic, relationships significant at p<0.05 are in bold.



	SON Nino 2	*DJFM Nino 2*	*TNA*	*PC1*	*Q*
SON Nino 2	1				
DJFM Nino 2	**0.768**	1			
TNA	**0.417**	0.195	1		
PC1	*-0.292*	**-0.519**	*-0.266*	1	
Q	**-0.312**	**-0.372**	**-0.310**	**0.798**	1

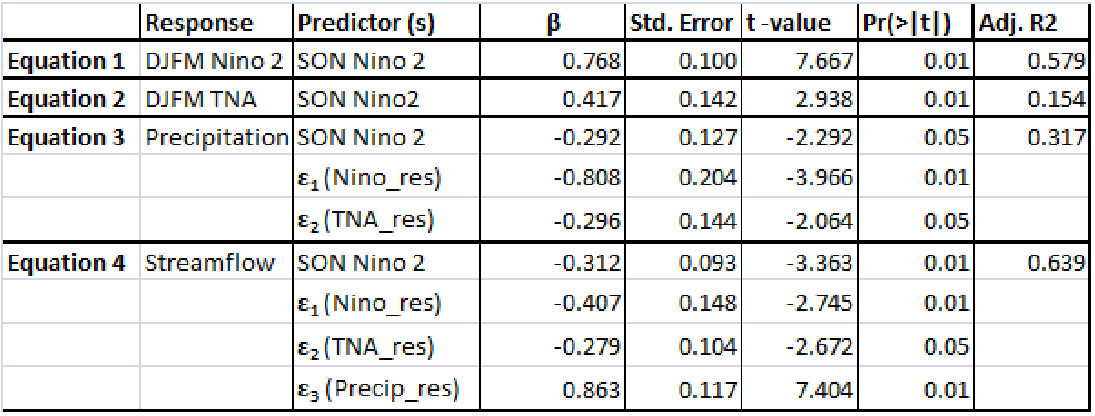
Figure 2.7 Path Diagram and equations for the relationships between Niño 2 SSTs averaged over two seasons (SON and DJFM), Tropical North Atlantic SSTs (DJFM), average regional summer precipitation (DJFM) (PC1), and streamflow (JFM).



Equation 1: $\text{DJFM Niño 2} = \alpha + (\beta_0 * \text{SON Niño 2}) + \varepsilon_1$ $\varepsilon_1 = \text{Niño\_res}$
Equation 2: $\text{DJFM TNA} = \alpha + (\beta_0 * \text{SON Niño 2}) + \varepsilon_2$ $\varepsilon_2 = \text{TNA\_res}$
Equation 3: $\text{Precip} = \alpha + (\beta_0 * \text{SON Niño 2}) + (\beta_1 * \varepsilon_1) + (\beta_2 * \varepsilon_2) + \varepsilon_3$ $\varepsilon_3 = \text{Precip\_res}$
Equation 4: $\text{Streamflow} = \alpha + (\beta_0 * \text{SON Niño 2}) + (\beta_1 * \varepsilon_1) + (\beta_2 * \varepsilon_2) + (\beta_3 * \varepsilon_3) + \varepsilon$

From the path diagram and equations it can be seen that DJFM Niño 2 and separately, DJFM TNA are each regressed against SON Niño 2 (Equations 1 and 2, respectively). The residuals from Equation 1 and Equation 2 ($\varepsilon 1$ and $\varepsilon 2$, respectively) represent the part of DJFM Niño 2 and DJFM TNA not predicted by SON Niño 2. The residuals are used as explanatory variables, together with SON Niño 2, in the multiple regression model with precipitation (PC1) as the response variable (Equation 3). The resulting error term in Equation 3 ($\varepsilon 3$) represents the variability in precipitation not predicted by SON Niño 2, $\varepsilon 1$, and $\varepsilon 2$. In Equation 4, the streamflow variable is regressed against SON Niño 2 and the error terms resulting from the earlier models. Summaries of model results appear in Table 2.4.

Table 2.4. Summary of covariate results for the regression models (Equations 1-4). Pr(>|t|) is the level of significance and Adj. R^2 is the adjusted R^2.



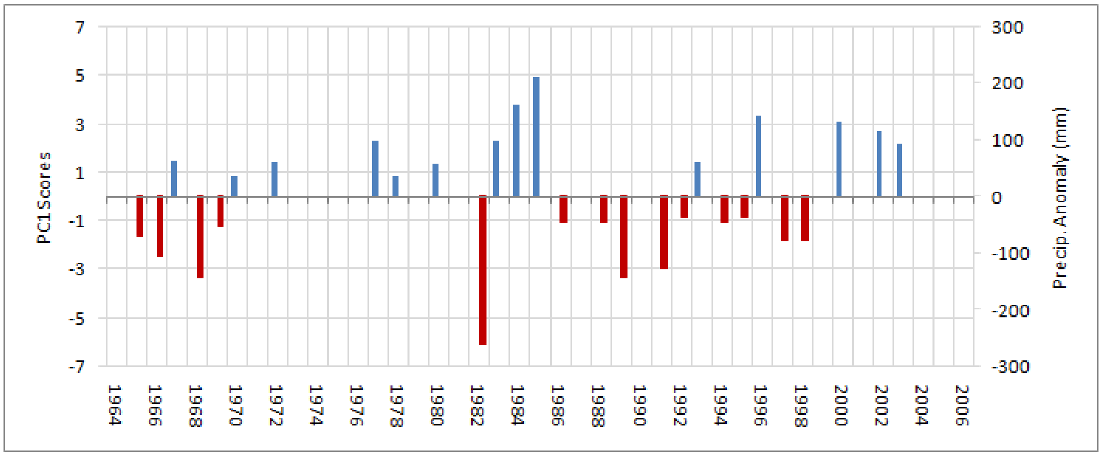
	Response	Predictor (s)	β	Std. Error	t -value	Pr(>|t|)	Adj. R2
Equation 1	DJFM Nino 2	SON Nino 2	0.768	0.100	7.667	0.01	0.579
Equation 2	DJFM TNA	SON Nino2	0.417	0.142	2.938	0.01	0.154
Equation 3	Precipitation	SON Nino 2	-0.292	0.127	-2.292	0.05	0.317
		ε_1 (Nino_res)	-0.808	0.204	-3.966	0.01	
		ε_2 (TNA_res)	-0.296	0.144	-2.064	0.05	
Equation 4	Streamflow	SON Nino 2	-0.312	0.093	-3.363	0.01	0.639
		ε_1 (Nino_res)	-0.407	0.148	-2.745	0.01	
		ε_2 (TNA_res)	-0.279	0.104	-2.672	0.05	
		ε_3 (Precip_res)	0.863	0.117	7.404	0.01	

The results show that all predictors in all models are significant at least at the $p < 0.05$ level. The covariate SON Niño 2 explains over half of the variance in DJFM Niño 2 but a much smaller percentage of the variance in DJFM TNA data (15%). The results from the third model indicate that together SON Niño 2, DJFM Niño 2, and DJFM TNA explain approximately 32% of the variability in regional precipitation. The beta coefficients (standardized) for SON Niño 2 and DJFM TNA in Equation 3 are similar while DJFM Niño 2 has a beta coefficient approximately two and a half times the magnitude of the other covariates. We reject the null hypothesis that no significant linear relationship exists between regional precipitation and DJFM TNA. The variance explained by the model is an improvement over the variance explained by any one of the predictors in the correlation analysis in the previous section. The results of the fourth model demonstrate that there is a significant relationship between streamflow and each of the predictors and we again reject the null hypothesis. It is noted that while 64% of the variability in streamflow is accounted for by the model, the r square value from the correlation analysis between streamflow and precipitation (Table 2.3) suggests that much of the variability is explained by precipitation alone.

2.5 Composite Analysis of Precipitation

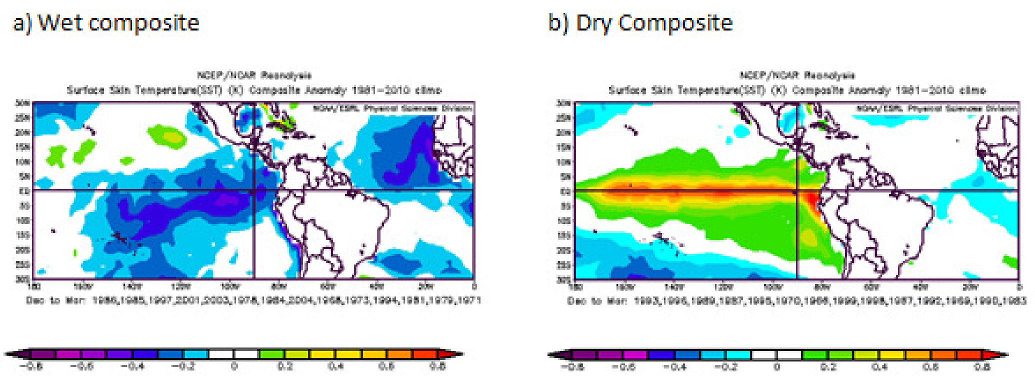
A composite analysis was performed on the PC1 scores. The upper and lower terciles (positive and negative precipitation anomalies, respectively) appear in the bar chart (Figure 2.8). Two observations can be made: 1) there are discernable clusters of wet and dry years, such as the "wet" 1970s into the mid-1980s (with the exception of 1982) and the "dry" years of the late 1980s into the late 1990s and, 2) the more recent years beginning at the turn of the 21st century appear to fall within a "wet" phase. There are no significant trends for either tercile. It is noted that the clusters of wet and dry years do not coincide with those observed by Vuille et al. (2000) for the larger Altiplano region.

Figure 2.8 Bar chart displaying the upper and lower terciles of the PC1 scores. The corresponding precipitation anomaly (mm) is displayed on the right vertical axis.



Pearson’s correlation analysis was performed for the upper and lower terciles with the various indices. The results appear along with composite maps displaying average SST anomalies for the months of December through March (Figure 2.9). The composite image that corresponds to the upper third of precipitation anomalies displays negative averaged anomalies in the equatorial Pacific and in the tropical northern Atlantic (TNA) (Figure 2.9a). The only significant ($p<0.05$) correlations with the upper third of PC1 scores (wet tercile) are with the Niño 2 region for the predictive season (SON months). An investigation of the data demonstrates that actually, the expected relationship between negative SSTs and positive precipitation anomalies is much stronger with contemporaneous Niño 2 SSTAs (Figure 2.10) with only two years (1972 and 1978) not meeting this expectation in the relationship. Correlations with other ENSO regions are remarkably weak. Aside from the Niño 2 region, associations are next strongest (but not significant) with the TNA contemporaneous season (DJFM months). All correlations are negative.

Figure 2.9 Composite maps for (a) upper and (b) lower precipitation terciles. The maps display the average December through March SST anomalies for the years in each tercile. The tables below each composite display the correlation coefficients between PC1 scores and the Tropical Northern Atlantic (TNA), Niño 3.4, Niño 1+2, and Niño 2 regions for SON and DJFM averaged SSTA values. Significant values in bold (p < .05).

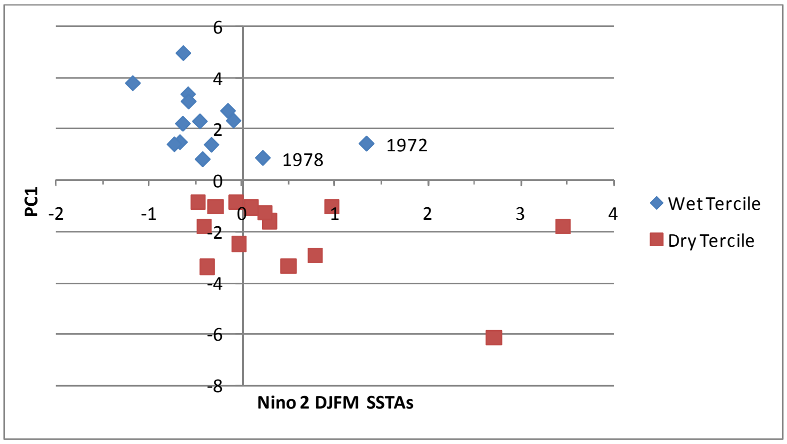

a) Wet composite

b) Dry Composite

Wet tercile	*PC1*
TNA_SON	-0.07
TNA_DJFM	-0.28
N1+2 SON	-0.05
N1+2 DJFM	0.10
Nino3.4 SON	-0.15
Nino3.4 DJFM	-0.12
Nino 2 SON	**-0.49**
Nino 2 DJFM	-0.43

Dry tercile	*PC1*
TNA_SON	0.30
TNA_DJFM	-0.01
N1+2 SON	-0.27
N1+2 DJFM	-0.40
Nino3.4 SON	-0.34
Nino3.4 DJFM	-0.42
Nino 2 SON	-0.36
Nino 2 DJFM	**-0.46**

Figure 2.10 Scatterplot of Niño 2 DJFM and PC1 scores for upper tercile (anomalously wet years) and lower tercile (anomalously dry years).



The composite image that corresponds to the lower third of precipitation anomalies displays strong negative SSTAs in the ENSO region and no anomalies in the TNA region (Figure 2.9b). Similar to the wet tercile, the only significant ($p<0.05$) correlations are with the Niño 2 region. In this case, contemporaneous season (DJFM) SSTAs have the strongest linear correlation (Figure 2.10). Correlations with the other ENSO regions, while not all significant, are more spatially consistent then with correlations between the upper tercile and ENSO regions.

2.6 Time Period Analysis

Correlation analysis between precipitation (PC1), streamflow, and the SST indices was performed for three time periods: 1964-1976; 1977-1997; and 1998-2006. The time periods were chosen based on the following: 1) 1976 marked a climate shift in the Pacific, 2) the 1980s and 1990s were active ENSO years, and 3) the wavelet analysis in this study displays oscillations with periods between 6-10 years that are significant between 1977 through 1997. Results of the correlation analysis appear in Table 2.5.

Table 2.5. Correlation coefficients (r) between PC1 scores and streamflow and the Tropical Northern Atlantic (TNA), Niño 3.4, Niño 1+2, and Niño 2 regions for SON and DJFM averaged SSTA values. Significant values are highlighted in bold (p < .05) and italicized (p < 0.1).

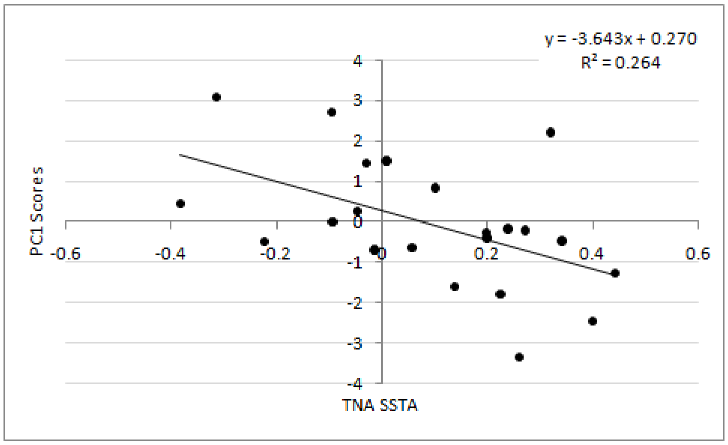
	1964-1976		***1977-1997***		***1998-2006***	
Index	Precip	Q	Precip	Q	Precip	Q
TNA SON	**-0.59**	*-0.54*	0.00	-0.09	*-0.59*	**-0.84**
TNA DJFM	**-0.70**	*-0.51*	-0.17	-0.20	-0.13	-0.48
N1+2 SON	-0.19	-0.28	*-0.41*	*-0.39*	0.17	-0.15
N1+2 DJFM	-0.21	-0.35	**-0.62**	**-0.48**	0.35	0.21
N3.4 SON	-0.17	-0.43	**-0.45**	*-0.41*	0.42	-0.03
N3.4 DJFM	-0.30	*-0.54*	**-0.60**	**-0.49**	0.46	0.04
N2 SON	-0.08	-0.26	*-0.42*	-0.34	0.19	-0.24
N2 DJFM	-0.10	-0.25	**-0.64**	**-0.47**	0.03	0.22

Between 1964 and 1976 there are significant (p<0.05) correlations between precipitation and both contemporaneous (DJFM) and predictive (SON) SSTAs in the Tropical North Atlantic. The p-values for the associations between streamflow and each of the TNA indices are significant at the p<0.1 level. The relationships between both precipitation and streamflow and ENSO SSTs are generally weaker and vary based on ENSO region. The Niño 3.4 region exhibits the strongest correlations with the watershed and this association is stronger with streamflow.

The results of the correlation analysis for the years 1977-1997 are nearly opposite the results for the earlier time period. Associations with the TNA disappear completely. Correlations between precipitation and streamflow and contemporaneous SSTs in all three ENSO regions are significant (p<0.05). In addition, the SON average SSTA for the Niño 3.4 region serves as a significant predictor of precipitation for this time period. Note the spatial cohesion between the various ENSO regions and the resulting correlations with precipitation and streamflow that is absent in the earlier time period.

The most recent time period (1998-2006) has a small sample size and therefore results are interpreted cautiously. Correlations for this time period are again significant for the TNA region but only for the SON months (streamflow ($p<0.05$); precipitation ($p<0.1$)). No associations between precipitation and streamflow and the ENSO regions are significant but this may be due to the small sample size. However, the expected inverse relationship between SSTs in the Pacific and precipitation in the region is not present but instead all associations are positive. A scatterplot of PC1 scores and TNA detrended SSTAs for the SON months (Figure 2.11) for the earlier and later time periods demonstrates a significant ($p<0.05$) linear relationship with 26% of the variance in PC1 scores explained by SSTAs in this region.

Figure 2.11 Scatterplot of PC1 scores vs detrended TNA (SON) for earlier (1964-1976) and later (1998-2006) time periods combined.



2.7 Discussion

Consistent with previous research, SSTAs in the ENSO region are the dominant mode of interannual variability in the precipitation and streamflow records. Of the ENSO regions analyzed, the Niño 2 region is the only one to have significant correlations with anomalously positive and negative precipitation seasons in the watershed. Wet precipitation extremes are consistently associated with the expected negative DJFM SST anomalies there with the exception of two earlier years (1972 and 1978). Consequently, SON Niño 2 SSTAs may be useful, from a statistical viewpoint, for predicting anomalously wet summer seasons. The expected relationship with anomalously low precipitation seasons and positive SSTAs in the Niño 2 region for the DJFM months, while significant, is not as robust. Out of 14 anomalously dry summer seasons, six do not correspond to the expected positive SSTAs in the Niño 2 region (SSTAs are negative throughout much of the equatorial Pacific in five of these years).

The strength of the relationship between ENSO and precipitation and runoff is due in part to the sequencing of four consecutive extreme years in the watershed (the drought year of 1982 and three years with anomalously wet precipitation seasons of 1983, 1984, and 1985) that correlate significantly with SSTAs in the ENSO region. Indeed, from 1976 to 1998, years of frequent and high amplitude ENSO events, the only significant source of variability is SSTAs in the ENSO region. The strength of the relationship is consistent across all three ENSO regions analyzed. For the time periods prior to 1976 and post-1998 there appears to be a shift in the relationship between interannual variability in the watershed and ENSO. The strength, sign, and spatial cohesion of the correlations vary according the time period. In the earliest time period the strongest correlations are with the Niño 3.4 region. In addition to the absence of significant relationships with the Pacific in the later time period, the sign of the correlations between precipitation and all ENSO indices is positive.

Several previous studies have described either periodic failure in the ENSO teleconnection or suggested a weakening over time. For example, Vuille et al. (2008b) presented findings of weak correlations following the climate shift in the mid-1970s elsewhere in the central Andean region. And a similar reversal of the expected relationship between SSTs during both wet and dry events in Ecuador since 2000 has been presented in Bendix et al. (2011). Lavado et al. (2012) analyze the hydroclimatology of 33 watersheds in the three major drainage basins in Peru for the years 1969-2004. The Ramis watershed is included in that analysis which utilizes runoff data from the same streamgage as that used in this study. Unlike this study, Lavado et al. (2012) calculate mean annual streamflow and precipitation as well as annual maximum and minimum monthly streamflow. These time series are then correlated (using the Mann-Kendall coefficient) with the Southern Oscillation Index (SOI) (representative of ENSO) and northern Tropical Atlantic SSTs. The authors conclude a weaker ENSO signal than previously described for the region. The associations between ENSO and streamflow indices were not significant and the association with precipitation was weaker then the results presented in this research. Thus it appears that the strength of the ENSO signal may be sensitive to the seasonal aspects of the hydrological time series and indices used as well as the specific ENSO index (SOI versus SSTs).

A comprehensive overview of ENSO behavior and variability is detailed in Trenberth and Stepaniak (2001) and Diaz et al. (2001). In addition to differences in amplitude, ENSO events exhibit both temporal and spatial variability in evolution. Decadal variability inherent to ENSO is further complicated by variability in the global climate system. Each of these factors plays a role in ENSO behavior and the strength of teleconnections with a region. The physical mechanism explaining the relationship between ENSO and hydroclimatic conditions in the Altiplano is the wind direction in the middle and upper troposphere. The lowlands to the east of the Altiplano are the moisture source for convection in the region (Garreaud et al. 2003). Easterly wind flow facilitates the transport of moist air from the lowlands while a westerly flow (as occurs during El Niño) facilitates the movement of dry air from the arid coast (Garreaud and Aceituno 2001). With this relationship in mind, Garreaud and Aceituno (2001) explore two years (1973 and 1989) when ENSO events do not produce the expected precipitation anomalies in the Altiplano. In both cases, the zonal wind anomalies are pushed further to the south and the expected El Niño and La Niña conditions, respectively, are not manifested in the region.

Episodic failures in the expected relationship between ENSO events and regional precipitation and streamflow occur in all time periods analyzed. We conclude that there is not a weakening of the ENSO relationship over time nor is it confined to only a few extreme events. Instead, it appears that the relationship is strongest for the 1976-1997 period and weaker both before and after this. Furthermore, there is spatial variability in the signal with time. Prior to the 1976/1977 climate shift correlations are significant with only the Niño 3.4 region. Post-1976 there is more consistency in the associations with all ENSO regions but strongest correlations are with the Niño 2 region. Furthermore, while nearly all positive precipitation anomalies in the watershed are associated with negative SSTAs in the Niño 2 region, unless the magnitude of the Niño 2

SST anomaly is more extreme than -0.5 then positive and negative precipitation extremes seem to occur with the same frequency.

In addition to the expected ENSO relationship we conclude that there is a TNA signal in the records. Streamflow, which spatially and temporally integrates the signal in the watershed, demonstrates significant associations with the TNA region for the record length. A slightly weaker association exists between precipitation and the tropical Atlantic. These results are consistent with those of Lavado et al. (2012) who found significant inverse correlations between SSTs in the northern tropical Atlantic and annual rainfall (but not runoff) in the Ramis watershed. The Atlantic Ocean is known to influence precipitation anomalies over some regions of South America such as the northeast and southeast, its role in the climate variability of the Altiplano is still debated. We have deduced via path analysis that the Atlantic signal while weaker than the ENSO signal in magnitude, is a separate contributor to variability in precipitation and streamflow. This signal, similar to the ENSO signal, appears to have stronger and weaker periods. Inverse linear relationships between precipitation and streamflow and preceding (SON) SSTAs in the TNA region are significant from 1964-1976 and again 1998-2006. The associations with TNA SSTs disappear during the active ENSO period.

The 8 to10 year oscillations in the streamflow and PC1 records indicate a decadal signal. While the oscillations with shorter periods are consistent with an ENSO signal no such decadal periodicity exists in the ENSO record. However, shifts in the PDO occur on a timescale of approximately 20 to 30 years. In the Atlantic, the NAO and the TNA both exhibit decadal (and multidecadal) variability. Additionally, the Atlantic Meridional

Mode (AMM) which is related to the gradient of anomalous SSTs in the tropical North Atlantic and the tropical South Atlantic exhibits interannual and decadal variability. Wavelet analysis for each of these indices for 1964-2006 (not shown) demonstrates that only the PDO and TNA have similar power spectrums with peak variance at eight (and 26) years. In an analysis dating back to the 1800s, Wainer et al. (2008) suggest that decadal variability in the tropical Atlantic may be episodic and not periodic in nature. Using a filtered time-series, they find that the largest decadal signature for the record occurs between 1965 and 1985.

Similar decadal periodicity exists in the Northern Northeast Brazil precipitation record. Kayano and Andreoli (2004), using partial correlation analysis, suggest a possible connection between PDO, NAO, and TNA as a physical mechanism for modulating the displacement of the intertropical convergence zone (ITCZ) and precipitation in that region. Given the stronger associations with the TNA during negative phases of the NAO and that the 8-year oscillations are similar in nature to the PDO and TNA, such an explanation for the Ramis watershed cannot be ruled out. However, based on the short length of the records in this study and the timescales involved, any cause and effect relationship between the PDO, NAO, and TNA and precipitation and runoff in the region is mostly speculative. Furthermore, mechanistic explanations that do not include the PDO or the ITCZ have been suggested by Baker et al. (2005) who relate decadal variability in sediment core records from Lake Titicaca to SSTs in the Tropical Atlantic. They hypothesize that cooler SSTs in the equatorial North Atlantic could lead to either an intensification of the South American Summer Monsoon or a lengthening of the wet season via increased Easterlies and advection (as occurs during the positive NAO phase).

2.8 Conclusion

This research serves to better define the hydroclimatology of a watershed in the northern Altiplano. It builds on previous research that has established that ENSO is a main mode of interannual variability in the region but it contributes to contemporary studies that suggest that ENSO teleconnections have not been consistent over time, particularly in recent years. In order to explore the ENSO-hydroclimate relationship for the purpose of understanding the utility for forecast use, we analyzed 1) the relationships between regional precipitation and streamflow with different ENSO regions, 2) how these relationships have changed over time, 3) whether there is a difference in the relationship for anomalously wet and dry years, and 4) whether other modes of variability have significant correlations with streamflow and precipitation in the watershed.

Based on summer season data from 1964 to 2006 it is concluded that there are spatial and temporal variations in the ENSO-hydrology relationship in the Ramis watershed. Furthermore, there are differences in the relationships between ENSO region SSTs and anomalously wet and dry summer seasons. Correlation analysis reveals a strong ENSO signal from 1977-1997 when as much as 40% of the variability in the precipitation record is explained by the relationship with SSTs in the Pacific. Prior to the climate shift of 1976/1977 associations are weaker, especially for the Niño 2 and Niño

1+2 regions. Interestingly, the Niño 2 region is the only analyzed ENSO region to correlate significantly with anomalously wet and dry summer seasons. For anomalously wet summer seasons the association with Niño 2 is markedly stronger compared to the other ENSO regions. For the anomalously dry summer seasons, there is consistency in the strength of the signal across the various ENSO regions yet several reversals occur in the expected relationship between precipitation and SSTs (e.g., 1988, 1989, 1995, and 1998). Such a reversal may extend to the last two anomalous wet seasons on record as well (2002 and 2003) when positive instead of negative SSTAs prevail over much of the central equatorial Pacific. Thus, we conclude that since the Pacific climate shift, the Niño 2 region is the main contributor to interannual variability in the watershed. Average SSTs in this region for the months of September through November may serve to forecast anomalously wet summer seasons. The application of SON SSTs for predicting anomalously low summer season precipitation is less useful given the weaker correlations.

In addition to the ENSO signal, sea surface temperatures in the northern Tropical Atlantic were identified as a significant contributor to hydrological variability in the Ramis watershed. The strength of this signal fluctuates over time and is strong both prior to the Pacific climate shift and post-1997. It is interesting to note that a negative NAO phase prevails during these time periods. Oppositely, during the positive NAO phase associations with the northern Tropical Atlantic signal disappear and only associations with the ENSO region are significant. Aside from interannual variability, there is decadal periodicity in the record that is similar in nature to the TNA and PDO.

We believe that future research should focus on better understanding the relationship between the tropical Atlantic and the hydroclimatology of this region since a significant, albeit smaller proportion of variability is explained by this relationship. Since both the Pacific and Atlantic contribute to precipitation and discharge variability to different degrees at varying timescales, this characterization, together with a better understanding of the relationship to PDO and NAO, may explain shifts in teleconnections. Furthermore, it might increase the predictive use of forecasts in the future.

CHAPTER 3

ENVIRONMENTAL CHANGE IN AN ANDEAN WATERSHED: AN NDVI ANALYSIS

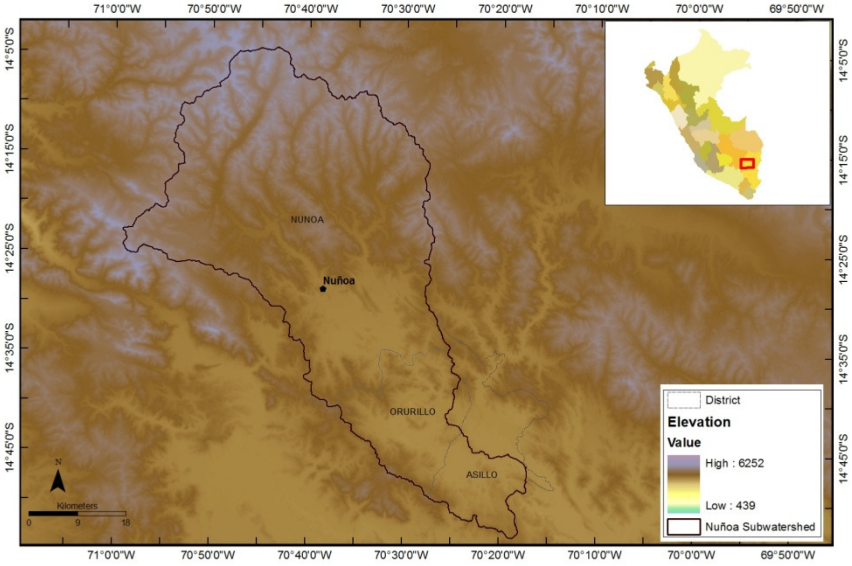
3.1 Introduction

Nuñoa, Peru located in the Department of Puno, is colloquially known as the alpaca capital of the world. There, the livelihood of the predominantly Quechua-speaking population is largely based on herding and small-scale agriculture. In a region with a pronounced dry season (June through August), wetlands, with their year-round vegetation, provide essential foraging grounds. These high Andean wetlands, locally termed *bofedales*, are sources of sustenance and income to local pastoralists. *Bofedales* are sustained by groundwater as well as precipitation and contributions from glacier melt and are therefore extremely responsive to changes in the water balance (Squeo et al. 2006). They are heavily vegetated and growth and species composition are a function of water availability, soil, and climate. Thus, variations in climate as well as differing land use and herding management strategies can result in significant changes in water quantity, water quality, plant diversity and plant cover in *bofedales*. Environmental change and its determinants is therefore an issue of consequence for the numerous herders in the Nuñoa watershed and elsewhere in the Andes.

Mountain regions are particularly sensitive to changes in climate (Diaz et al. 2003). Temperature in the Andean region has increased by approximately 0.1°C per decade for nearly 70 years (Vuille et al. 2008) and this is above the global average. Andean tropical glaciers are receding at accelerating rates (Buffen et al. 2009; Jordan et al. 2005) and some are disappearing. Furthermore, recent research suggests shifts in the precipitation cycle that include later onset of the rainy season (Thibeault et al. 2010) and therefore a longer dry season in some areas. In addition to changes in climate, a myriad of social and economic changes are occurring in the Andes. These changes affect the governance and management of natural resources, including *bofedales*.

The objective of this study is to investigate the vegetation dynamics during the dry season (June through August) in the Nuñoa watershed (Figure 3.1) between 1985 and 2010 using Landsat derived Normalized Difference Vegetation Index (NDVI). Landsat derived NDVI has been used elsewhere in the Andes to investigate spatial changes in vegetation cover both over time (Yager 2009) and in response to drought (Washington-Allen et al. 1998), and specifically to map the distribution of *bofedales* (Otto et al. 2011). *Bofedales* have the highest vegetation cover relative to the surrounding montane ecosystem, particularly during the dry season. This density of photosynthetic vegetation has high reflectance in the near infra-red making *bofedales* easily distinguishable using the NDVI.

Figure 3.1 Elevation map of the Nuñoa Watershed and showing the three districts that form the political boundaries in the watershed. The insert displays the location of the watershed within the Department of Puno, Peru.



The specific research goals of this research study are to:

1) Calculate mean NDVI for the Nuñoa watershed for each of 20 dry-seasons from 1985 to 2010 (not all years had usable imagery) and perform a multiple linear regression with annual watershed-wide mean NDVI as the response variable in order to determine:
    a) If there is a trend in watershed-averaged dry-season NDVI from 1985 to 2010 and;
    b) The relationship between this dry-season NDVI index and the covariates precipitation and temperature.
2) Delineate *bofedales* based on the 1985 to 2010 dry-season mean NDVI for each pixel in the watershed.
3) Perform a multiple linear regression for each pixel in the watershed (3,070,160 regressions) using cell specific annual dry-season NDVI as the

response variable (n=20) and year, Julian day, regional precipitation, and regional temperature indices as the predictor variables in order to:

   a) Review the spatial nature of NDVI changes in vegetation in the watershed through time (1985-2010), particularly with respect to *bofedales*.
   b) Determine the relationship between modeled NDVI in the watershed and regional precipitation and temperature.

4) Discuss changes in NDVI throughout the watershed with respect to changes in precipitation, temperature, and land tenure and management strategies.

3.2 Site Description

The study area is the 2,763 km^2 Nuñoa watershed that ranges from 3875-m to 5,550-m above sea level (Figure 3.1). The watershed is characterized by three ecological zones: the sub-alpine humid puna ecosystem which extends from 3,700 to 4,600 meters, the alpine zone or humid tundra zone from 4,600 to 4,800 meters, and the nival (permanent snow and ice) zone above 4,800 meters. The landscape is mostly open, rolling hills at lower elevations in the puna ecosystem and lichen and moss covered rock in anticline formations at higher elevations. Generally, agriculture, in thin soils of relatively low productivity (Brush 1982; Josse et al. 2009), is possible up to an altitude of approximately 4,200 meters. Herding of llama (*Lama glama*) and alpaca (*Vicugna pacos*) is possible at elevations up to approximately 4,600 meters. Herding therefore provides the primary livelihood for many residents of the Nuñoa watershed. The region has the densest populations of camelids in the Andes, and is Peru's largest producer of alpaca fiber.

The climate is semi-arid and the seasonal cycle of precipitation is characterized by dry months (June through August) when there is often no precipitation to the wet months of December through March when precipitation may be 200 mm per month. Annual precipitation for the region averages 760 mm but varies according to elevation and an increasing west to east rainfall gradient. Relatively frequent drought and heavy rainfall periods are common and are associated with El Niño and La Niña events, respectively. The dry season months of June and July are the coldest of the year averaging 4˚C while the wet season months of November through December are warmer with monthly averages of 10˚C (ATDR-Ramis 2008). However, the region experiences greater variation in diurnal temperatures than in annual temperatures and this is most pronounced in the dry season when the daily temperature often ranges between -12˚C and 12˚C.

Ecologically, the humid puna is one of four phytogeographic regions distinguished in the Central Andes (according to the Rivas-Martinez model: Josse et al. 2009). It extends from northern to southern Peru, along the Cordillera Oriental and into western Bolivia at elevations between 3,800 and 5,000 meters. Like other vegetation zones, it is the result of the interaction of topography and climate. Forests of small woody trees with twisted trunks called *Polylepis* may have covered most of the landscape some 12,000 to 15,000 years ago at the beginning of human occupation.

Today, only sparse forests of *Polylepis* remain and the dominant vegetation is a tussock or bunch grass known as *Stipa* (e.g., *Stipa ichu*). Other common bunch grasses include *Festuca* (e.g., *Festuca dolichophylla*, locally known as Ch'illiwa) and *Calamagrostis*.

Bofedales are common in the humid puna. They are characterized by saturated soils, a high percent of vegetation cover, and significant wet and dry biomass. As a result, they provide essential forage during the dry season and in drought and are used more intensely during these times. In the Department of Puno, vegetation coverage in wetlands may be as high as 85% to 98% (ALT-PNUD 2001). Vegetation includes grasses (Poaceae) such as *Deyeuxia rigescens* and *Festuca d.*, sedges (Cyperaceae) including the species *Carex sp*. and *Scirpus rigidus*, flowers in the Asteraceae family such as *Hypochoeris*, and cushion plants such as *Distichia muscoides* (Juncaceae family) and *Plantago tubulosa* (Plantaginaceae family). A large percentage of the vegetation in *bofedales* (for example *Deyeuxia r.*, *Festuca d.*, and *Distichia m.*) is consumed by alpacas. In a case study of two *bofedales* in the Nuñoa watershed, upwards of 60% of the vegetation cover was considered high quality forage preferred by alpaca (ALT-PNUD 2001).

Bofedales range in shape and size according to geomorphic setting (bordering streams, at the toe of a slope, or on relatively flat ground) and can cover several square kilometers (Warner et al. 2008). In the Nuñoa watershed the *bofedales* are classified as one of two types based on altitude, either Altiplanico (3880 to 3940 masl) or Altoandino (4150 to 4400 masl). The wetland systems may be managed privately but many are managed by one or several communities that jointly decide on land management practices. In some instances, *bofedales* that belong to a community may be divided among families and managed separately. Often, if resources allow, communities or land holders will maintain a wet season and a dry season pasture so that a given wetland system will only be grazed in a particular season; thereby reducing grazing pressure.

3.3 Data and Methods

3.3.1 Landsat 5 Thematic Mapper (TM) Image acquisition and preparation

Landsat 5-TM (30 meter resolution) satellite imagery was obtained through USGS/EROS (Earth Resources Observation & Science Center) and the Brazilian National Institute for Space Research (INPE). Images available for the months of June through August from 1985 through 2010 were downloaded and reviewed for quality, including cloud coverage. Relatively cloud free, dry season-imagery (June through August) exists for 20 of the 26 years of interest. The images that were processed and included in the NDVI analysis appear in Table 3.1 along with image properties and associated climate variables.

Table 3.1. List of images used in the analysis along with image properties and the associated temperature and precipitation values.

[redacted]

Bands 1-5 and 7 were stacked using ENVI 4.7 software. Georeferencing was performed on images in their original datum (four images have SAD 69 datum while all others have WGS84 datum). This was done in ENVI software package (Version 4.5, ITT Visual Information Solution) using an ETM scene as the base image. An attempt was made to obtain the smallest Root Square Mean Error (RMS) possible with a goal of 0.5 pixel error or less. Images were first warped using a linear stretch. If, after warping and upon inspection, a location was off by more than one pixel then the image was warped using a second degree polynomial method.

Atmospheric correction (haze reduction) in the form of Dark Object Subtraction (DOS) was performed on each scene using open lake water as the dark object (Ahern et al. 1977). Images were converted from raw digital numbers to represent true reflectance using rescaled gain and bias factors provided in Chander et al. (2009).

Converting from DN to radiance, then to reflectance, and performing dark pixel subtraction was done following *Equation 1* below and calculated in ENVI using the Spectral Math tool (Version 4.5, ITT Visual Information Solution).

(Equation1)

$$RefL = [\pi * d^2/\cos(zenith\ \Theta)] * [(DN - DkPixel) * G_{rescale} + B_{rescale}] / Esun$$

Where:

RefL = Top of the atmosphere reflectance (unitless)

π = Mathematical constant (unitless; ~ 3.14159)

d = Earth-Sun distance (astronomical units) (Table 6, Chander et al. 2009)

zenith Θ = Solar zenith angle (degrees)

DN = pixel value (unitless; 0-255)

DkPixel = minimum dark pixel value

$G_{rescale}$ = Band-specific rescaling gain factor [(W/(m^2 sr µm))/DN] (Table 3, Chander et al. 2009)

$B_{rescale}$ = Band-specific rescaling bias factor [(W/(m^2 sr µm))] (Table 3, Chander et al. 2009)

Esun = Mean exoatmospheric solar irradiance (W/ m^2 µm) (Table 3, Chander et al. 2009)

3.3.2 NDVI Calculation

The NDVI (Normalized Difference Vegetation Index) is one of several remote sensing vegetation indices used to represent vegetation characteristics (e.g., leaf area index, plant cover) in an area (pixel) (Rouse et al. 1973; Tucker et al. 1985). The index is a single value derived from the ratio of the difference in spectral bands that are sensitive to the spectral characteristics of leaf tissue (infrared reflectance is sensitive to plant cells and water content while reflectance in the visible red wavelengths is sensitive to chlorophyll) to the sum of these bands. Specifically NDVI is calculated as (near infrared – red)/ (near infrared + red). Using Landsat TM images, this results in the following:

NDVI = (Bands 4-3)/(Bands 4+3)

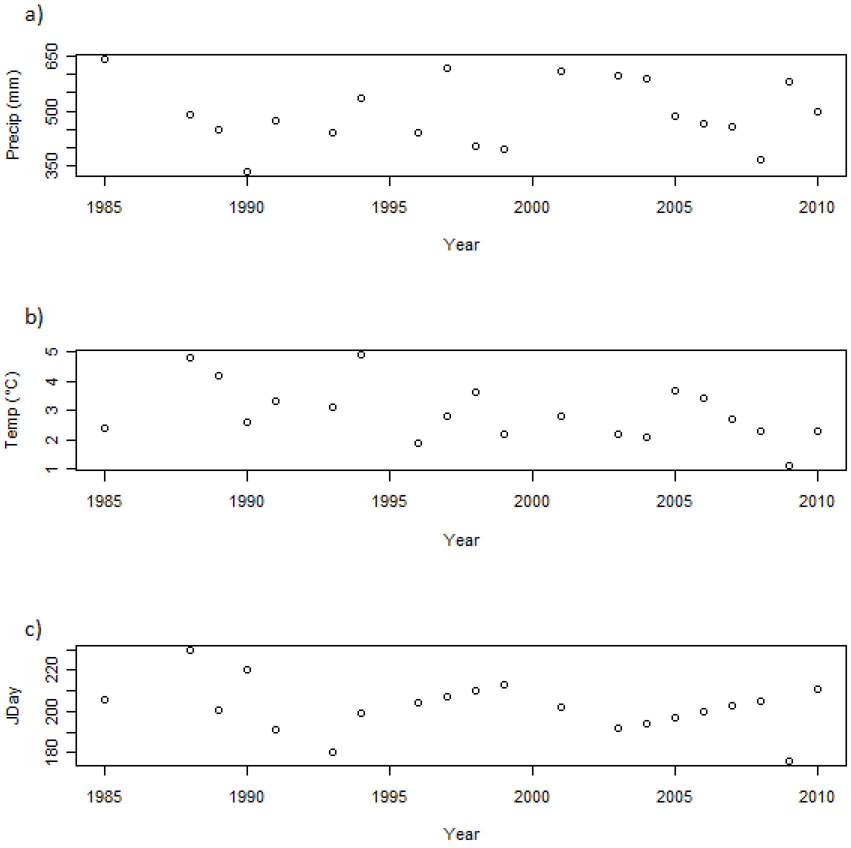
Typically, NDVI values range between -1 and 1. For this study, in order to remove erroneous values and convert to unsigned integers with precision to the hundredths place, values were transformed to an integer scale of 0-20,000 by adding one to the original NDVI value, multiplying by 10,000, and rounding. When values appear in these transformed NDVI units they will be denoted as $NDVI_T$ and where non-transformed units are provided they will be denoted as NDVI.

The 20 transformed NDVI Images were then stacked and cropped to a grid containing the Nuñoa watershed. The stacked and cropped image was exported as a band interleaved by line (BIL) file for compatibility with R to perform the regression analyses. Additional spatial data analyses, such as delineation of the *bofedales* were performed using ArcMap 10 (ESRI 2012). *Bofedales* were delineated using the 20 scene NDVI average (1985 through 2010) for each pixel and classified as such if the NDVI average value was above 13000 (0.3 on the untransformed NDVI scale).

3.3.3 Covariate Data

The same four explanatory variables were used for both the watershed-wide mean NDVI regression analysis and the NDVI regression analysis performed for each pixel in the watershed. The four covariates are precipitation, temperature, and the Julian day and year the image was taken. Precipitation values associated with an image represent the sum of precipitation for the preceding months of December, January, February, and March (Table 3.1, Figure 3.2a) (Appendix A). These are the wet season months in the Altiplano when collectively, approximately 71% of precipitation falls (based on data in this study). For the images acquired from 1985 to 2007, the wet-season value is an average across nine meteorological stations. The meteorological stations are currently maintained and operated by *Servicio Nacional de Meteorologia e Hidrologia del Peru* (SENAMHI-Peru) in the Department of Puno, southern Peru. They are located at the northern extent of the Altiplano from 14˚41’ to 15˚29’ south and 69˚45’ to 70˚42’ west and range in elevation from 3820 meters to 4400 meters. Seven monthly values were missing in total from two stations corresponding to three wet seasons. Using backward stepwise regression and the Akaike information criterion (AIC), approximately 2% of the wet season totals across all nine stations for the 17 years were imputed. The consistency of station records was reviewed with double mass analysis (Searcy and Hardison 1960).

Figure 3.2 Graphs of the explanatory variables: a) Precipitation (mm); b) Temperature (°C) and; c) Jday, in their original values.



Precipitation values for the last three years of image analysis (2008 through 2010) were available from one station (also used in the 1985-2007 analysis). This station, located at 3971 meters, is quality checked through a local university. The correlation result between this station and the nine station average for the years 1985 through 2007 is $r = 0.52$, $p < 0.05$.

Temperature is the second explanatory variable in the regression models. Temperature data for all years was obtained from the meteorological station located at 3971 meters and maintained by SENAMHI-Peru. The temperature value associated with each image is the average for the month preceding the image acquisition date if the scene was acquired within the first 15 days of the month. If the image was acquired after day 15, then the temperature average for the month of acquisition is used (Table 3.1, Figure 3.2b).

Julian day and Year are also explanatory variables in the regression models. Julian day (included as a nuisance variable), is the Julian day of image acquisition. For the 20 images used in the analyses it ranges from day 176 (June 25) to day 230 (August 18) (Table 3.1, Figure 3.2c). The covariate Year is simply the year of image acquisition (Table 3.1).

3.3.4 Mean NDVI analysis (Objective 1)

The NDVI values in the watershed were averaged for each analysis year (n=20) from 1985-2010. Originally, a trend analysis was performed on mean NDVI values with only Year as an explanatory variable. Examination of the residuals however, indicated that variance was heteroscedastic and therefore problematic. As a result, several other models that included the predictor variables discussed above were considered. After model selection efforts using the AIC criterion, the following model was chosen to best represent mean NDVI in the watershed (Mean NDVI_T):

(M.1 Mean NDVI_T)

$$\text{Mean NDVI}_T = \alpha + (\beta_0 * \text{Year}) + (\beta_1 * \text{Precip}) + (\beta_2 * \text{Temp}) + (\beta_3 * \text{JDay}) + (\beta_4 * \text{Year:Precip}) + (\beta_5 * \text{Year:Temp}) + \varepsilon$$

In this model, α is the intercept, β is the slope coefficient for each of the six predictor variables, and ε is the residual error. Not only are the four predictor variables (year, precipitation, temperature, and Julian Day) considered but the interactions between year and precipitation and between year and temperature are included as well. All predictor variables are centered (Cx=(x-mean(x))). In addition, a log base 10 transformation was applied to temperature and precipitation values. Variance inflation factors (VIF) for each predictor were calculated in order to review the level of multicollinearity in the model. The largest VIF was 1.4 (for the estimated coefficient Temperature) and therefore multicollinearity was deemed not to be an issue.

3.3.5 Pixel by pixel NDVI regression analysis (1985-2010) (Objective 3)

The following ordinary least squares regression model was applied to each pixel (30 m x 30 m) in the watershed using the BIL file containing the 20 stacked NDVI processed images:

(M.2 $\mathrm{NDVI}_{\mathrm{cell}}$)

$$\mathrm{NDVI}_{\mathrm{cell}} = \alpha + (\beta_0 * \mathrm{Year}) + (\beta_1 * \mathrm{Precip}) + (\beta_2 * \mathrm{Temp}) + (\beta_3 * \mathrm{JDay}) + \varepsilon$$

Where the response variable is NDVI for a given cell, α is the intercept, β is the slope coefficient for each of the four predictor variables (precipitation, temperature, Julian day, and year of image acquisition), and ε is the residual error. Again, each predictor variable was centered (Cx=(x-mean(x))) to reduce high correlations between slope and intercept parameters. In addition, a log base 10 transformation was applied to temperature and precipitation values to improve homoscedasticity of residuals. Model parameters are assumed to be spatially stationary and each cell is assumed to be independent of its neighbors. The model was run in R using the package ‘raster’ (Hijmans and van Etten 2011) (Appendix C) which allows for the following output in the format of raster images:

1) Intercept values
2) slope coefficient values for each of the covariates: Year, Precipitation, Temperature, and Jday;
3) p-value (f-statistic) values for each of the covariates;
4) r-square values for the model
5) p-value (f-statistic) for the model

Utilizing the various data from the model output, predicted NDVI was then calculated for each cell in a given analysis year as were residuals and error. For analyses involving slope coefficients a mask was applied to remove cells within lakes. The lake perimeters were digitized from the National Map (Carta Nacional) covering the region at a scale of 1:100,000 (Instituto Geografico Nacional 1972).

3.4 Results

3.4.1 Watershed-wide Mean NDVI Analysis

NDVI values in the watershed for each of the 20 scenes in the study period appear in the boxplot (Figure 3.3). There is greater variability in median NDVI values for the years between 1988 and 1999 than for the median values between 2003 and 2010. It is also noted that the highest median NDVI value in the watershed is for the year 1985. This year also has the highest mean NDVI value (Table 3.2). Note that values in the boxplot and in the second column of the table are the transformed NDVI values ($NDVI_T$) that range between 0 and 20,000. For comparison, the values have been converted to traditional NDVI units in the third column of the table.

Figure 3.3 Boxplot with weights of NDVI values in the Nuñoa watershed. Placeholders for the six years for which scenes were not analyzed are represented as bars at $NDVI_T$ value of 13000. Whiskers extend to the lowest (highest) datum within 1.5 IQR of the lower (upper) quartile.

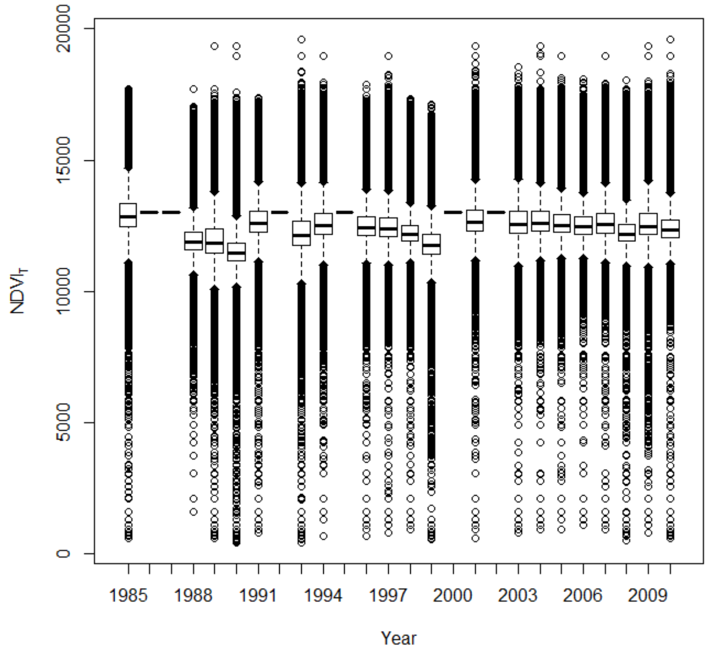


Table 3.2. Mean NDVI for each scene. Both transformed ($NDVI_T$) and non-transformed (NDVI) values are provided for comparison.

Year	Ave $NDVI_T$	NDVI
1985	12948	0.295
1988	11984	0.198
1989	12023	0.202
1990	11594	0.159
1991	12710	0.271
1993	12290	0.229
1994	12656	0.266
1996	12528	0.253
1997	12491	0.249
1998	12282	0.228
1999	11843	0.184
2001	12783	0.278
2003	12701	0.270
2004	12756	0.276
2005	12661	0.266
2006	12580	0.258
2007	12681	0.268
2008	12303	0.230
2009	12664	0.266
2010	12484	0.248

Mean NDVI values for the 20 years with data from 1985 to 2010 are plotted along with a trendline in Figure 3.4. The issue of heteroscedasticity is evident from the graph and hence, we consider only the results of the regression model M.1 described in Section 3.4. The model accounted for 77% of the variance in mean NDVI in the watershed, $F(6, 13) = 11.53$, $p< .001$, Adjusted $R^2 = 0.77$. Model results (Table 3.3) indicate that each of the predictor variables, except Temperature, had a significant ($p< 0.1$) partial effect in the full model with Precipitation significant at the $p< .001$ level. There is an inverse relationship between mean NDVI and Julian Day and a positive relationship between mean NDVI and precipitation, as expected. Regressing mean NDVI on precipitation indicates that roughly half (56%) of the variability in average NDVI in the watershed can be attributed to this variable alone (if one assumes a stationary relationship). A linear trend analysis of the precipitation index over time however reveals no trend (similarly, there is no trend in Julian Day data).

Figure 3.4 Scatterplot of mean NDVI values for the Nuñoa watershed with trendline for the years 1985-2010.

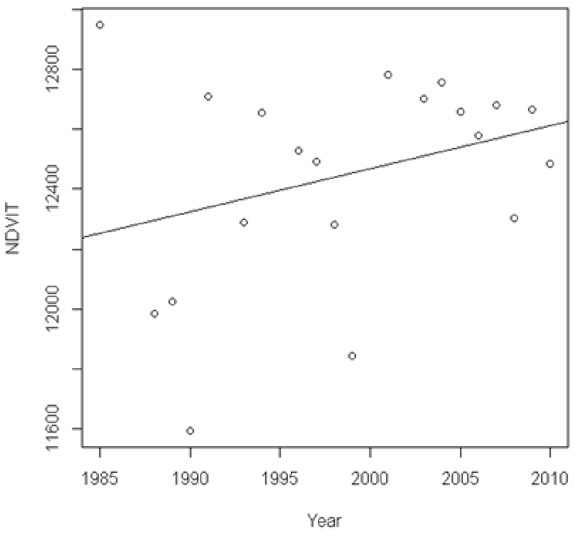


Table 3.3. Covariate results for the regression model M.1 with Mean NDVI_T as the dependent variable. Significant values in bold ($p < .1$) and italicized and bold ($p < 0.05$).

Predictor	**β**	**Std. Error**	**t -value**	**Pr(>|t|)**
Jday	-10.55	3.67	-2.87	***0.013***
Year	10.74	5.81	1.85	**0.087**
Precip	2718.76	556.15	4.89	***0.000***
Temp	144.36	306.68	0.47	0.646
Year:Precip	-154.31	69.81	-2.21	***0.046***
Year:Temp	62.83	35.27	1.78	**0.098**

There is a significant positive relationship between year and NDVI for average conditions (a mean of zero for the other covariates) in the watershed. Based on these results, it appears that mean NDVI in the watershed slightly increased between 1985 and 2010. However, the fact that the interaction terms in the model are significant indicates that the effects of the explanatory variables (year, precipitation, and temperature) on mean NDVI are conditional upon one another. These modeled interactions can be viewed as three dimensional surface plots, or perspective plots (Lenth 2009) (Figures 3.5a and 3.6a). Data distribution for the interactions (year versus temperature and year versus precipitation) and model residuals accompany the plots (Figures 3.5b and 3.6b).

The surface of the modeled interaction between temperature, year, and mean NDVI (Figure 3.5a) is a complex one and indicates that mean NDVI in the watershed decreases over time at lower temperatures and with increasing temperatures in the earlier part of the record. Conversely, the model predicts an increase in mean NDVI over time at higher temperatures and a sharp increase in NDVI with increasing temperature but only in the most recent years. These results are most likely an artifact of data distribution and model fit. For example, in the data distribution for year versus temperature (Figure 3.5b) there is only one temperature value below -0.2 and this occurs in the second most recent year. Likewise, the highest temperature values occur only in the earlier part of the record. An additional issue is the fact that the largest residuals all occur in the first half of the record. This is most likely due to the greater variability in NDVI values during the first half of the study as described above.

Figure 3.5a) Three dimensional surface plot for the interaction between mean NDVI in the watershed and year and temperature in the regression model M.1. b) Distribution of temperature versus year. The size of the point is related to the absolute value of the residual. The color of the point indicates the sign of the residual (positive residuals are black and negative residuals are red).

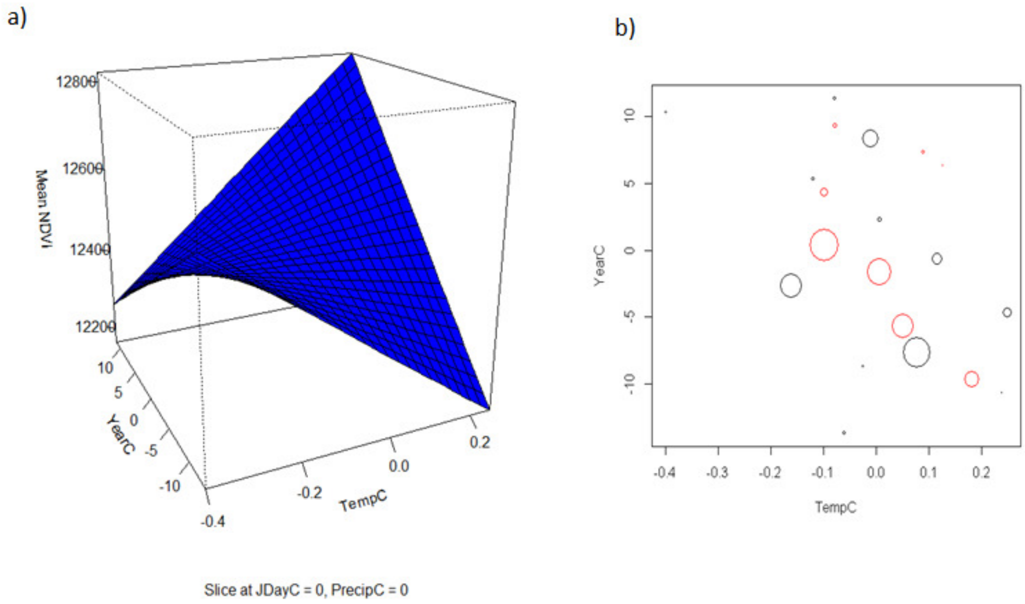
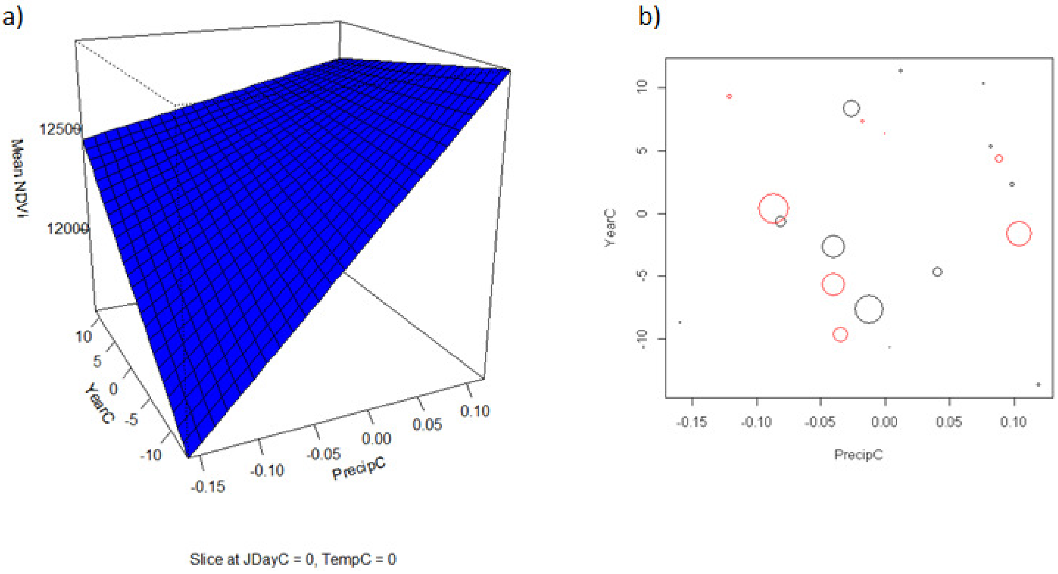


Figure 3.6a) Three dimensional surface plot for the interaction between mean NDVI in the watershed and year and precipitation in the regression model M.1. b) Distribution of precipitation versus year. The size of the point is related to the absolute value of the residual. The color of the point indicates the sign of the residual (positive residuals are black and negative residuals are red).



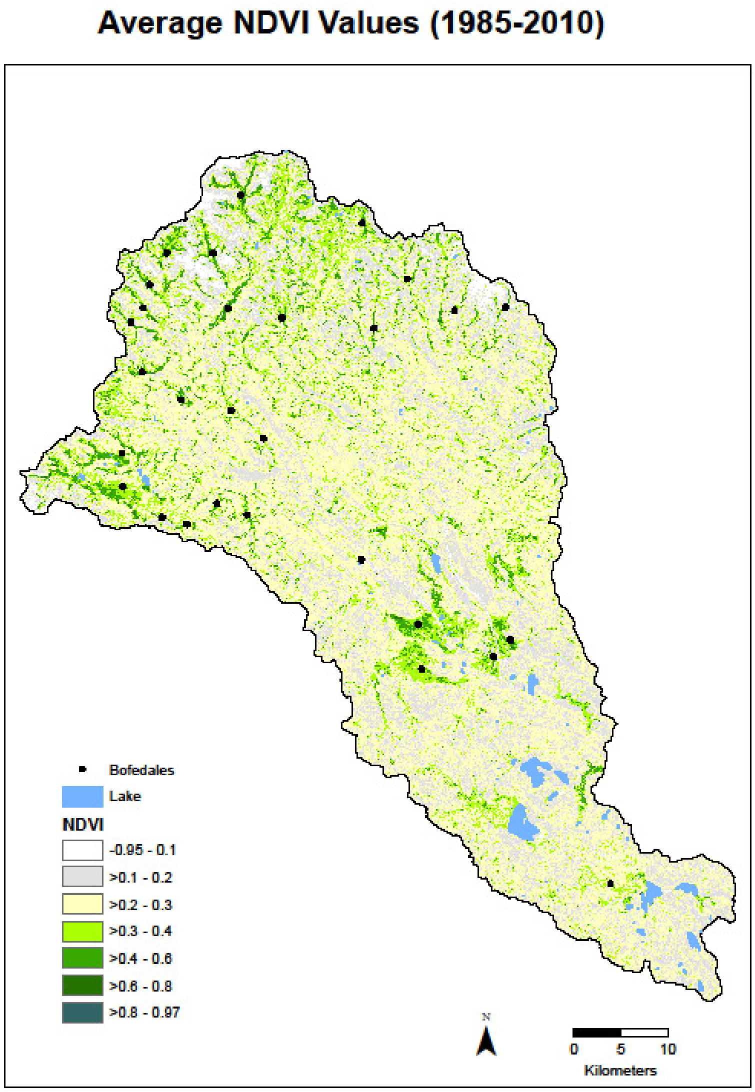
The distribution of the temperature data over time is a reflection of the fact that nighttime temperatures during the winter season months in the Altiplano have been below average in many recent years. Thus depending on the months and years used in an analysis, a decreasing trend may be present. Such is the case for the temperature index used in this study. It should be noted that this trend is at odds with the increasing mean annual temperature trends observed in the region (Vuille et al. 2008). Any interpretation of the relationship between mean dry season NDVI in the watershed and the temperature index used here should be a cautious one. Instead, we focus our efforts on reviewing and interpreting the results of the relationship between precipitation and NDVI over time.

The surface plot displaying the interaction between year, precipitation and mean NDVI (Figure 3.6a) shows that the model predicts a sharp increase in mean NDVI with increasing precipitation in the early years and only a slight increase in NDVI with increasing precipitation in later years. The model predicts a steep increase in mean NDVI over time at low values of precipitation and a slight decrease in mean NDVI over time at high values of precipitation. Overall, the precipitation versus year data is rather well distributed albeit with a scarcity of data in the low precipitation range (Figure 3.6b). The residuals indicate that the model fit for predicting mean NDVI is better in the second half of the record however, all values at the extremes are well fitted (Figure 3.6b). Thus, the predicted surface seems reasonable and it suggests two things: 1) the effect of precipitation on NDVI is less in recent years and 2) NDVI is generally higher in recent years. However, the highest point on the predicted surface is in the early year and high precipitation corner of the plot. Indeed, the first year in the record (1985 image) has the highest mean NDVI and corresponds to the greatest precipitation value (1984/1985 wet season). And while the NDVI imagery starts in 1985, it is insightful to know that the 1983/1984 summer season (DJFM) was also anomalously wet in the region. These two wet years occurred after the severe drought in 1982-1983. It may be that this particular sequence of events, rather than a single season precipitation value, is a factor behind the high NDVI in 1985. The variability in precipitation in the mid-1980s is the most extreme example for the time period in consideration. However, interannual variability in precipitation is inherent to the climate of the Altiplano and so understanding the sequencing (and magnitude) of dry and wet years and the effects on NDVI is a rather complex issue that may warrant further investigation.

3.4.2 Delineation of *Bofedales*

Figure 3.7 shows a map of the 20 scene NDVI average for the time period 1985 through 2010 for the Nuñoa watershed. Snow, ice, and riverbeds have average NDVI values between -0.95 and 0.1 while average NDVI values for bare rock and soil are between 0.1 and 0.2. “Background vegetation”, namely grassland and steppe vegetation such as the *Stipa* grasses, has an average NDVI value in the 0.2 to 0.3 range. *Bofedales* are easily visible on the map with average NDVI values in the 0.3-0.8 range. It is noted that forests of *Polylepis*, which do not go dormant, have similar spectral characteristics to *bofedales* making it difficult to distinguish between the two based on this alone. However, these forests represent less than 0.2% of the watershed and so were not separated out. General locations of many of the bofedal systems are marked by points on the map as they were part of a field study by the Peruvian Government (ALT-PNUD 2001).

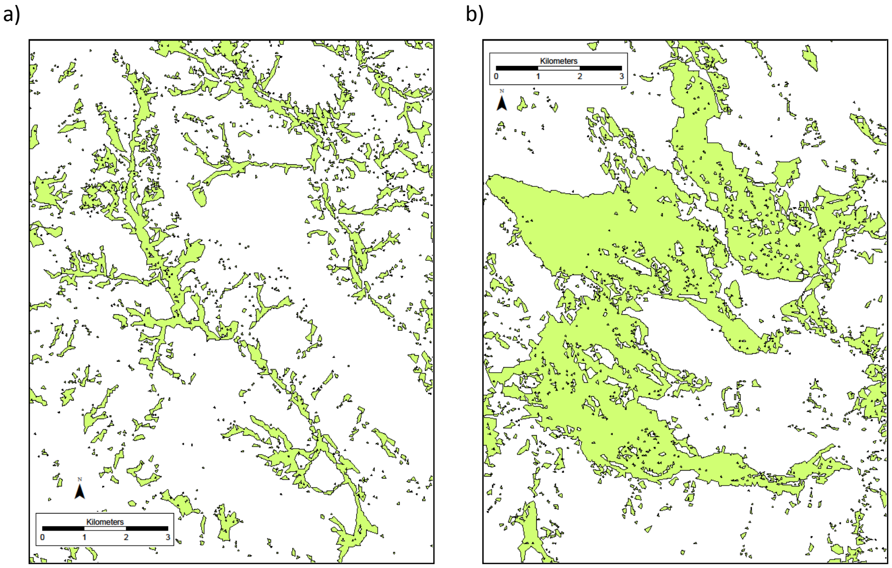
Figure 3.7 Mean NDVI for the 20 scenes analyzed for the time period 1985 through 2010. NDVI values are provided in non-transformed units.



Average NDVI Values (1985-2010)

Using the average NDVI value of 0.3 as a threshold, approximately 451 km^2 are classified as *bofedales*. This represents approximately 16% of the watershed area. The majority of *bofedales* are of the riparian type. Their features are narrow and dendritic, paralleling river and streambeds (Figure 3.8a). There are a few wetland systems, namely in the northwest and in the south of the watershed that are of the broader type found in shallow depressions (Figure 3.8b). NDVI change in the wetlands is discussed following the presentation of the pixel regression results below.

Figure 3.8 Two examples of wetland types in the Nuñoa watershed. Map (a) displays an example of a riparian bofedal associated with a stream or river and; (b) displays an example of a broader bofedal, in this case associated with an alluvial fan.



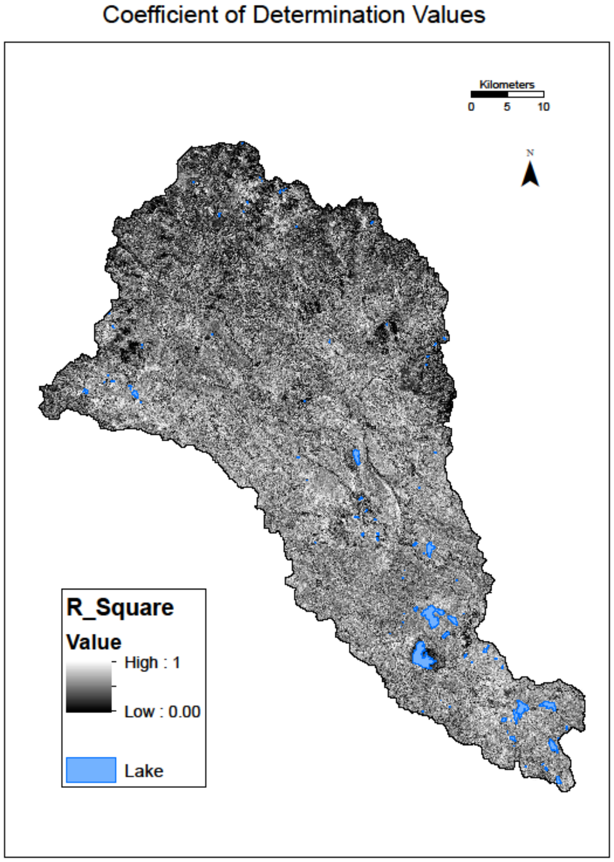
3.4.3 Pixel by Pixel NDVI Regression Analysis

In this section we present the results of the regression model (M.2) applied to each cell in the watershed with cell NDVI as the response variable. First we review the model output for the coefficient of determination and error terms. This is followed by a review of the spatial distribution of each of the covariates and finally, the results of the NDVI change analysis in the *bofedales* and otherwise.

3.4.3.1 Model Review

A review of the spatial distribution of the coefficient of determination (R^2) values (Figure 3.9) reveals many cells in the north and northeast of the watershed with very low values. This region of the watershed contains the highest elevations (see Figure 3.1) therefore some low R^2 values may be the result of the mountainous terrain and related slope, aspect, and shadow effects. A Pearson's product-moment correlation analysis between elevation and R^2 indicates a low inverse association between the two (Pearson's $r = -0.31$, $p < 0.05$). Very narrow linear features, such as streambeds and some wetlands, may also exhibit low R^2 values due to the 30-m pixel resolution.

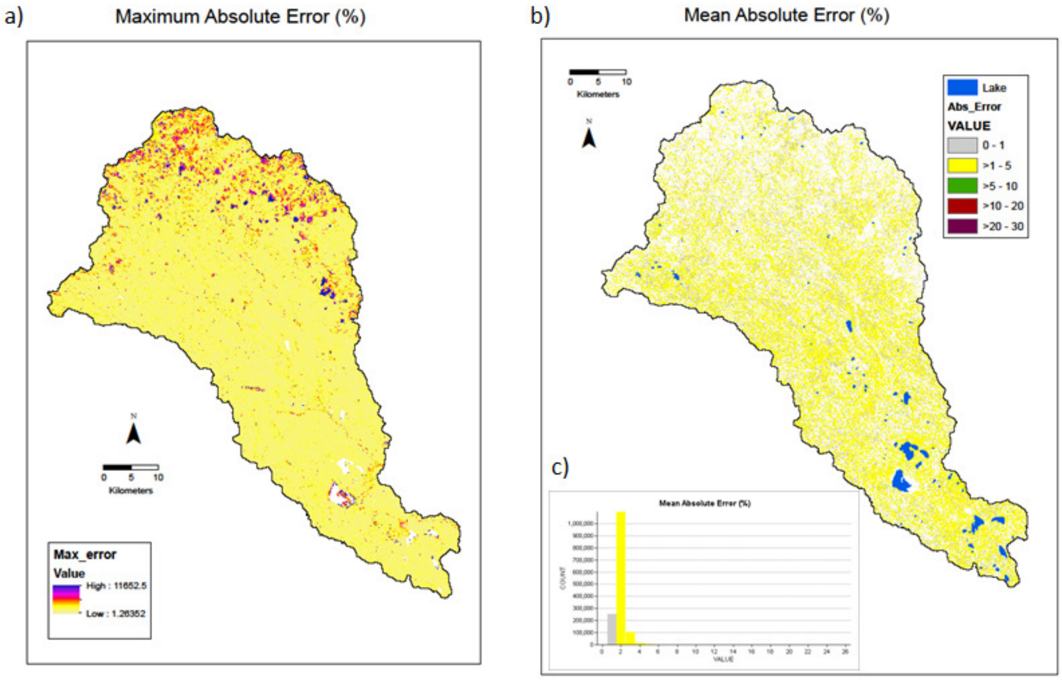
Figure 3.9 Coefficient of determination (R^2) values for all cells in the watershed for model M.2.



In order to evaluate autocorrelation in the error term, Global Moran's I was calculated on all residuals (Predicted-Observed) for each analysis year. The results reveal significant positive autocorrelation (clustering) in every year with values ranging from 0.29 to 0.75 ($p < 0.01$). While this is not surprising given the resolution and scale of the analysis, it also indicates that one or more key explanatory variables (e.g., elevation) are not accounted for with the current regression model. Land cover and features such as snow and wetlands may be driving the positive autocorrelation as might the presence of clouds, crop rotation practices, and sensor errors.

Absolute percent error (100*|Predicted-Observed|/Observed) was calculated for each cell in the watershed. To investigate the magnitude of absolute percent error for all years and the spatial distribution of this error, a map displaying the maximum absolute error for each cell was created (Figure 3.10a). The range of maximum absolute percent error is great and extremely large values appear mostly in the north and northeast of the watershed (similar to R^2). Again, this is presumably due to the topography of the watershed and varying snow and cloud coverage which is difficult to account for. There are also some extreme error values in the southern portion of the watershed (near lake shorelines, for example). These values are associated with the changing lake boundaries and also the area of intensive agricultural use in this region.

Figure 3.10 Error maps: a) maximum absolute error (%) in the 20 years of analysis for each cell (with the exception of cells within lakes) and b) absolute percent error in the watershed averaged over the 20 scenes and limited to significant cells only. c) Counts for mean absolute percent error categories.



For some analyses presented here, only significant cells are displayed. In these instances, cells that were not significant in the regression model at a $p < 0.05$ have been excluded from that analysis. In total 1,588,491 cells in the watershed were not significant at the 5% level. This represents slightly more than half of the total cell count in the watershed. Average absolute percent error for cells that are significant at the model $p < 0.05$ appears in Figure 3.10b. The bar chart in the figure (Figure 3.10c) shows that the majority (92%) of significant cells in the watershed have an average absolute error value of 2% or less.

3.4.3.2 Covariate Results

Figure 3.11 shows the spatial distributions of the slope parameter β_i for each of the four explanatory variables. Corresponding histograms appear in Figure 3.12. Cells in the watershed that are not significant at a $p < 0.05$ for the model are not included in the analysis. Additionally, a lake mask was applied. Minimum and maximum values are the result of truncation of the original data sets to eliminate extreme data values with low counts. The majority of these values represent cells along changing lake shorelines that were not included in the lake mask. The slope parameter values vary in space but they do not vary in time (i.e., for each explanatory variable only one slope parameter value is calculated for each cell in the watershed). Summary statistics for each covariate along with the corresponding change in NDVI for the given mean and mode slope parameter appear in Table 3.4.

Figure 3.11 Slope parameters, β, for the four explanatory variables in the regression model M.2: a) Jday; b) Precip; c) Temp and; d) Year. Only significant cells are included.

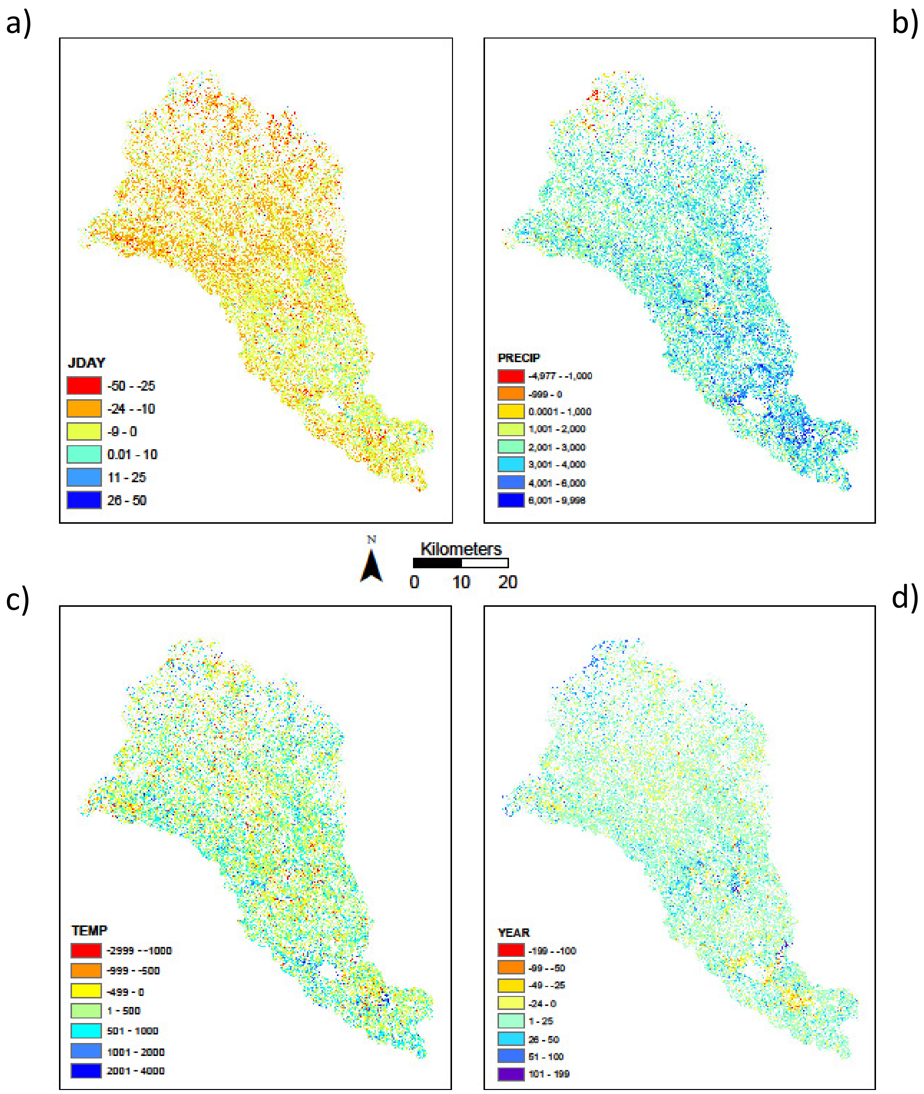


Figure 3.12 Histograms for each of the slope parameters, β, for the four explanatory variables in the regression model M.2: a) Jday; b) Precip; c) Temp and; d) Year. Only significant cells are included.

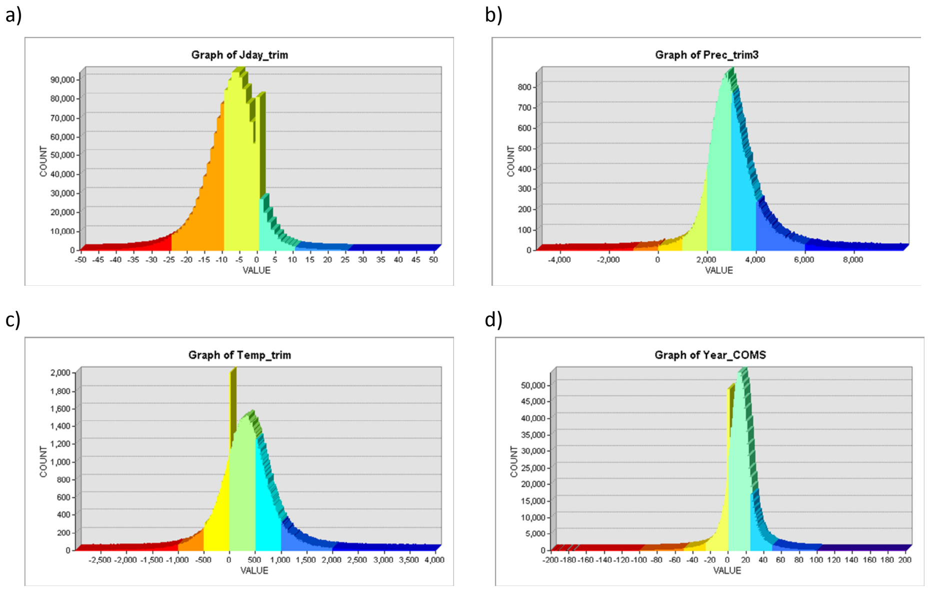


Table 3.4. Summary statistics for the four covariates in the M.2 analysis. The corresponding change in NDVI based on the mean and mode slope parameters are also provided.

	Summary Statistics for the Slope Parameter					**Corresponding Change in NDVI**	
Covariate	***Min***	***Max***	***Mean***	***Mode***	***Std Dev***	***Mean* β**	***Mode* β**
Precip	-4977	9998	2933.83	2802	1072.2	0.08	0.08
Temp	-2999	4000	290.87	0	520.78	0.02	0.00
Jday	-50	50	-8.03	-6	7.54	-0.04	-0.03
Year	-199	199	10.91	13	17.91	0.03	0.03

Of the four covariates Jday (Figure 3.11a and 3.12a) is the only one to have a negative mean and mode slope parameter. This indicates that generally, as the dry season progresses NDVI values decrease. This relationship is logical if falling NDVI values are the result of plant water stress and one assumes that there is a decrease in soil moisture as the dry season progresses. The southern half of the watershed, characterized by flatter terrain and lower elevations, contains the largest percentage of cells with a positive relationship between Julian Day and NDVI. This may be due to several factors including processes such as infiltration and subsurface flow in the region and irrigation activities.

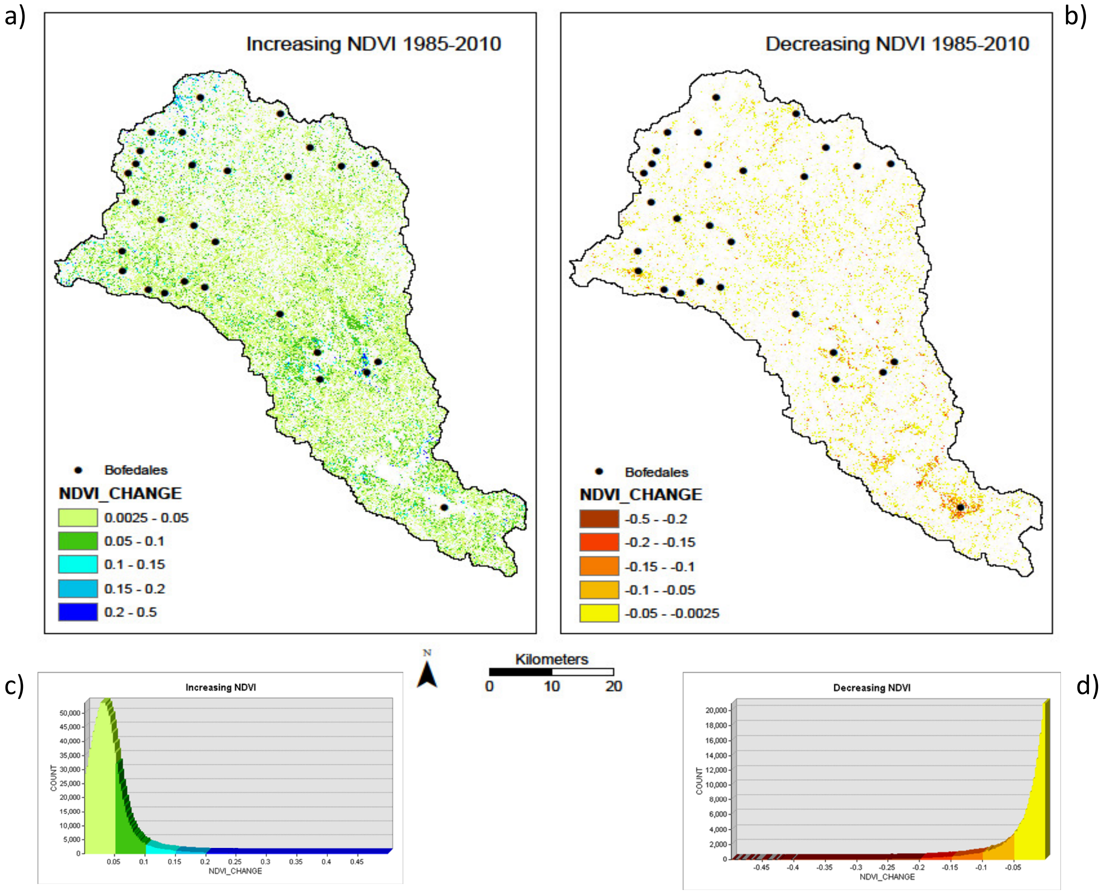
The slope parameter values for the Precipitation covariate (Figure 3.11b and 3.12b) are mostly positive indicative of the relationship between increased precipitation and the resulting increase in NDVI. Few cells such as on mountain tops and in the depths of the *bofedales* exhibit an inverse relationship between the two. The reasoning for this may be that as precipitation falls on mountain tops in the form of snow, NDVI decreases. In the *bofedales* increased precipitation may raise the water level to a critical point that may drown out vegetation, thereby reducing the NDVI values.

The slope for Temperature (Figures 3.11c and 3.12c) exhibits considerable variation in magnitude and sign throughout the watershed as demonstrated by the mode and standard deviation of the slope parameter (Table 3.4). This may be due to the difference in vegetation response to temperature at various elevations and to various landforms and vegetation species. Furthermore, the use of a static temperature variable may not be the most appropriate choice ecologically. However, a review of model performance at the cell level at various locations indicates that while the covariate itself may not be significant in many instances, model performance is enhanced when it is included.

The slope for the covariate Year (Figures 3.11d and 3.12d) is mostly positive with both mean and mode slightly above zero (Table 3.4). Since the beta coefficients represent the associated change in $NDVI_T$ with respect to a unit increase in year (holding the other covariates constant) we can calculate the total change in $NDVI_T$ over the time period for a given beta value. For example, the mode slope parameter value for the covariate Year is 13 (Table 3.4). The change in $NDVI_T$ that is associated with this beta value is calculated as 325. And since $NDVI_T$ was scaled by a factor of 10,000, this equates to an increase of 0.03 units on the untransformed NDVI scale. In other words the change in NDVI from 1985 to 2010 most encountered in the watershed is the modest increase of 0.03 units. We continue to use this method to analyze the increasing and decreasing NDVI trends in the watershed.

The Nuñoa watershed is 2,763 km^2. After removing pixels that are well within lake perimeters and along shorelines as well as pixels that are not significant in the model at a $p < 0.05$, the area summarized for change in NDVI over time is 1,329 km^2 or approximately 48% of the watershed area. The spatial patterns of positive and negative NDVI trends are shown in Figure 3.13a and 3.13b, respectively. The trends are in total NDVI units of change from 1985 to 2010. Of the summarized area, 81% exhibits an increase in NDVI from 1985 through 2010 (Figure 3.13a). Another 16% of the cells exhibit a decrease in NDVI (Figure 3.13b) over this time and approximately 3% of the cells display no change in NDVI. Frequencies for the changes in NDVI appear in the histograms (Figure 3.13c and 3.13d). Cells with an increase in NDVI of 0.1 or greater appear mostly in three locations in the watershed: in the north/northwest along the watershed boundary; in the central section of the watershed in association with the wetland below the alluvial fan; and in the southern portion of the watershed. Cells with decreasing NDVI trends appear as linear features in the north and northeast of the watershed area of the watershed. This is in association with the stream network. However, the majority of cells exhibiting a large magnitude of decreasing NDVI appear in the south of the watershed.

Figure 3.13 Maps displaying significant a) increasing NDVI and b) decreasing NDVI from 1985-2010. Many, but not all of the bofedal systems are marked. NDVI values are provided in non-transformed units. Histograms for cells with c) increasing NDVI and d) decreasing NDVI appear below the maps.

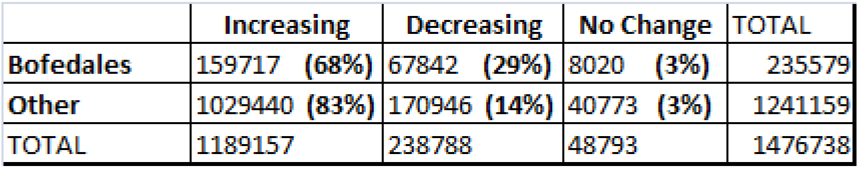


3.4.4 NDVI Change in *Bofedales*

Of the 451 km^2 classified as *bofedales* approximately half that area (47%) was included in the NDVI change analysis. If we calculate the number of cells with a given

NDVI trend (limited to model significance of $p < 0.05$) within *bofedales* we find that 68% of the analyzed wetland area exhibits an increase in NDVI, 29% exhibits a decrease in NDVI, and 3% exhibits no change in NDVI values for the 1985-2010 period (Table 3.5). There are over twice as many increasing NDVI cells compared to decreasing NDVI cells in *bofedales*.

Table 3.5. Cell counts and percent of cells (in parentheses) with increasing, decreasing, and no change NDVI that occur within *bofedales* and otherwise in the landscape.



	Increasing	**Decreasing**	**No Change**	TOTAL
Bofedales	159717 **(68%)**	67842 **(29%)**	8020 **(3%)**	235579
Other	1029440 **(83%)**	170946 **(14%)**	40773 **(3%)**	1241159
TOTAL	1189157	238788	48793	1476738

How do these percentages compare with NDVI change in vegetation outside of *bofedales*? We find that 83% of the analyzed cells in the watershed not classified as wetland have increasing NDVI values while 14% of those analyzed cells have a decreasing trend and 3% display no change in NDVI (Table 3.5). There is an overwhelming percentage of vegetation in the watershed that exhibits an increase in NDVI values. These results might be expected since there is a positive trend in mean NDVI in the watershed for the 1985 to 2010 period.

The question remains whether the decreasing vegetation trends in wetlands (29% versus 14% in background vegetation) constitutes a significant clustering of decreasing cells. It should be noted that the percentage of decreasing cells quantified in *bofedales* is conservative given the methods used in the regression analysis and the resulting significance filter. Furthermore, a few areas may have undergone rapid and extreme changes in land cover so that while these areas may have been wetlands in the past, they no longer classify as such due to low mean NDVI values. An example of this is a portion of the large patch of decreasing cells in the south of the watershed (see Figure 3.13b). Much of the area was classified as wetland on earlier maps but due to intensive use for agriculture and cultivated pastures in more recent years it would no longer meet the mean NDVI threshold to be classified as a wetland for this study.

Finally, we would like to comment on the spatial configuration of increasing and decreasing NDVI cells in the *bofedales* in the watershed. There appears to be no consistent pattern throughout the watershed. That is to say that there are *bofedales* that contain a majority of cells with decreasing NDVI values such as the wetland in the northwest and several of the wetland systems in the south, while others contain a majority of cells with increasing NDVI values, and still others, such as the large wetland just south of the town of Nuñoa that contain a good number of both. These spatial relationships and the processes behind them warrant further attention.

3.5 Discussion

3.5.1 Discussion of methodology

A candid discussion of the methods used in the NDVI analysis reveals the strengths, limitations, and transferability of such an approach. First, access to satellite images from repositories around the globe (at little to no cost) has only been possible in the last decade and certainly this study would not have been possible were this not the case. The spatial resolution and spectral properties of Landsat 5-TM were more than adequate for the purposes and scale of this study. We were fortunate that the years of analysis fell within the period of operation for the sensor (1982-2011). We were also able to obtain a good number of images due to that fact that, for the most part, relatively cloud free scenes exist for the region during the months of low to no precipitation (June-September). This timing is favorable since the contrast between *bofedales* and background vegetation is most distinct at this time. Additionally, the *bofedales* are easily visible due to the absence of dense forest cover in the watershed (except for small areas of Polylepis forest). Therefore, the methods employed here in identifying and analyzing change in wetlands would be suitable in other high elevation watersheds with an arid to semi-arid climate as well as in many regions in Africa and the Middle East, for example.

The amount of data that results from processing 20 satellite images covering nearly 3,000 km^2 is substantial. This fact, combined with an interest in both the spatial and temporal dynamics in the watershed presents several challenges, not the least of which is finding an efficient and effective means of presenting results. Regarding methods: owing to advances in computing power and the existence and compatibility of remote sensing and imaging software and programs such as R, a cell by cell multiple regression was possible. However, we were limited in our model choice by available degrees of freedom. For example, terms may have been better expressed as polynomials, and we would have liked to have included additional covariates such as elevation, slope or aspect, or an El Niño Southern Oscillation (ENSO) proxy. This was simply not possible. We recognize the limits to the assumption of spatial independence that is inherent to the cell by cell regression method. While a geographically weighted regression

(Brunsdont et al. 1998) may increase prediction power of the regression model and increase degrees of freedom, it presents additional challenges such as choosing an appropriate bandwidth and spatial weighting function. It is also more computationally intensive and was not feasible. And while the assumption of spatial independence at the cell level leads to a more conservative estimate of change in the watershed, we believe that it does not alter the general results presented here. Lastly, the issue of parsimony is not unique to this analysis and we are confident that the chosen model has provided valuable insight on the vegetation dynamics in the watershed.

3.5.2 Discussion of Results

We have reviewed dry season vegetation conditions in the Nuñoa watershed between 1985 and 2010. The results show that there is reduced interannual variability in dry-season productivity in the watershed post-2000 and a general increase in NDVI with time. Van Leeuwen et al. (2013) conducted an NDVI analysis for a similar time period (1982-2011) and for a wider geographic region along the Andes. Vegetation trends were calculated using Advanced Very High Resolution Radiometer (AVHRR) composite derived (8 km) annual mean NDVI. They found increasing vegetation trends along the Andes of southern Peru, including the region presented here. These results suggest that the greening of the Nuñoa watershed may be part of a more regional phenomena occurring in the Andes.

Many studies have related NDVI to temperature and precipitation at global and regional scales (e.g., Tucker et al. 1991; Liu et al. 2013; Piao et al. 2011; Sun et al. 2013).

Productivity may be limited by either variable or more sensitive to one over the other. In a recent study by Frensholt et al. (2013), the authors analyzed inter- and intra-annual trends in vegetation for semi-arid regions across the globe between 1981 and 2007. Trend analysis was performed on temperature and precipitation data as was correlation analysis between these climate factors and NDVI. It was concluded that, for the time period analyzed, semi-arid regions across the globe do not exhibit a singular trend in NDVI nor is there a dominance of a climate factor driving the trends in semi-arid regions.

We have shown that approximately half of the variability in mean annual dry-season NDVI in the Nuñoa watershed is attributable to summer season (DJFM) precipitation. In the absence of a trend in the summer season precipitation index, the slight but significant increasing trend in NDVI is not explained by this relationship. However, the results from the regression model indicate that the relationship between precipitation and NDVI is highly sensitive to the sequencing of wet and dry years and that the relationship may not be static through time. For example, it appears that there is less effect of precipitation on NDVI in more recent years. Given that the second half of the record is slightly wetter there may be a buffering effect on NDVI in a year of lower than average precipitation (for example 2008). It is plausible though that there are additional factors elevating NDVI in recent years. These possibilities are discussed in more detail below. With respect to temperature and mean NDVI in the watershed, we believe that our choice of a temperature index renders our method insufficient to determine the relationship between the two.

The climate of the Altiplano, including interannual variability in precipitation, is known to be strongly influenced by El Niño Southern Oscillation (ENSO) (Aceituno 1988; Vuille 1999; Garreaud and Aceituno 2001). Drought years often correspond to El Niño events and years of above average precipitation often correspond to La Niña events. A growing number of studies suggest that the correlation between ENSO and precipitation events in the region is weaker in the past decade and that possibly, the relationship is inverse compared to earlier decades (Lavado-Casimiro et al. 2011; Mazzarino pers comm.). The reasons behind this shift are not entirely known and might be explained by either a weaker ENSO regime or a breakdown in the teleconnections in the region. Despite the reasoning, the 1970s and 1980s were decades with strong ENSO events which are correlated with extreme drought (1982/83) and flooding (1984/85) in the watershed. The years from 1986 through 1998 were dominated by below average precipitation and generally high correlations with ENSO events while the years from 2000 on have been dominated by above average precipitation and a weak association with ENSO events. Therefore, the strength of the relationship between ENSO and precipitation in the watershed and the strength of individual ENSO events may explain a good part the reduced variability in NDVI observed in the watershed, the increase in NDVI values, and the nature of the relationship between precipitation and mean NDVI.

Based on results of the multiple regression model applied to each cell in the watershed and the identification of wetland areas, an increasing NDVI trend from 1985 to 2010 is present in 81% of all analyzed cells and in 68% of the bofedal area analyzed. A decreasing trend in NDVI occurs in 16% of the analyzed watershed area and in 29% of the analyzed area classified as wetland. The analysis shows an overall greening of the watershed with a concentration of decreasing vegetation in wetland areas. Unlike the mean NDVI analysis, the analysis at the pixel level allows us to see the spatial distribution of the NDVI trends and the magnitude of the trends throughout the watershed. Thus, the processes behind the trends in various locales can be discussed in the context of documented and observed changes in water resources and climate together with contemporary changes in land management and production systems.

In addition to the changes in the precipitation regime and ENSO cycle discussed above, increased air temperatures and accelerated retreat of glaciers in the tropical Andes are both well documented (Vuille et al. 2008; Diaz et al. 2003; Buffen et al. 2009; Silverio and Jaquet 2012). Glaciers, like wetlands, are important regulators of flow. Accumulation at this latitude occurs mostly during the wet season while ablation occurs year round. As a result, glacier melt water in the dry season is the main constituent of streamflow. Melt water also contributes to subsurface flow and resurfaces in many locations in the form of springs. Alterations in glacier melt will therefore impact the hydrological pathways by which vegetation, particularly in *bofedales*, is sustained.

There are currently several small (less than 2 km^2) ice-capped mountains in the north of the watershed. No studies regarding the change in glacier coverage in the Nuñoa watershed are known to exist. However, trends for Quelccaya Ice Cap, located just kilometers to the north and outside the watershed, have been well documented. Qori Kalis, one of the outlet glaciers has been measured since 1963 by a team of researchers at Ohio State University. When compared to the time period of 1963-1978, the retreat rate between 1991 and 2005 was 10 times greater (approximately 60 m/yr compared to 6 m/yr) (Buffen et al. 2009). Salzmann et al. (2013) came to a similar conclusion for Quelccaya Ice Cap and other glaciers in the range, suggesting the mid-1980s as the beginning of the period of strong retreat. Furthermore, temperature measurements since 2004 from a weather station on Quelccaya show that for the majority of the year (September to May) daily maximum temperatures are frequently above freezing (Bradley et al. 2009). Precipitation then, even at the higher elevations, will more often be in the form of rain rather than snow and watersheds will have a continued reduction of snow and ice coverage, therefore altering the volume and timing of hydrological flows.

Such changes may account for the increasing trends in NDVI seen along the northwestern periphery of the Nuñoa watershed. This is the mountainous snow and ice dominated region. The magnitude of increasing trends seen here can be explained by a reduction of snow and ice cover and the exposure of bare rock. And, while the overall effect of the small glaciers on vegetation in the watershed may be slight and confined to a subwatershed, it may also be that *bofedales*, which are characterized by saturated soils, would register a change in glacier melt contributions before background vegetation. Therefore, it is also plausible that the decreasing NDVI trends seen in the riparian *bofedales* and otherwise in the north of the watershed are related to an increasing water deficit in the dry season due to decreased glacial melt contribution. It is noted that conversations with herders in the upper reaches of the watershed have elicited statements regarding decreasing volumes of water in springs and streams with significant changes circa 2000 (Mazzarino 2011, unpublished interview data). A remote sensing analysis of glacier coverage in the watershed from the 1980s through present would provide insight into these observations. Hydrological studies, similar to those being undertaken in other watersheds in the Andes (Baraer et al. 2009; Mark et al. 2010) could also help characterize the changing contribution of glacier melt and the response of vegetation in the Nuñoa watershed.

Two recent socio-economic trends may also provide an explanation for the vegetation trends seen in the watershed. Owing to low fiber prices and increased demand for raw milk for cheese production, there has been a trend toward increased cattle production throughout the region. Unlike camelids with their soft hooves and split lips (making them efficient browsers who cause little compaction of soil), cattle are quite damaging to soil and vegetation. Due to altitudinal constraints, the greatest increases in cattle numbers are expected to be seen in the lower half of the watershed. This includes the southern portion of the District of Nuñoa and the Districts of Orurillo and Asillo. Milk and cheese production are primary economic activities in both of these districts that report an increase in cattle numbers in recent years (PIEP 2007; Inquilla 2013), similar to regional trends (INEI 2012). The large patch of decreasing NDVI in the south of the watershed (Districts of Orurillo and Asillo), in what was once a wetland connected to a lake system, is likely directly due to increased cattle production and agricultural activities there. However, many cells adjacent to the area display increasing trends in NDVI. The juxtaposition of the opposing trends may in fact be related in that the same districts also report an expansion of cultivated pasture for forage (oats, alfalfa, barley) (Inquilla 2013; DIA Puno 2012) and these fields may be irrigated with canals.

Finally, as a result of climate disturbances and the heterogeneity of the environment, herders in the Andes have developed several adaptive responses that ensure increased access to critical resources. These responses include flexibility, predictability, and the use of a multiple resource base, supported by a rotation system that includes daily and seasonal movement of herds (Thomas 1979). In recent years, several communities in the watershed are dividing previously communal land into household territories. This trend has been documented elsewhere in the Andes (Postigo et al. 2008). The implication for the distribution and management of natural resources, such as pasture land and *bofedales* is not entirely clear. One plausible result however is reduced access to *bofedales* in different microenvironments and therefore the loss of a rotation system. A study in 2000 by the Peruvian government stated that 44 out of 48 *bofedales* analyzed in the Department of Puno were used year-round rather than seasonally (ALT-PNUD 2001). A more detailed analysis of land management strategies (such as seasonal versus year-round use of *bofedales*) and herd demographics throughout the watershed combined with the results of the present NDVI analysis would be useful in eliciting relationships between these variables.

3.6 Conclusion

We performed a vegetation analysis in a high elevation Andean watershed for the years 1985-2010 and described trends in mean dry-season NDVI values over this time and spatially within the watershed. The area of study represents a region that historically and currently produces the greatest number of alpaca in Peru. The livelihood of the predominately Quechua speaking pastoralists is tightly connected to the vigor of vegetation, particularly that found in wetland systems (*bofedales*). The plant assemblages there are the most nutritious for alpaca and sustain them throughout the dry season. The time period for the study (owing to the availability of satellite imagery) correlates to significant changes in land tenure and production systems in Peru and to observable and accelerating changes in climate. Because *bofedales* are a natural resource heavily used by herders throughout the watershed, it is difficult with the methods employed here, to untangle the anthropogenic effects of land use and herding strategies from exogenous climate factors on vegetation. However, we have demonstrated that there are concentrations of decreasing vegetation density, as measured by the NDVI, in bofedal systems in the Nuñoa watershed. This is occurring within the broader context of a greening of the puna grassland that dominates the vegetated land cover. Processes from the biophysical and social environments are surely interacting to create the pattern in changing NDVI discussed here. To what degree each process is contributing to the trends is unclear. However, the information garnered from the present study is useful in understanding the current state of vegetation density in the watershed as well as potential future trajectories of a valuable natural resource.

CHAPTER 4

SOCIAL-ECOLOGICAL VARIABILITY AND TRENDS IN AN ANDEAN AGRO-PASTORALIST SYSTEM: A CASE STUDY USING THE SUSTAINABLE LIVELIHOODS FRAMEWORK

4.1 Introduction

Mobile pastoralist systems have evolved to reduce the risks and, in consequence, the site-specific vulnerability associated with natural resource unpredictability and climate extremes. Across the globe, from Mongolia to Kenya to Bolivia, pastoralism is an effective strategy to mitigate altitudinal, thermal, and water-related stresses. Hence, in variable and extreme environments, such as dry lands, mountain and subarctic regions, husbandry of livestock, when it entails movement is considered a viable livelihood. These regions however, may be more sensitive to climate change (Diaz et al. 2003) and the resulting changes in natural resources more profound. Observations and research in many regions support this (Houghton et al. 2001; Sokona and Denton 2001; Serreze et al. 2000). Pastoralists rely on a natural resource base and tend to be socially and economically marginalized with access to fewer assets and alternative livelihood options (Escobal and Torero 2000). As a sector they are deemed one of the more vulnerable to the potential impacts of climate change, including increased variability and increased uncertainty in the system. As a result, there has recently been an increased focus on the livelihood sustainability of pastoralists especially with respect to climate variability and climate change (O’Brien et al. 2004; Hann et al. 2009; Sperling et al. 2008; Eakin and Appendini 2008).

The *Sociedad Peruana de Criadores de Alpacas y Llamas* (SPAR 2005) reports that there are 170,000 pastoralist households at elevations above 4,000 meters in Peru. The Altiplano is among the poorest rural areas in the Andes (Quiroz et al. 2003). In one study, household poverty rates in the Department of Puno, located in the Altiplano of southern Peru, ranged between 63 to 95 percent (Kristjanson et al. 2006). The Department of Puno also has the densest populations of camelids (alpaca and llama) and is the country's largest producer of alpaca fiber. In the remote upper elevations of the region, pastoralists, mainly of Quechua ethnicity, live in an environmentally harsh and food energy limited system (Thomas 1976). Traditional husbandry of alpaca, llama, and more recently sheep and cattle too, represents security in the heterogeneous and highly variable environment. The persistence of communities and the long pre-Columbian history of camelid husbandry demonstrate the resilience and adaptive capacity of this human-camelid-complex, despite various limitations and stresses (Baied and Wheeler 1993; Murra 1984). For biological reasons and due to grazing habits, herding of camelids is seen as a critical mode of adaptation to the high Andean environment (Thomas 1979; Baied and Wheeler 1993). Domestication of ancestors of the modern day vicuna date back millennia (Baied and Wheeler 1993). Before the period of colonial rule (1532-1781) large polities centered at high elevations were successful in a range of agricultural and herding activities. Murra (1984) described how a social system of dispersed settlements across different ecological zones coupled with a network of storage warehouses contributed to this success. Climate phenomena such as cold, frost, drought, variability in microclimate and conditions of seemingly low productivity were countered with innovations such as freeze-drying foods, storehouses, terracing, irrigation, and a vast knowledge of the environment (Murra 1984). Thus, one important risk aversion strategy in dealing with the heterogeneity of the Andean environment in space and time is the use of a multiple resource base.

Relatively few scientific studies have focused explicitly on the response of Andean pastoralist communities to contemporary environmental and climate change (Young and Lipton 2006; Postigo et al. 2008; Bury et al. 2011; Sperling et al. 2008; Valdivia and Quiroz 2003; McDowell and Hess 2012). Some of these studies, together with research elsewhere, suggest that mobile pastoralist systems are inherently resilient and therefore capable of adapting to climate change (Berkes and Jolly 2001; Young and Lipton 2006). On the other hand, in a review of the term “adaptation”, Orlove (2009) suggests that for highland Andean herders, migration to other sites may be the only solution. Vulnerability is multidimensional and a result of several interacting stresses (Eakin Bojorquez-Tapia 2008). Kratli et al. (2013) distinguish between the vulnerability that is characteristic of the pastoralist system (which can be managed effectively) and the vulnerability that is the result of additional constraints on the system (that limit the possibilities for effective and efficient production strategies). Therefore, the exact nature and magnitude of changes as well as the vulnerability context will play a role in determining if herding communities will be able to remain in-situ and cope with or adapt to the additional challenges presented by climate change and social and economic changes.

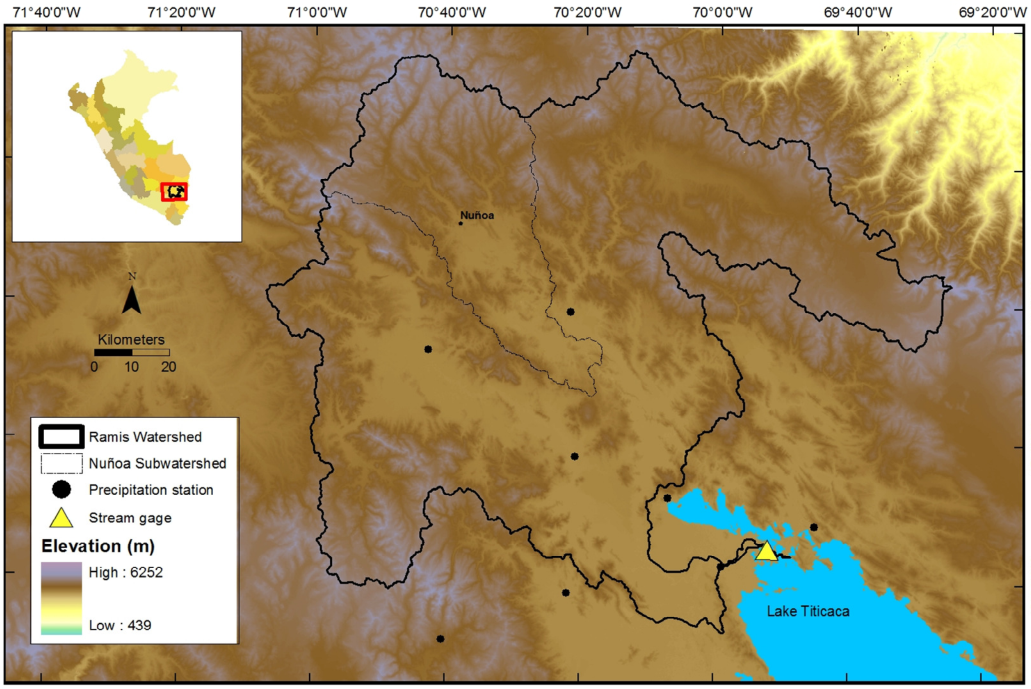
4.2 Objective

This study uses a sustainable livelihood (SL) framework (Chambers and Conway 1991; DFID 1999; Scoones 1998) to model and characterize key components of an agro-pastoralist community in the Central Andes. The focus is on the vulnerability context of agro-pastoralist livelihoods which includes three aspects: climate variability, trends over time in pasture vegetation, and the sequencing of stresses (climate related and animal illness). Specifically, this case study quantifies the relationship between variability in precipitation and the availability of "green" vegetation or pasture in a herding community in extreme and "neutral" climate years. The impact that this variability (together with other stressors) has on crop yields and herd productivity is described. Finally, I review the trend in vegetation from 1985 through 2010 in the community territory and consider this in light of climate change and herding management strategies. Regional generalizations regarding livelihood strategies and environmental change are discussed.

4.3 Background

This case study involves a *comunidad campesina* (peasant community) located in the District of Nuñoa in the Department of Puno, Peru (Figure 4.1). The Peruvian Constitution recognizes *comunidades campesinas* as self-governing social institutions with individual and collective access to land. Peasant communities were formed in the latter portion of the land reform movement (as recently as the mid-1980s in the District of Nuñoa), following earlier reforms when larger hacienda lands were reallocated from landlords to the workers to form government administered cooperatives. In this sense they are relatively “new” forms of social institution. However, peasant communities retain elements of pre-Hispanic “*ayllus*” (Indigenous communes), colonial communes, and the *Comunidades Indigenas* formed during the early 1900s. The formation and institutionalization of communities are the result of historical repression and marginalization of the indigenous population. Today, there are approximately 6,000 legally recognized *comunidades campesinas* in Peru (Del Castillo 2006), the majority of which are in the Andes. In the 1990s at least 40% of Peru’s agricultural lands were in the control of these communities (INEI 1994).

Figure 4.1 Location map displaying the Nuñoa subwatershed within the Ramis watershed in southern Peru. The land of the study community is within the Nuñoa watershed. Precipitation and streamflow analyses for the region use data from stations shown.



The case community, hereafter called Community C or the case community, is one of 13 Quechua speaking *comunidades campesinas* in the District of Nuñoa. Community C formed as a legal community in 1986 on a portion of land that was formerly a social cooperative, and prior to that hacienda land. The community has 1,200 hectares of land that ranges in elevation from approximately 4,100 to 4,600 meters. In 2010 the community consisted of 116 individuals in 22 households (*socios*). Members maintain communal herds, grazing land, and gardens, but also private herds and gardens. There are several tasks, such as the maintenance of irrigation canals, construction of animal fencing and corrals, shearing and vaccination of the animals, seeding and harvesting that are performed communally. Members also participate in the typical Andean type of labor reciprocity (*ayni*) during times of need such as seeding and harvest periods. Other, less formal types of reciprocity have also been recently documented (for a more detailed description of the communal tasks and types of reciprocity typical in a communal community see Lyle 2013). While the majority of individuals live on community land, several individuals and households live in the town of Nuñoa but maintain plots and herds in the community.

4.4 Analytical Framework

The sustainable livelihood framework is the organizational template for this analysis. Specifically, it is used to map the components that are inherent to or highly influential in this Andean agro-pastoralist system. The Sustainable Livelihoods concept was originally put forth in a 1987 World Commission on Environment and Development report (WCED

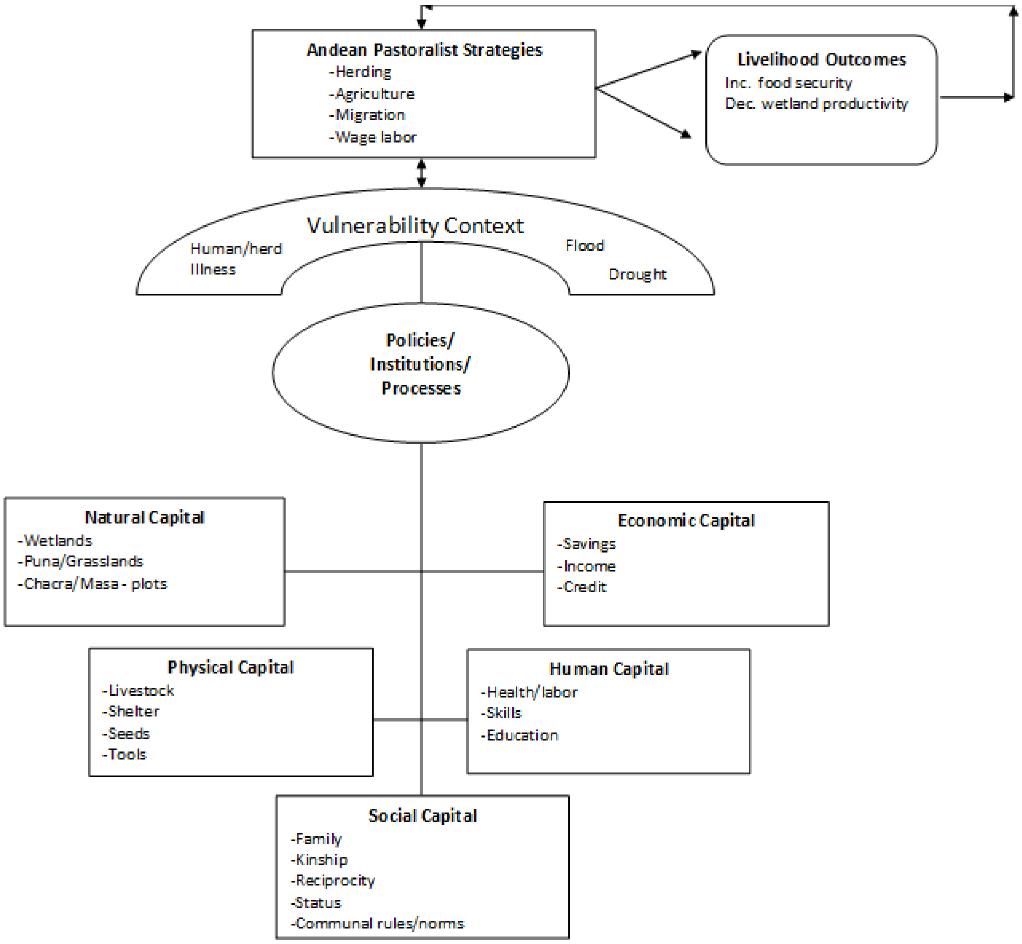
1987). It was modified and articulated by Chambers and Conway (1991) where they used the term “sustainable rural livelihoods”. The SL approach is often adopted by the United Nations, OXFAM, Institute for Development Studies (IDS), Great Britain’s Department for International Development (DFID), and others as an operational framework. It is also becoming more widely used in scientific initiatives. Mahdi et al. 2009, for example, combine the framework with that of integrated watershed management in their study concerning natural resource management and livelihoods in Indonesia.

The SL concept draws on perspectives offered in the fields of social science and political economy (specifically Sen 1981). Centered on people, it has three core objectives: capability, equity, and sustainability, where the latter refers to both social and environmental sustainability. The framework therefore integrates both social and biophysical systems. Of note is the following definition by the Institute for Development Studies (IDS) (Scoones 1998):

> “A livelihood comprises the capabilities, assets (including both material and social resources) and activities required for a means of living. A livelihood is sustainable when it can cope with and recover from stresses and shocks, maintain or enhance its capabilities and assets, while not undermining the natural resource base.”

This research will follow, yet slightly adapt, the analytical framework provided by the DFID (Figure 4.2). The base of the SL framework consists of physical capital, natural capital, social capital, human capital, and economic capital. These five capitals as discussed by Sen (1990) are the services, goods, or assets that form the “resource base” for a given livelihood. This resource base influences and is influenced by formal and informal “institutions and policies”, the second component in the model. Institutions and policies may be exogenous to the system, as is the case with government or NGO interventions, or they may be endogenous, such as decision-making at the family or community level or in social regulation. A “vulnerability” dimension appears in the model and is directly linked to the five assets that form the resource base. The vulnerability context is mediated through policies and institutions since the latter can either support or constrain acquisition and access to resources. As a result of the interaction of these three components (the resource base, policies and institutions, and the vulnerability context), various “livelihood strategies” emerge (the fourth element) along with specific livelihood outcomes (the fifth element).

Figure 4.2 Schematic of the Andean agro-pastoralist livelihood using the DFID framework.



4.5 Methods

This study synthesizes information gathered in the field with remote sensing analysis of vegetation and statistical analysis of climate data. The vegetation and climate analyses were each the focus of prior research by the author. As such, the methods employed in those studies are explained in detail in Chapters 2 and 3. Where, for the purposes of this study, those original analyses have been adapted and additional methods applied, this is noted in the appropriate sections below. In this section the focus is on the field methods which are explained for the first time.

Participatory Rural Appraisal (PRA) techniques were used in the field to collect information on community boundaries, herd demographics, current spatial and temporal rotation of herds, important natural resources used by the community, and natural resource management strategies (such as seeding and harvesting practices). Activities with community members included a mapping exercise, a timeline activity, and walking community land. Two lead researchers, two field assistants, and a local sociologist (who aided in translation between Spanish to Quechua) met several times with community members on community land over the course of several weeks in July 2010. Work with the community members began only after gaining formal permission by majority vote to do so and following the drafting and signing of a formal agreement.

A community mapping exercise was carried out with the participation of 15 community members (nine men and six women). The members were asked to draw a map of the community and include important resources (natural and otherwise). This activity facilitated discussions regarding the general characteristics of the community and the availability and management of vegetation, herds, crops, and water resources. Questions asked of the community appear in Appendix D.

Over the course of several days the research team was accompanied by the president of the community and one other member on walks of the community land. These walks were partly informal and provided a chance to discuss various subjects as well as to photograph and record the locations of landforms, resources, and residences with global positioning systems (GPS). Another purpose of these walks was to visit household members at their residence or in the field for interviews. In these instances, the researcher for the current study served only as an observer. However, some information gathered during these interviews, such as herd numbers and crop yields at the family level for the year 2010 is included in this study. In total, 21 of the 22 households participated in the interviews.

Information on the major environmental shocks and stresses to the herding system was compiled in a timeline activity. An interpreter helped translate between Spanish and Quechua. The group consisted of four men and two women. The group was asked: “What are the principal environmental stressors for the community?” “¿Cuáles son los principales factores de estrés ambiental para la comunidad?” Through discussion on impacts to herds and crops, information was provided on herd size for various years and on the herd mortality or reduction in crops due to a given stress event. Additional information on crop yield and herd numbers is obtained from a community development plan. This document was part of a project conducted by a Peruvian development NGO in 2006.

4.6 Results

The key components of the agro-pastoralist livelihood are modeled according to the sustainable livelihoods framework in Figure 4.2. Each component in the model is discussed below with respect to the case community. The objective is not to include every element for all of the components but rather to focus on those elements which are critical from the biophysical perspective.

4.6.1 Assets

The main focus in this study is on two of the five assets in the sustainable livelihoods framework: natural and physical capital. Data collection on the economic, human, and social assets was beyond the scope of this research. However, herds represent the greatest financial asset to Andean herders, so in this sense the study captures this aspect of economic capital. Some information regarding human capital is available from the National Agrarian Census (2012). Aspects of social capital such as group cooperation and support networks are discussed in more detail in Lyle III (2013).

Natural Capital

As expected, land, vegetation, and water are all essential natural resources in the agro-pastoralist system. Cultivable land is important for crops while natural pasture and areas with saturated soils year round (*bofedales*) are critical resources for herds. There are approximately 200 hectares of cultivable land in the community. The collective gardens or “*chacra*” can be quite large and depending on the crop type are located on flat terrain at lower elevation (e.g., quinoa) or on steep slopes to avoid freezing temperatures in topographic lows (potatoes and cañihua). There are eight to ten gardens in the community that are tended by members and the harvest is shared equally among households. Additionally, each household maintains a smaller, private garden or “*masa*” adjacent to the communal garden and commonly next to their household hut.

The community estimates the availability of approximately 700 hectares of natural pasture. In the puna ecosystem it is specifically the *Stipa ichu* (ichu) and *Festuca* *dolicophylla* (chilligua) vegetation in these pastures that are important for sheep and cattle. Llamas also graze drier pasture vegetation such as paja. Alpaca however, require vegetation with greater nutritional value and they graze in the moist *bofedales*. These areas are critical in that they provide dense vegetation in the dry season months and during drought. Important species of vegetation in *bofedales* noted by community members include *Hypochoeris sp.* (pilli pilli) and *Notriche sp.* (thurpa).

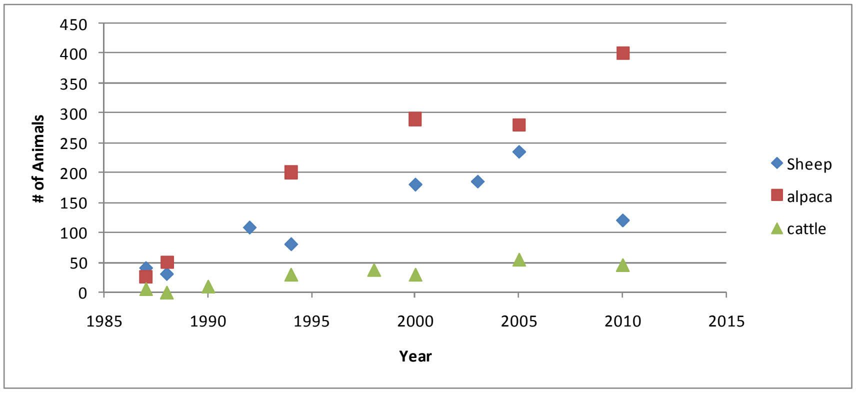
In order to take advantage of the variable environments and seasonal resource availability, similar to other communities in the Andes and pastoralists elsewhere, the case community maintains separate wet season and dry season pastures. In this region of the Andes the seasonal calendar is broken into the rainy season months (December through March), dry season months with frost (April through July), and the dry season months with a scarcity of water (August through November). In May or June, households and herds will move to the dry season “cabanas” or homes. The pasture that was used in the previous months is allowed to rest without grazing activities. The dry season land is typically lower in elevation and has more abundant *bofedales*, streams and creeks. At the beginning of the rainy season (December), households and herds will rotate to the wet season cabanas and pastures. The land is typically at higher elevations and has more hills and slopes. Due to the abundance of pasture in the wet season, herds are grazed closer to the household huts. In the case community, the wet and dry season land both have several springs that mark the mouths of tributaries that feed into a small stream system. Both the wet season and dry season areas contain *bofedales* that border the stream systems.

Physical Capital

Crops (papa amagra, papa dulce, quinoa, cañihua, barley, mashua, and ulluco) are grown mainly for subsistence but surplus may be sold for cash or used for barter and trade. Members of Community C stated that occasionally potatoes, chuno negro (dehydrated potato), and quinoa will be sold outside of the community. The quantity of crops harvested varies with precipitation and soil type. Additionally, diseases, some of which may vary with climate, also impact crop yield. Different crops are planted and harvested at slightly different times. Cañihua and quinoa for example are planted in August or September. Cañihua is harvested in March or April while quinoa is harvested later in May. Meanwhile, bitter potatoes are planted later, at the end of September or October and harvested in May. Chuno, or freeze-dried potato is prepared in June to take advantage of the freezing nights and the strong daytime sun.

Herds represent security and are a great source of pride. Llama, alpaca, and sheep provide fiber, dung, meat, and hides. Llamas have historically been important for transporting goods however, the use of donkeys for this task may be increasing. In recent years, cattle have become a valuable source of milk for personal consumption and for sale for market cheese production. Herders sell fiber in national and international markets. Animals and animal products may be bartered in exchange for necessary supplies or sold locally and in national markets. Herd numbers for communal alpaca, sheep, and cattle from the formation of Community C through 2010 appear in Figure 4.3. Llama numbers are not considered because while some families maintain small herds of llama, the community did not.

Figure 4.3 Communal herd numbers for alpaca, sheep, and cattle.



In addition to herds and crops, Community C began farming trout in the early 2000s. The trout is mostly for subsistence but is occasionally sold in the town of Nuñoa. Other material assets important to the herding livelihood include both a dry season and wet season dwelling which consists of small adobe huts with thatched roofs. Seeds and tools are necessary for preparing fields. Corrals and vaccinations are important for animal health and shelters protect from hail that is so damaging at times it has put holes larger than the size of a quarter through corrugated hard plastic used as temporary roofing material.

Economic Capital

Herds are the primary source of currency at the household and community level in Community C. In a typical year (i.e. one without a climate hazard or disease) the community might sell three or four dozen sheep and alpaca along with several head of cattle. While alpaca are worth slightly more than sheep, cattle yield nearly five times as much as alpaca. Herds also act as a savings account during times of stress. If crop yield is low, for example, animals are sold to obtain goods in markets in Nuñoa or elsewhere.

Human Capital

Over time the population of Community C has decreased. Population is often provided as the number of *socios* rather than the number of individuals. A *socio* is a member of the community who represents a household and whose membership has been voted on and agreed to by two thirds of the existing representatives. The current number of *socios* is approximately one third that when the community was originally formed. It is unknown whether the families who left the community joined another community, moved to town, or permanently migrated from the area. Seasonal migration is common in the region and is often done by males. However, according to the latest National Agrarian Census (INEI 2013), only 13% of 1,288 individuals in the District of Nuñoa said they typically left their agricultural unit during the year to pursue other activities. The top two off-farm activities are construction and farming and herding at other locations.

Social Capital

As a result of the heterogeneity of the landscape in space and time and the limitations of a single household in the scales of production, two components are viewed as essential in the Andean herding system: predictable access to land across a variety of production zones and cooperation across households (Mayer 2002). Traditionally, cooperation and reciprocity are extremely important in Andean society and labor exchange is customarily largely built on kin and fictive-kin relationships

(Mayer 2002; Escobar 1976). In communities with resources owned by the collective, such as in the case community, access and production levels are controlled via social regulation (Thomas 1979). While the maintenance of common pool resources was not the focus of this research, a discussion of natural resources with community members raised several interesting issues of potential conflict between households. One issue that sparked a debate between group participants was that of dung as fertilizer. A second and related issue revolved around the households and individual members who resided in town. The participants stated that these members do not contribute time and labor to communal tasks as much as other members. Additionally, several households do not contribute dung to the communal gardens. Since the community divides crops and other gains equally amongst households, regardless of input, these issues suggest that "free-riding" is occuring in the community. According to the participants there are no consequences for individuals or households who do not contribute resources or labor for communal tasks and goods.

4.6.2 Policies/Institutions/Processes

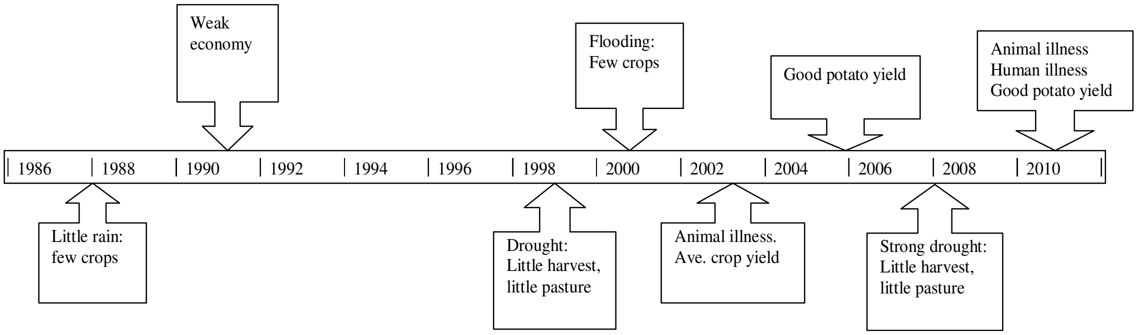
The governing body of Community C is a board of directors. The board coordinates meetings and general actions of the community. There are also several committees including an agricultural committee and a livestock committee. Responsibilities for each include organizing work parties for communal tasks, ensuring equitable distribution of land, and maintaining rotation schedules for both livestock and crops. In part, social norms and rules are regulated within the community and between the community and other institutions via participation in the *ronda campesina*. *Rondas* are organized bodies with male membership that operate at the community and regional level for the purposes of defense and security. Within the community the *ronda* protects against cattle rustling and other thievery and if necessary, will intervene in cases of family violence. Community members meet with *ronda* members from other communities at the district/regional level every three months.

Community C has on several occasions agreed to work with NGOs and individuals on projects that include social development, economic development, and herd management/breeding assistance. As a result, in 2010 they held their first farmers market in the community, which attracted buyers from the region and as far away as Cusco interested in purchasing animals and animal products. Additionally, there is some indication that outside assistance has improved breeding and pregnancy rates in alpaca (S. Purdy, personal communication). With respect to alpaca numbers, during the timeline activity members explained that since the community formed they have received assistance at three different times in the form of a donation or loan of animals from four different sources. These include the donation of alpaca from a private farm in 1988 to help the community increase the start-up herd numbers. Alpacas were loaned by an NGO and by the Ministry of Agriculture in 1995 following the decimation of herds by earlier guerilla activity. More recently, the community received the donation of colored alpaca from Heifer International as part of a biodiversity project.

4.6.3 Vulnerability Context

Results from the timeline activity appear in Figure 4.4. Six different environmental stresses (and one non-environmental stress) were mentioned by the group. These are drought, flooding, frost, cold temperatures, rapid shifts in weather (from cold to strong sun), animal illness, and a weak economy.

Figure 4.4 Timeline of stress events and years of good crop yield according to participants from Community C since the formation of the community in 1986. Some events span two years or more. For more detail, see the text.



Years with little rain or classified as drought according to the group are 1987, 1998, and 2007/2008. In these years, participants noted that there was little pasture and little harvest or few crops. A strong frost in June and July 1987 was also recalled. The year 2000 was considered a bad year because of flooding of crops.

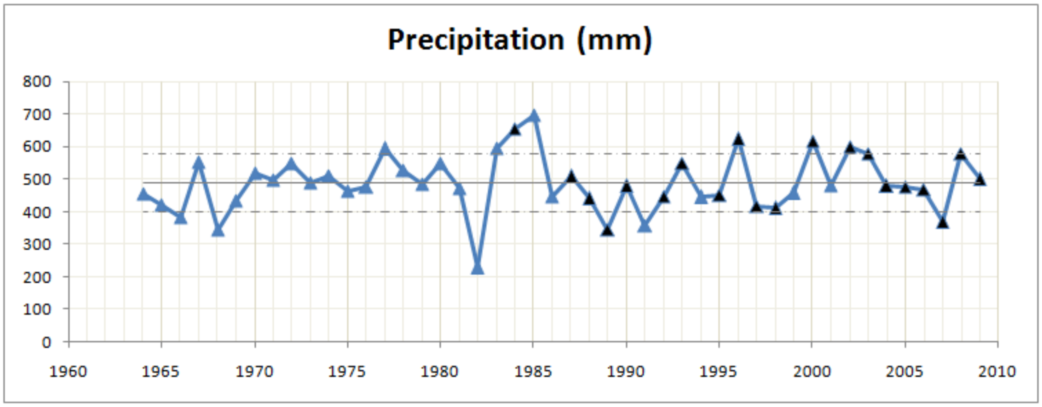
Years of stress due to animal illness include 2001, 2002, 2003, and 2010. In 2001 and 2002 approximately 60 pregnant alpacas and fetuses died of fever (out of approximately 300 communal animals). While the fiber from these animals was useable the meat could not be consumed. An additional 20 to 40 mother sheep and their young (out of 180 animals) died of pulmonary problems this same year. In 2003, an outbreak of gastrointestinal illness in the animals is blamed on standing water and rapid shifts from cold nights with light hail to “strong sun” in the day. As a result approximately 150 community and family owned young and baby animals died. Frigid temperatures in 2010 resulted in the loss of approximately 30 communal animals. This year was particularly consequential for human health as well and this is noted by the community. In fact, a state of emergency was declared in the region. Young children were especially affected, many dying from pneumonia and other respiratory illnesses.

While not an environmental stress, participants stated that 1990 through 1991 was a difficult time because of a weak economy and inflation. Despite the El Niño years in the early 1990s, no environmental stresses were mentioned for the years in the late 1980s to mid-1990s. This is not surprising since Nuñoa and the surrounding region were targets of guerilla activity from the mid-1980s through the early 1990s (see Leatherman and Thomas 2009 for a more detailed account). Many agricultural activities were suspended as a result.

In addition to stresses, participants highlighted years that were considered “normal” for crops and good for potatoes. Normal crop years include 2001, 2002, and 2003. Years with good potato harvest include 2004, 2005, 2006, and 2010. The years with average crop yields tend to correspond to above average precipitation during the wet-season while high yield years correspond to average precipitation.

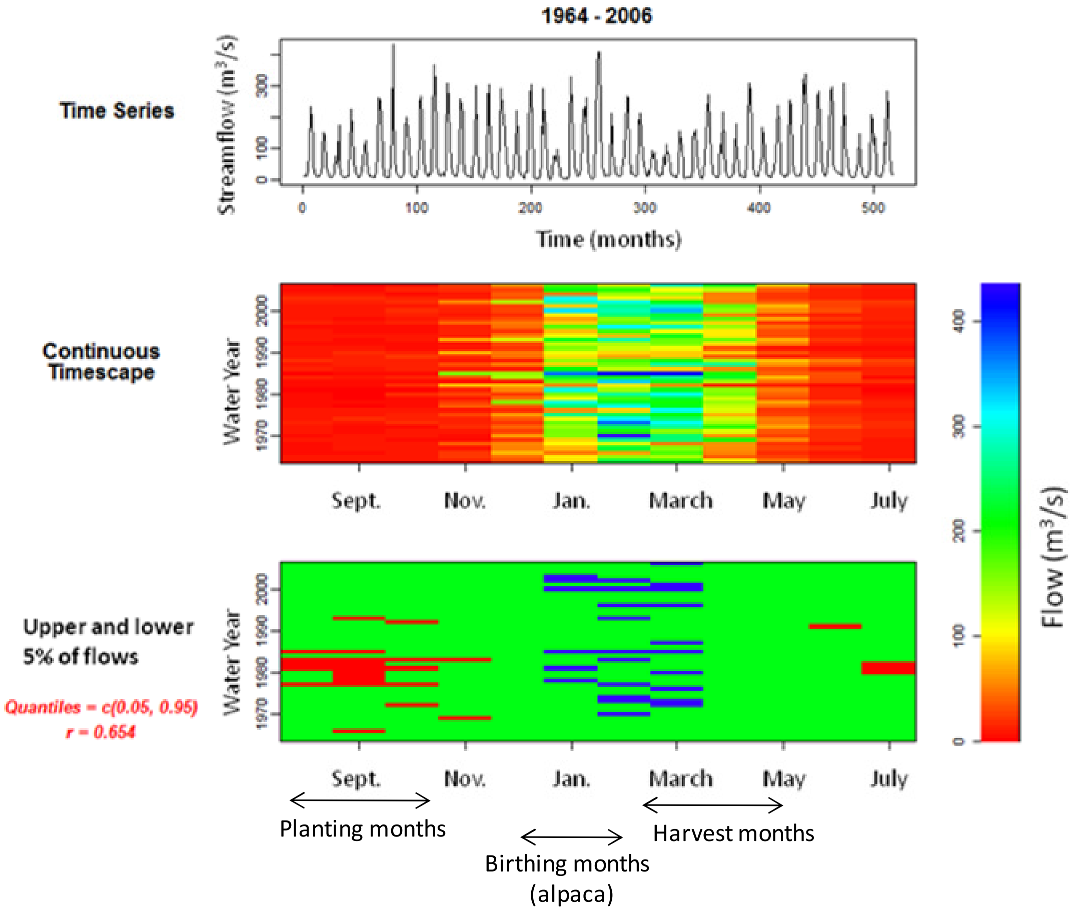
The year to year variability in precipitation that is characteristic of the Altiplano is exemplified in Figure 4.5. Yearly data points are a regional 8-station average of precipitation totals for the wet season (DJFM) months. For example, the first value corresponds to the average precipitation total for December 1964 through March 1965. This record captures regional variability associated with the wet season months (December – March) when approximately 70% of precipitation occurs. Many of the accounts by community members regarding drought and flood events coordinate well with this precipitation record.

Figure 4.5 Eight station average of precipitation totals for the months DJFM. Black triangles denote years (n =20) for which Landsat scenes were processed for the original NDVI analysis (Chapter 3). Gray solid line is the precipitation average (488 mm) for 1964-2010. Gray dashed lines are +/- 1 SD.



The District of Nuñoa is situated in the Ramis watershed; thus streamflow in the Ramis River provides another indicator of climate variability for the region. Streamflow lags regional precipitation by one month. The intraannual variability and interannual variability in streamflow in the region can be viewed together in a single figure called a timescape, or raster hydrograph (Koehler 2004). Figure 4.6a displays the running average monthly streamflow for the Ramis River for the 1964 through 2006 water years (August-July). Unfortunately, data was available only through the 2006/2007 water year. Intraannual and interannual variability in flow is best depicted in the continuous timescape in Figure 4.6b. Months with average streamflow less than the 5th percentile or greater than and 95th percentile are represented in the quantile timescape in Figure 4.6c with the use of red or blue color respectively. Flows greater than the 95th percentile are contained to the months of January through March and occur throughout much of the record. Flows less than the 5th percentile occur mostly in the months of August through October and less frequently in November, June, and July. Interestingly, there is an absence of low flow anomalies since the mid-1990s. With the labeling of the planting months, harvest months, and birthing months below the figure, it becomes clear how extreme variability in a given month or year can impact different aspects of the agro-pastoralist livelihood.

Figure 4.6a) Time series of average monthly streamflow for 1964-2006. The x-axis is time in months beginning with August 1964 and ending with July 2006. b) Intraannual and interannual variability in flow. Data are displayed as bars spanning a given month for a given year. The colors correspond to flow as displayed in the color ramp to the right. c) Quantile timescape displaying flows less than the 5th (red) and greater than the 95th percentile (blue).



Variability in Crop Yield

Crop yields vary in part because of the extremes seen in the climate record. Variability in crop yield is also attributable to other factors such as the availability of seeds and tubers (especially in the initial years of the formation of the community), pests (although this stress was not mentioned), and community processes involved with planning, managing, and executing seeding and harvesting. Below I quantify generally the range of crop yield during times of environmental stress and otherwise. Thus, we can quantify and understand what community members consider a bad year, a neutral year, and a good year for crops and how this relates to climate variability.

A description of a neutral crop year allows some baseline information. Several years of decent crop yields were noted in the early 2000s. There is no data on crop yield for a specific year but members stated a general harvest amount of 850 kilograms at the community level in the years leading up to 2004. An average amount of 400 kg of potatoes per family was noted for these years. Thus, these are considered average yields in a decent year.

The scenario of low crop yield is considered using community data from 1987, a year with less than average precipitation. This year was classified as a year with few crops as a result of low rainfall amounts by community members. A slightly below average regional precipitation total is seen for the 1986/1987 wet season (Figure 4.5). A meteorological station was in operation at this time in Nuñoa and so a more detailed local picture is available. To elaborate, precipitation in February and April 1987 was below average, thus impacting mature crops near harvest. No rainfall was recorded during the initial planting season month of September and below average rainfall was recorded in October through December. Thus, crop yields in 1987 and 1988 would be expected to be below average. Indeed, members reported communal potato yields of 300 kg and 100 kg for 1987 and 1988, respectively. Household yields were 100 kg/family in 1987 and 40 kg/family in 1988. Also in July of 1987, 34 mm of precipitation (most likely in the form of one snowfall event) was recorded at the Nuñoa meteorological station. Herd numbers were few at this time because the community was newly formed but these occasional (perhaps every five years or so) cold season snow events are a hazard to both animals and humans. Both the crop assets and the herd assets were depleted. Thus, it may have been with some urgency that several alpacas were donated to the community in 1988.

A good potato yield year is represented by 2005, a neutral climate year. Local precipitation data do not exist post-1992. However, as seen in Figure 4.5, regional wet season precipitation total for 2004/2005 was near average. Community members reported a communal harvest of 1300 kg and household yields of 250 kilograms in 2005. Although the number of households at this time was nearly one-third that in 1987/1988, the total household harvest is still more than 2.5 times what it was in 1988 (the lowest reported quantity).

Variability in Vegetation

We now look at how wetland area, an essential natural asset in the community, varies in an anomalously wet year, anomalously dry year, and a neutral year. To do so, a remote sensing derived vegetation index known as NDVI (normalized difference vegetation index) is used (Chapter 3). Essentially, the index, which ranges from -1 to 1, represents vegetation vigor or greenness in that it is a measure of photosynthetic capacity in a given area. Thus, healthier, greener vegetation has higher values. However, the density of vegetation as well as species composition also affects the values. For the NDVI analysis, described in detail in Chapter 3, Landsat 5-TM imagery was used with a resolution of 30 m (each cell, or pixel is 30m x 30m). One dry season (June through

August) image was obtained for 20 of the 26 years from 1985 to 2010. Because images are from the dry season months, wetland vegetation has much higher NDVI values than grassland vegetation. Thus, the wetland areas are prominent and can be isolated for analysis if a threshold value is assumed. For the current analysis, cells with an NDVI value equal to or greater than 0.4 were considered to be wetland vegetation. The area of wetland was then calculated based on the number of cells classified as such.

Twenty scenes were used in the original NDVI analysis and in the trend analysis described in the next section. These years of image analysis and the corresponding precipitation values are denoted in Figure 4.5 with black triangles. For the current analysis, a subset of 12 images was used. Based on wet season precipitation totals in the region, five scenes were selected to represent years with above average precipitation (at or beyond +1 standard deviation), four scenes were chosen to represent below average precipitation years (approaching or beyond -1 standard deviation), and three scenes represent average precipitation years. This information is summarized in Table 4.1 along with the month, day, and Julian Day of image acquisition, the results of the wetland calculation, and stress events mentioned by community members. Note that the year associated with each image in Table 4.1 corresponds to the year the image was acquired but is associated with a precipitation value from the previous wet season (which began in the prior calendar year). Thus the image acquired in the year 1985 in the table corresponds to the precipitation value at x=1984 in Figure 4.5.

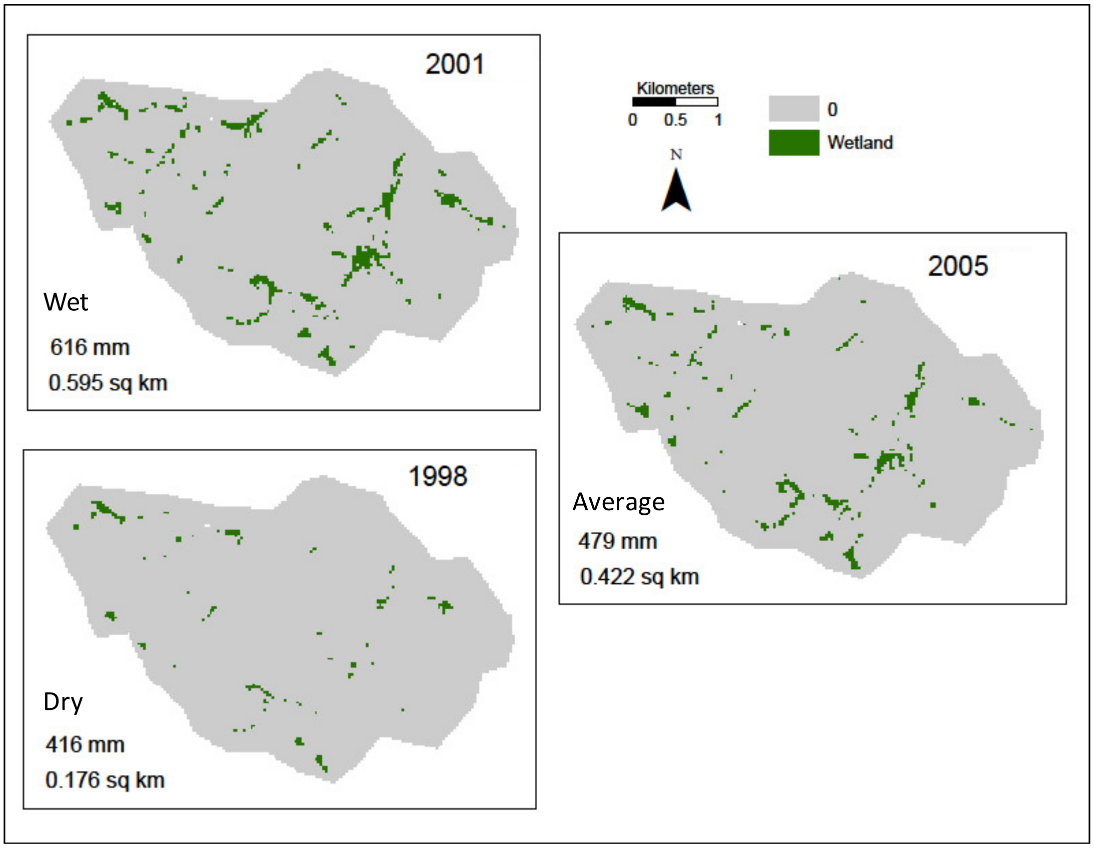
Table 4.1. List of the 20 images used in the original NDVI analysis along with image properties and the associated precipitation values. For the 12 images that were analyzed for wetland variability, the area calculated as wetland and stress events, when noted by the community, appear. Anomalously wet years are shaded blue, anomalously dry years are shaded orange and, neutral climate years are shaded gray.

Year	Month	Day	Julian Day	Precip (mm)	Cells >14000	Area (sq m)	Area (sq km	Stress
1985	7	25	206	655	1040	936000	0.936	
1988	8	18	230	490		0	0	
1989	7	20	201	449		0	0	
1990	8	8	220	344	170	153000	0.153	
1991	7	10	191	472		0	0	
1993	6	29	180	447	521	468900	0.4689	
1994	7	18	199	533		0	0	
1996	7	23	204	443		0	0	
1997	7	26	207	623	449	404100	0.4041	
1998	7	29	210	416	195	175500	0.1755	Drought
1999	8	1	213	411	156	140400	0.1404	
2001	7	21	202	616	661	594900	0.5949	Flood
2003	7	11	192	600	634	570600	0.5706	o.k crops
2004	7	13	194	587		0	0	
2005	7	16	197	479	469	422100	0.4221	Good papas
2006	7	19	200	467		0	0	
2007	7	22	203	458		0	0	
2008	7	24	205	368	219	197100	0.1971	strong drought
2009	6	25	176	579	560	504000	0.504	
2010	7	30	211	500	352	316800	0.3168	Good papas

Based on the analysis of the 12 images, the range of wetland area in the community territory in below average precipitation years (drought years) is 0.140 – 0.197 km^2 (average = 0.1665 km^2). In years of average precipitation, the range of wetland area is between 0.317- 0.469 km^2 (average = 0.403 km^2). And in above average precipitation years the wetland area ranges between 0.404 – 0.936 km^2 (average = 0.602 km^2). The greatest range in any one category is in the anomalously wet years. This is in part due to the fact that the 1984/1985 wet season is the second wettest year on record and follows another anomalously wet year.

Images from two stress years noted by community members and one neutral climate year (with good potato harvest) were selected to represent the variation of wetland area and the associated impacts to assets. Note that the chosen years do not correspond to the extreme minimum and maximum wetland area calculated in each category but instead to years with stresses noted by the community members. These years of analysis, displayed in Figure 4.7 are the 1998 image corresponding to the 1997/98 below average precipitation year, the 2001 image acquired in the 2000/2001 above average precipitation year, and the 2005 image that represents a neutral precipitation year (2004/2005).

Figure 4.7 Wetland maps for the years 1998, 2001, 2005. Associated precipitation values and area of calculated wetlands are included on maps.



It is clear that a below average wet season has a dramatic impact on the wetland area during the dry season months. The 1997/1998 wet season is just within one standard deviation of the regional precipitation mean for the period from 1964 to 2010 yet there is a 58% reduction in the wetland area in July of this year compared to July 2005. The lack of pasture in the wetlands during such years is particularly stressful for alpaca. Depending on the onset and the duration of a drought, herders must make decisions regarding the sale or slaughter of animals in seasons or quantities that differ from non-stress years. Furthermore, malnutrition in alpaca as a result of a lack of nutritious vegetation impacts the quality of fleece. Thus, fiber shorn from stressed animals will not be as valuable. Unfortunately, data regarding the decisions of the case community with respect to the culling of animals during drought was not collected. Certainly, this information, together with understanding the direct impacts of climate variation and other stresses on assets is important and warrants further study.

In contrast, an anomalously wet year, such as 2000/2001 provides an increase of 41% in area of green vegetation (Figure 4.7) compared to a neutral year. This seems beneficial for all animals and especially alpaca, but this benefit may come with other costs. Anomalously wet years are often associated with higher rates of animal illness, as is the case with 2001. The numbers provided by the participants of the timeline activity and discussions with individuals in the region suggest that 15 to 30% of a herd may die as a result of illness or disease. These results, coupled with the potential reduction in crop yields suggest that flood events, while shorter in duration than the typical drought, introduce several vectors of vulnerability.

Trends/Changes

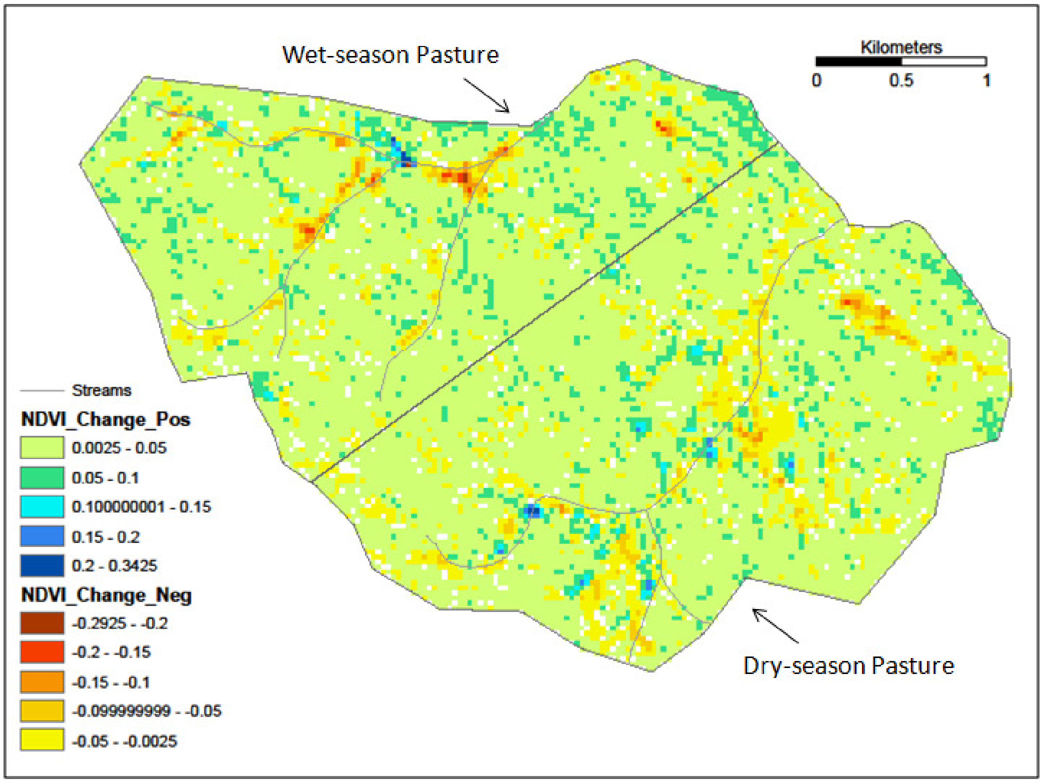
The information above provides insights into the year to year variability in the region and the related stresses experienced by the case community. Some argue that pastoralists are well adapted to such inherent variability in the system. Certainly, variability from year to year in crops and herds does not necessarily translate into increasing or decreasing trends over time. This case study exemplifies this. For example, herd numbers have continued to increase despite climate and illness stress events that periodically reduce these assets. This is in part due to interventions at critical times but also due to the management strategies of the community. Similarly, crop yields appear to be increasing over time. Unfortunately crop yield data was only provided for five interspersed years in the record. And the two earliest data points coincide with stress events while the most recent data point is for a year with good harvest yield during a time of neutral climate. Thus, while variability in crop yield is a function of climate, other factors also play a role such as increased human, social, and economic capital that may come along with a more mature social institution.

There is however one trend occurring in the watershed at the community and the district levels that concerns the natural resource base. Results from the NDVI vegetation analysis (Chapter 3) indicate that 30% of the wetland area in the Nuñoa watershed exhibits a decreasing NDVI trend from 1985 to 2010. While the vigor of vegetation in the watershed during the dry season is highly correlated with precipitation in the preceding wet season ($R^2 = 0.56$, $p < 0.05$), wet season precipitation exhibits no increasing or decreasing trend. Thus, the authors speculate that reductions in ice and snow melt contributions as a result of climate change may be one factor that explains the wetland trend. Another possibility is that frigid temperatures during the winter in recent years adversely impacted the vegetation in some locations. Other explanations include changes in land management and agricultural strategies such as changing herd demographics and rotation practices. A closer analysis of the vegetation trends within the boundaries of Community C, together with an understanding of herd management strategies and herd numbers provides insight into the issue.

The NDVI trend analysis method is explained in detail in Chapter 3. Briefly, a multiple linear regression model was applied to each pixel in the watershed. The response variable in the model is cell specific annual dry-season NDVI (for the 20 years that appear in Table 4.1) and the predictor variables are year, Julian day, a regional precipitation index, and a regional temperature index. Using the beta coefficients for the covariate year, the total change in NDVI from 1985 to 2010 for each cell in the watershed was calculated. The result of this analysis limited to Community C land appears in Figure 4.8. Similar to the findings for the Nuñoa watershed, decreasing trends in NDVI are seen mostly in the wetland areas bordering streams while slight increasing NDVI trends occur in the majority of vegetation elsewhere. The case community seasonally rotates herds between a wet-season and a dry-season pasture area and these are labeled on the map. The boundaries of the community are not exact and the area of the mapped community land is slightly greater than the actual size. Regardless, the total area of decreasing NDVI (normalized for total wet season or dry season pasture) and the total area with decreasing NDVI trends more extreme than -0.1

were calculated for each pasture. The dry season pasture is slightly larger in area then the wet season pasture and has a greater percentage of area exhibiting a decreasing trend in NDVI (16% versus 12%). Many of these decreases are slight and are in areas not considered wetland. The wet season pasture on the other hand contains a larger area with more extreme decreasing NDVI values (1% versus 0.3%) and these cells are within wetland areas.

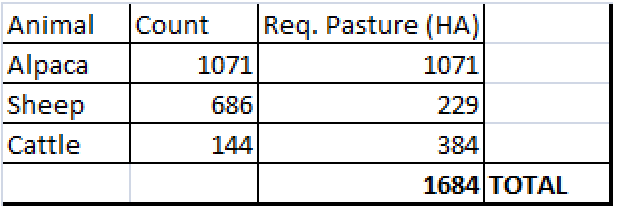
Figure 4.8 Results of the NDVI trend analysis for the Community C land displaying cells with increasing or decreasing NDVI for 1985-2010.



Approximate herd numbers and practices of herd management and sustainability were discussed with the community. First, it is acknowledged that the rotation system is more complex than simply alternating herds between the dry and wet season pastures.

Herds are often separated by species, age, sex, breed, etc. and rotated on a daily or weekly basis. The information here is simplified to a rotation of herds only between the wet and dry season pasture for several months at a time. From discussions with community members, based on feed requirements of an average adult animal, one hectare of land is suitable for three sheep or one alpaca per year. A cow is considered the equivalent of eight sheep, therefore 2.7 hectares are needed to meet foraging needs. These values are consistent with acceptable foraging requirements in the region (PNUD 2001). The carrying capacity depends on both the attributes of the animal and the attributes of the vegetation. Thus, the calculation might vary greatly with spatial and temporal variability. However, these numbers are assumed to be annual averages. Total animal counts (community and household level) for the three main species of animals in July of 2010 were: 1071 alpaca; 686 sheep; 144 cattle. The area of pasture required to meet the foraging needs of the current herd size in Community C can has been calculated and appears in Table 4.2.

Table 4.2. Total numbers of alpaca, sheep, and cattle including communal and familiar herds for the year 2010. Pasture requirements for the total number of each species are in hectares.



Animal	Count	Req. Pasture (HA)	
Alpaca	1071	1071	
Sheep	686	229	
Cattle	144	384	
		1684	**TOTAL**

The community self-reports 700 hectares of natural pasture available for forage. However, approximately 1684 hectares of pasture are needed to support the current herd size and composition (Table 4.2). Thus, it appears that overgrazing is a concern.

Furthermore, from the NDVI analysis it appears that the impacts of overgrazing are more severe in the wet-season pasture. Adler and Morales (1999), in a study of the factors influencing vegetation composition and diversity in a similar steppe-ecosystem in Argentina also found that wet-season pastures were more susceptible to change. Using ordination techniques, they showed that the percentage of total coverage, forage volume, and plant species diversity is significantly less in the wet season pastures. The authors hypothesize that one explanation for this is the seasonal cycle of vegetation and the interactive effects of grazing. In the current study, the differential seasonal effects appear to be largely confined to the *bofedales* (a habitat not present in the Argentina study). If indeed the more extreme decreasing NDVI trends in the wet-season *bofedales* are a result of overgrazing, one reason for this may be that *bofedales* in the wet season months have a lower carrying capacity compared to *bofedales* in the dry season (ALT-PNUD 2003). And so, if herd numbers are not adjusted to account for this difference in seasonality, the wet-season *bofedales* would be more susceptible to grazing pressure.

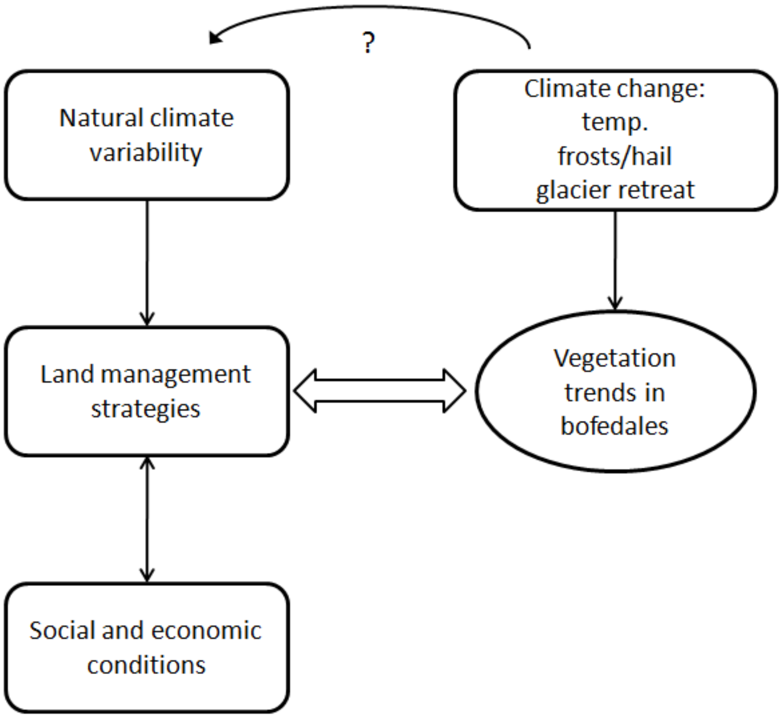
With respect to changes in water resources, community members on several occasions stated that many of the springs supply less water in recent years. Additionally, it is common for the lower lengths of the two small stream systems to run dry as the winter progresses, however, members noted that increasingly, upper segments of the streams are also running dry and as a result nearby pasture is drying out. The spatial patterns of the NDVI trends support these observations. However, cause and effect is difficult to establish and no local surficial or ground water studies have been undertaken. At the regional level (Figure 4.6) streamflow does not appear to be diminishing but instead, minimum flows (August-October) seem to be increasing since the mid-1980s (Figure 4.6c and Lavado et al. 2012). It is possible that more locally in the Nuñoa watershed changes in the storage of ice and snowcapped mountains are leading to decreasing water contributions to *bofedales*. Assuming warmer mean annual temperatures, precipitation at higher elevations would be increasingly in the form of rain rather than snow. Thus the timing of runoff would be altered but the spatial effects of this throughout the watershed are not known. Since there are only two or three small ice capped mountains in the north of the watershed the effect of this is thought to be relatively small, especially compared to other catchments. Finally, community members, along with other individuals in the region stated that in recent years the frosts are stronger and occur out of season. Frosts are typical from April through July. Herders note that frosts are an important water resource. As frost melts in the late morning sun, it provides water for the animals but also seeps into the soil and helps maintain vegetation. Heavy frost can damage vegetation. Thus, a change in the intensity and timing of frosts could potentially have a significant impact on vegetation during the dry season.

4.6.4 Livelihood Strategies and Outcomes

Both in the case community and in the region there is increasing interest in entering formal markets at the local and regional level. Already occurring activities include the newly initiated farmer’s market, production of cheese and yogurt for sale, and a breeding program for colored alpaca in conjunction with the formation of an artisanal group in town that produces colored fiber textiles. Temporary migration and off-farm wage labor are also strategies that are commonly employed, although no data for these activities was collected. However, there appears to be a growing number of community members (individuals and families) who move to town. Conflict regarding the management of resources may be increasing between households who in their entirety reside permanently in the community and those who do not.

Despite extreme interannual variability in climate and natural and physical capital, increasing trends in crop yields and herd numbers, together with the increased commercialization of products, suggest that the current livelihood strategies have the outcome of increased food security. However, the current strategies, together with climate change, may also be responsible for the decreasing vegetation trends in the wetland areas. The relationships between the key variables hypothesized to be driving the vegetation trends in the community wetlands are depicted in Figure 4.9. As a result of the changes observed in the resource base, from a livelihoods perspective, the current strategies do not appear to be sustainable. Since similar trends in wetland areas are seen elsewhere in the watershed we can broaden the focus from the community level out to the scale of the District of Nuñoa (the District is wholly contained within the watershed).

Figure 4.9 Schematic displaying the key factors impacting vegetation in *bofedales* and the relationships between these factors .



Similar to Community C, herd numbers have increased for the District of Nuñoa in recent decades. Data from the Ministry of Agriculture are for the years between 1985 and 1995 and for the year 2008. From 1985 to 2008, the number of cattle increased 41% and the number of alpaca increased 51%. There has been no trend in sheep numbers. In this region in the 1980s redistribution of land and accompanying changes in land tenure were occurring. And so in one sense, we have a good picture of how herd numbers have accompanied these social and political changes. What is unknown is how these numbers compare to previous years during the hacienda and the cooperative systems. Legacy effects of past land use and management strategies may also play a role in the current vegetation trends. Despite this, alpaca and llama herding is a critical mode of adaptation to the Andean environment (Thomas 1979; Flores de Ochoa 1977). For biological reasons, camelids are well adapted to the environment, particularly the low primary productivity of its thin and loose soils (Brush 1982, Josse et al. 2009), and its climate and resulting vegetation (Baied and Wheeler 1993). Sheep and cattle (especially cattle) are more intensive grazers with higher energy requirements and greater vulnerability to the variable and extreme environment of the Altiplano. Thus with respect to the decreasing vegetation trends seen in Community C, and elsewhere in the watershed, it can be asked whether it is the number of animals or the composition of animals, or both that is partly responsible for the trend.

Kristjanson et al. (2006) show that improved breeding and diversification of livestock related activities are significant factors that help reduce poverty in the Puno region. This underscores the importance of maintaining a sustainable natural resource base. Can smaller numbers of herds be sustainable to both livelihoods and the resource base? Within this context, since herds represent security, what is the balance between herd numbers great enough to provide a buffer against environmental stresses and extreme climate but not beyond the degradation of the resource base? With regard to products that are sold to market, namely meat and fiber, can an increase in quality of products and increased market options reduce the quantity of animal products needed to achieve food security and more? One aspect of this is that within the community there needs to be a focus on animal well-being and management strategies that maximize herd health. However, this can’t be done without the economic and social capital necessary to access and organize the proper vaccinations, participate in breeding improvement programs, and construct shelters, for example. The second aspect, regarding market options, also falls squarely within the realm of exogenous political-economic conditions. In a report to the FAO, Fairfield (2006) outlines several policies that might promote economic opportunities for small-scale producers in the camelid sector in several poor regions of Peru, including Puno. Several of these suggestions would increase or strengthen the representation of alpaca herders in the political and economic spheres and decrease dependency on third parties. However, the report also discusses past barriers and current trends and limitations with respect to these policies and highlights the fact that several previous interventions by well-organized groups have not succeeded. Despite this, because camelids are seen as especially well adapted to the high Andean ecosystem, development programs and interventions should continue to focus on products derived from these animals such as fiber, meat, and hides. Emphasis on livelihood strategies using products derived from cattle and sheep might result in intensification of these species and thus, lead to increased deterioration of the resource base. Examples of this are already occurring in the lower portions of the watershed. There has been an increase in the dairy market in Peru since the 1990s. And small-scale producers who have diversified their strategies and intensified cattle livestock for mild production have seen positive economic outcomes. However, areas where increased agriculture is occurring also display decreases in vegetation as seen in the NDVI analysis (Chapter 3). Furthermore, herders in the upper elevations of the watershed, such as Community C, will not benefit from these new market incentives. Associated activities with dairy production include improved pasture for cattle. Members of Community C for example explained that they have tried to grow alfalfa for forage but it does not grow well at higher altitudes. Thus, with the current market trends and incentives there will most likely be increasing economic disparities between herders at different elevations. Without other initiatives targeted for higher elevations, this could lead to further exclusion of the alpaca pastoralists.

4.7 Conclusions

Multiple stressors, such as climate events and animal and human illness occur frequently and often sequentially or simultaneously in the District of Nuñoa, Peru. In the case community presented here, animal illnesses alone can reduce herd numbers 20%. Crop yields can decrease from an average yield year by more than 50% and the decrease from what is considered a good crop year to a bad one is nearly 80%. Furthermore, foraging area in wetlands decreased by 58% in a typical drought year compared to a neutral climate year. Years with a singular stress event that reduces both crop yield and herd numbers (or herd health), such as drought years, are therefore particularly taxing. Vulnerability also increases when a stress event one year reduces one asset and is immediately followed by a second stress event that reduces another. Thus, when reviewing critical moments of vulnerability in the agro-pastoralist system, the concepts of multiple-stressors and sequencing should be taken into account.

While interannual climate variability is inherent to this region of the Andes, modeling studies of projected precipitation tend to agree that future changes in the regime may only be slight (Lavado et al. 2011; Urrutia and Vuille 2009). And while a portion (approximately 40%) of the variability in interannual variability is attributable to the El Niño Southern Oscillation (ENSO) , it is currently unclear how ENSO dynamics will change in the future and what this means for the frequency and intensity of droughts and floods in the region. Similar to the global mean, mean annual temperature in the region has increased approximately 0.7 °C (Vuille et al. 2008) since the mid-1900s. This may increase crop and animal disease vectors in the future. It may also result in reduced water availability if increased evaporation and evapotranspiration is assumed. However, there is some evidence to suggest that humidity in the Altiplano may be increasing (Salzmann et al. 2013), thereby offsetting the increase in evaporation. Observations by herders and results of the vegetation analysis suggest that a decrease in water resources during the dry season months may already be occurring.

Of immediate concern to the sustainability of the agro-pastoralist livelihood are the decreasing vegetation trends in areas that are considered essential foraging grounds especially to alpaca. It is likely that climate factors and herding management strategies are both contributing to these trends at the community and watershed level, and there may be some interesting interactive effects. If one considers overgrazing to be a main contributor, then the social and economic conditions that lead to overstocking must be considered. It is recognized that agro-pastoralists in the region are not a homogeneous group. Likewise, the case community does not consist of homogeneous households. However, at various levels there are generalities in trends and conditions and in the circumstances that govern the vulnerability context of pastoralists in the region. All must contend with the variability in climate and the uncertainty that comes with climate change. The increasing trends in cattle and alpaca numbers are a regional phenomenon. The decreasing trend in a large portion of the wetlands is also a regional phenomenon.

Policy, development, and market initiatives and interventions need to be sensitive to the variability and possible future changes in the climate system. There should also be increased awareness of the changes in the natural resource base that are occurring now and how these changes are related to other components in the agro-pastoralist system. This information provides context and something by which to judge the utility and limitations of future planned alternative strategies.

CHAPTER 5

CONCLUSIONS

5.1 Conclusions

This research bridges three spatial scales of analysis to improve our understanding of the inter-related components of a complex human-environmental system. Research efforts included gathering data about hydro-climatological variability and environmental trends, the vulnerability context of Andean herders, and the factors (environmental, social, and economic) that drive changes in a communal agro-pastoralist system. The biogeophysical components of the system under study consisted of wet-season precipitation and streamflow and dry-season vegetation dynamics. Based on the extreme seasonality of the Altiplano and the herding calendar, an increased understanding of these parameters in the given seasons is useful in addressing various aspects of herder vulnerability to environmental change. The main findings of Chapters 2 through 4 are summarized below together with questions generated from the research methods and results. This is followed by concluding remarks.

Chapter 2 characterized the hydroclimatology of the Ramis watershed in southern Peru. Periodicities in precipitation and streamflow were described and the relationship of this variability with Pacific and Atlantic sea surface temperatures was explored. Results show that from 1964 to 2006 prevailing periodicities of three to five years in both wet season streamflow and precipitation in the watershed (Figure 2.5) represent an El Niño Southern Oscillation (ENSO) signature. Wet season (December through

March) precipitation over the 42 years correlates best with contemporaneous Niño 2 region averages ($r = -0.52$; $p < 0.05$) (Table 2.2). A review of the predictive power of Niño 2 (September-November SST averages) on December through March precipitation indicates a significant but low prediction potential, with only 8% of the variation in wet season precipitation explained by the linear relationship with preceding Niño 2 SSTs (Table 2.2). However, it appears that the strength of the ENSO-hydroclimatology relationship fluctuates over time. Analyses between station precipitation (and streamflow) and SSTs performed for three time periods (1964-1976; 1977-1997; 1998-2006) suggest that the strongest ENSO teleconnections are for the years 1977 through 1997 (Table 2.5). Some of the most extreme ENSO events on record occurred during these years. In the analyzed time periods prior to 1977 and post-1997 the ENSO relationship in the watershed is much weaker and instead, there is a significant relationship with the Tropical Northern Atlantic (TNA) in both periods (Table 2.5). Variations in the location, timing, and intensity of ENSO events play a role in determining teleconnections and these characteristics are difficult to capture with the methods employed. The apparent on again and off again ENSO relationship may also be due in part to small sample size in the earlier and later time periods. Thus, our understanding of the relationship between interannual variability in the Ramis watershed and ENSO may be enhanced in the future with the availability of longer data sets together with methods that utilize indices representative of the varying spatial and temporal developments of ENSO events.

If there is a cause and effect relationship between the TNA and regional hydrology the mechanisms are still unclear as the relationship has not been the focus of previous research. However, this study has shown that decadal variability in the precipitation record (Figure 2.5) has a structure similar to both the TNA and Pacific Decadal Oscillation (PDO). This signal is captured in the second principal component which explains an additional 13% of the variance in the precipitation record. While the first principal component is a regional precipitation signal the second principal component represents localized variations in precipitation at the decadal timescale. Stations to the east and along Lake Titicaca display decadal trends in precipitation that are opposite to stations in the west (Figure 2.4). Considering the potential to attribute these variances in precipitation at the decadal timescale to global scale phenomena and the utility that this has for forecasting, these relationships should be further explored.

Chapter 3 analyzed the spatial and temporal changes in vegetation in the Nuñoa watershed from 1985 to 2010 using a remote sensing derived calculation known as the normalized difference vegetation index (NDVI). One main objective of this chapter was to delineate wetlands and review the vegetation trends in these key grazing areas. It was found that wetlands represent approximately 16% (451 km^2) of the watershed area. The results of the vegetation analyses indicate that there is a slight increase in NDVI for the majority of the pixels (81%) in the Nuñoa watershed (Figure 3.13a) but approximately 30% of the wetland areas display a decrease in NDVI over the time period (Table 3.5). Variability in dry season NDVI is highly correlated with wet season (December through March) precipitation ($R^2 = 0.56$, $p < 0.05$) but, given the absence of a trend in precipitation, the trends in NDVI in the watershed are not explained by precipitation. Socio-political factors and contemporary changes in land management and production systems in the region were speculated to result in more intensive use of wetland areas, thereby causing the decreasing vegetation trends seen there. These factors, together with potential reductions in glacier melt from several small ice-capped mountains in the north of the study area may also be contributing to locally decreasing NDVI trends in wetlands. These drivers of change were explored in more detail in Chapter 4.

Methodologically, Chapter 3 was the most complex of the analyses in the dissertation. The choice of methods was based on available data and technology which changed dramatically over the course of the research. Based on the heterogeneity of the Andean landscape, future endeavors might include more localized temperature and precipitation indices. Depending on the timeframe of the analysis, the Tropical Rainfall Measuring Mission (TRMM) gridded rainfall data (operated by NASA and the Japanese space agency JAXA) might be useful. Similarly, including elevation in regression models would help to account for landscape heterogeneity. Finally, the remote sensing findings would be complemented by a ground truth component whereby increasing and decreasing NDVI trends could be understood in the context of vegetation composition and density in the field.

Chapter 4 demonstrated the connections between livelihood strategies of a *comunidad campesina* (peasant community) and changing physical and natural capital within the context of climate variability and climate change in the Nuñoa watershed.

Drawing on the results from Chapters 2 and 3, a case study approach using the sustainable livelihoods framework (Figure 4.2) allowed for further investigation into the processes behind trends. This study provides a broader characterization of the vulnerability context of agro-pastoralists in the upper elevations of the Nuñoa watershed. Specifically, it was found that despite moments of vulnerability created by the highly known climate stressors on livelihood, such as floods, droughts, cold, hail, and frost, at the community level herd numbers and crop yields have increased over the time of study (1985-2010) (Figure 4.3). Livelihood strategies in recent years have diversified to include an increase in market activities and the production of new goods such as artisan cheese and yogurt from cow milk. Chapter 4 also concluded that decreasing trends in wetland vegetation (Figure 4.8) are at least in part due to herding management strategies (Table 4.2). Thus, if existing trends in herd numbers continue it is expected that so too will the decreasing vegetation trends.

These findings raise several questions for future research. How, for example, does this scenario compare to a community without communal herds and communal gardens? It is suspected that the social assets that are particular to communal organization reduce the risks of climate variability and therefore reduce vulnerability. Thus, livelihood strategies and trends in herd numbers and crop yields could be compared in communities with varying institutional and property rights to better understand the differential impacts of climate change on herder sensitivity. It also raises the question of how food security (or insecurity) in these moments of vulnerability compare at the household level both in communal communities and parcelized communities. An understanding of the recovery process to various shocks and stresses at the household and communal level would contribute greatly to this research.

Intensified livestock production is a current livelihood strategy by many herders in the region since there are economic incentives to do so. Intensification may include increasing animal numbers, shifting focus from one species to another (e.g., alpaca to cattle), application of synthetic fertilizer, and replacing natural pasture with seeded forage with greater irrigation requirements. While these strategies may increase livelihood well-being in the short-term, they may be contributing to decreasing vegetation trends in the wetlands in the Nuñoa watershed. Deterioration of this important natural resource base will increase herder vulnerability to the extreme seasonal and interannual variability that is inherent to the climate of the Altiplano.

With respect to trends in climate variables, this research focused mainly on regional winter season precipitation and streamflow since contributions to the hydrological balance are greatest during these months. For the years of study no trends in either variable were found. However, observations by herders include decreasing water levels in springs and streams in the last decade. These hydrological changes suggest a lowering of the water table which would certainly contribute to the decreasing vegetation trends in wetland areas. Decreasing ground water levels can result from changes in hydrological pathways as a result of land use or climate change. It is probable that changes to the 23 km^2 of snow and ice-capped mountains in the Nuñoa watershed are resulting in hydrological variations at the local scale that are not captured in the regional streamflow data. As a result, this particular aspect of climate change (alterations in the hydrological pathways) will exacerbate the decreasing vegetation trends and therefore increase herder vulnerability.

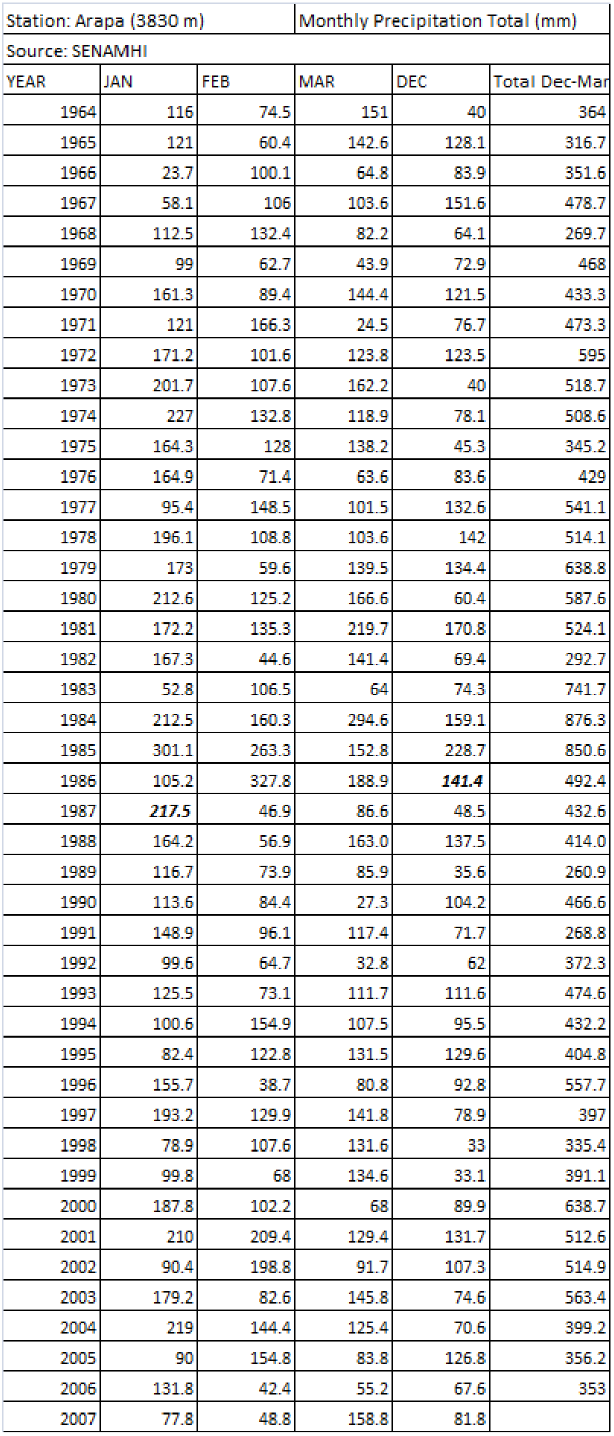
Global mean surface temperatures are expected to continue to increase as a result of climate change. Changes in the precipitation regime in the Andean region are less predictable but observations and studies in other areas of Peru suggest that while future mean annual changes may be slight, seasonal variations may already be occurring. This research has found that there is decadal periodicity in the wet season streamflow and precipitation records. Keeping this in mind, future research might include trend analyses at the monthly level and a hydrological balance model of the Nuñoa watershed.

Synthesizing these conclusions, I surmise that climate change will increase the vulnerability of the agro-pastoralist livelihood to decreasing water resources and vegetation during the dry season and in droughts and to increased exposure to shocks, such as hail and cold spells. I also believe that social and economic institutions are playing an equally important, if not more important, role in establishing processes that promote vulnerability. This dissertation has highlighted changes in a resource base that is essential to the herding livelihood. In many ways, the matter of climate change has helped bring the issue of vulnerability of marginalized sectors to the forefront. The growing attention in the research and development fields may address the political and economic conditions that help shape the vulnerability context thereby reducing herder vulnerability to climate variability and change. The description of direct links between social and economic conditions, climate, livelihood strategies, and conditions of the resource base will help formulate appropriate policies and economic incentives that reduce herder vulnerability and maintain natural resources. To this end, it is hoped that this dissertation research makes a positive contribution to the body of work that addresses the vulnerability of marginalized populations to climate variability and climate change. It is also hoped that the methodology lends itself to furthering the interdisciplinary approach to human-environment systems.

APPENDIX A

PRECIPITATION DATA

Station: Chuquibambilla (3971 m)						Monthly Precipitation Total (mm)							
Source: SENAMHI													
YEAR	JAN	FEB	MAR	APRIL	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	Total Dec-Mar
1964	98.4	78.7	169	70.4	19.5	0	0	0	30.5	58	139.1	124.8	688.4
1965	235.9	132.1	195.6	46.7	0	0	0.2	1	14.1	30.4	66.6	186.8	486
1966	90.1	109.5	99.6	13.5	29.4	0	0	0	25.5	62.5	75.5	96.8	471.4
1967	65.9	165.9	142.8	22.1	10.2	0	22.2	4.4	17.4	102.5	25.2	235.5	750.7
1968	147.8	233.2	134.2	43.9	0	0	11	8.2	20.4	37.3	118.7	83.3	396.2
1969	111.2	125.5	76.2	47.3	0	0	2.9	2	7.1	50.6	33.7	62.8	447.4
1970	185.7	97.4	101.5	66.7	16.5	0.5	0	0	42	55.8	24.9	194.9	508.7
1971	86.5	169.7	57.6	46.3	1	0	0	3.5	0	23.1	68.5	102.9	544.2
1972	199.1	126.3	115.9	26.5	2.3	0	4.3	2.6	2.5	12.8	21.9	131.2	488.9
1973	115.1	84.8	157.8	110.4	7.7	0	1.5	9.2	37.7	38.1	84	55.3	453.3
1974	167.2	102.3	128.5	47.9	0	4.2	0	25.4	18.8	28.5	43.3	61.1	494.2
1975	225.3	101.9	105.9	37.3	22	0	0	0	34.2	59.6	43.6	131.4	584
1976	208.8	88.9	154.9	27.4	15.4	1.5	0.8	2.8	33.8	1.9	26	43.3	417.4
1977	95.7	138.3	140.1	31.7	4	0	2	0	38	54.6	106.5	82.5	572.4
1978	295.2	127.7	67	64	0.9	0.6	0	0	24.7	19.9	101.9	122.3	408.5
1979	150.9	56.6	78.7	54.2	1.4	0	0	4.4	4.7	29.1	34.6	122.4	484.3
1980	109	103.7	149.2	11.8	11.2	0	1.3	2.4	4.8	87.2	64.2	105.8	600.9
1981	174.3	176	144.8	77	7.6	3.1	0	11.6	31	77.4	41.5	106.8	447.9
1982	148.3	91.7	101.1	82.2	0	0	0	0	27	95	154.2	67.9	231
1983	51.4	51.1	60.6	47.6	2.4	0	0	0	15.5	21.3	24.5	88.3	619.9
1984	216.3	175.4	139.9	30.5	20.9	0	1.3	0.7	2.7	120.6	124.1	180.1	508.1
1985	114	123.5	90.5	34.6	14.7	25.9	0	0.5	65.7	24.6	140.8	106.9	451
1986	99.4	114.8	129.9	90.5	12.9	0	1	4.1	35.5	2.7	60.1	146.8	405.6
1987	111.2	75.1	72.5	32	1.1	1.4	7.3	0.9	3.2	9.3	96.6	79.8	507.6
1988	201.8	72.6	153.4	71.3	16.9	0	0	0	11.6	26.7	4.9	94.5	371.7
1989	78.6	84.7	113.9	86.8	3.8	0.7	0.7	40.1	30.9	59.8	55.9	95.5	465
1990	137.5	82.4	149.6	68.3	8.8	48.1	0	0.2	9.8	136.1	70.4	74.4	445.2
1991	191.4	61.4	118	30.1	28	39.1	0	0	1	48.3	29.8	94.5	359.7
1992	109.8	71.1	84.3	35.4	0	2.4	0	42	0	57.5	99.4	90.4	485.7
1993	183.4	29	182.9	46.9	0	16	0	28.6	9.3	94.1	162	98.1	580.2
1994	209.4	133.1	139.6	61.3	0	0	0	5.8	6.1	43	76.3	120.6	467.9
1995	119.7	102.8	124.8	15.8	2.1	0	0	0	2.5	27	56.7	123.8	495.8
1996	162.2	112	97.8	61.9	1.4	0	3.4	5	6.6	11.8	57.1	98.5	700.6
1997	205.1	204.3	192.7	63.3	4	0	0	16.5	31	35.4	111.6	121.7	533.3
1998	128.7	131.5	151.4	22.5	0	2	0	2	8.8	72.6	107.3	50.9	467.5
1999	114.1	162.6	139.9	146.8	9.8	0	1.4	1.7	20.3	58.1	28	94.1	578.8
2000	183.4	180.6	120.7	14.4	17.3	6.5	7	5.3	6.9	94.1	17.4	139.1	631.9
2001	238.6	127.3	126.9	25.1	19.3	1.2	4.7	7.5	10.8	40.4	18.2	69.9	519.8
2002	156.8	175.5	117.6	92.6	29.2	2	13.5	13.6	22	94.2	102.5	128	665.7
2003	137.9	154.8	245	43.6	4.3	3.3	0	12.6	23.3	18.7	33.6	97.6	545.9
2004	215.6	137	95.7	42.6	1.1	2	3.3	21.9	59.6	13.3	58.3	142.5	542
2005	88.1	213.7	97.7	39	0	0	0	7.9	0	118.3	75.7	98	497.3
2006	188.8	115.9	94.6	20.5	0	3.2	0	3	3.6	48	90.8	208.3	531.6
2007	95.6	96.9	130.8	81.9	3.5	0	4.6	0	22.1	21.1	67.2	72.9	368.1
2008	154.5	92.3	48.4									236.1	579.3
2009	115.2	87.2	140.8									131.1	499.7
2010	185.7	72.5	110.4										

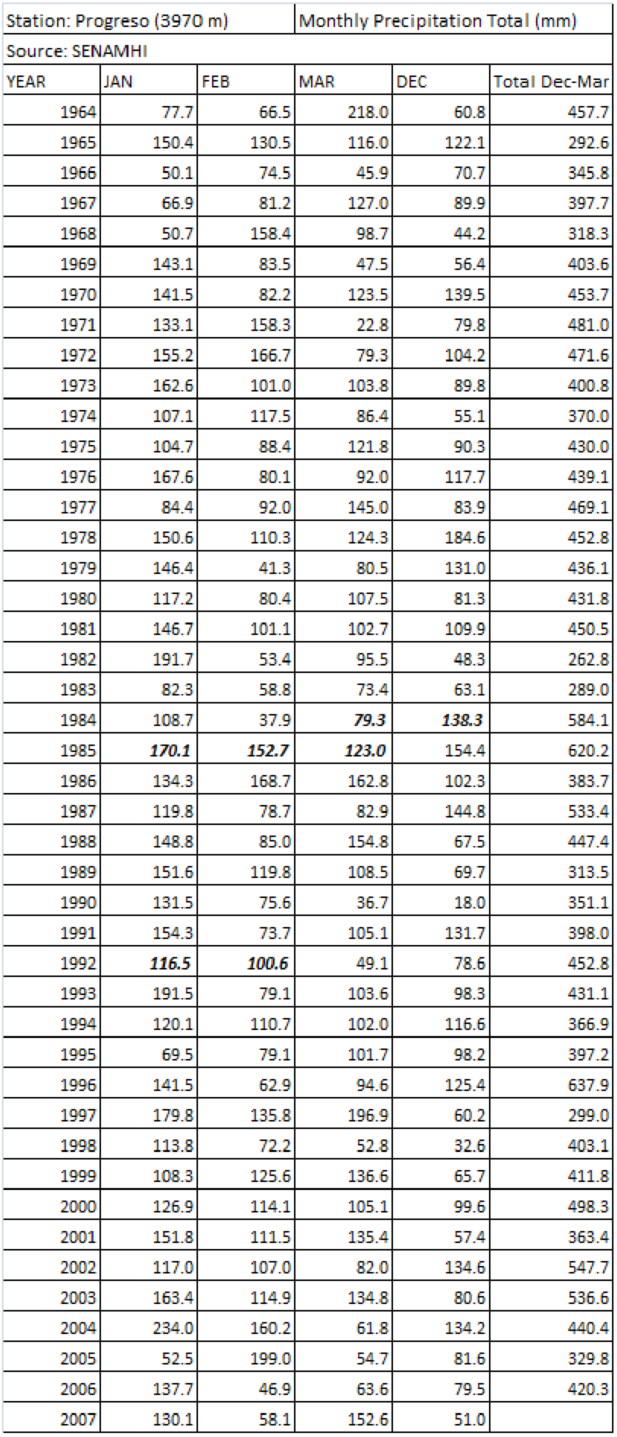


Station: Arapa (3830 m)			Monthly Precipitation Total (mm)		
Source: SENAMHI					
YEAR	JAN	FEB	MAR	DEC	Total Dec-Mar
1964	116	74.5	151	40	364
1965	121	60.4	142.6	128.1	316.7
1966	23.7	100.1	64.8	83.9	351.6
1967	58.1	106	103.6	151.6	478.7
1968	112.5	132.4	82.2	64.1	269.7
1969	99	62.7	43.9	72.9	468
1970	161.3	89.4	144.4	121.5	433.3
1971	121	166.3	24.5	76.7	473.3
1972	171.2	101.6	123.8	123.5	595
1973	201.7	107.6	162.2	40	518.7
1974	227	132.8	118.9	78.1	508.6
1975	164.3	128	138.2	45.3	345.2
1976	164.9	71.4	63.6	83.6	429
1977	95.4	148.5	101.5	132.6	541.1
1978	196.1	108.8	103.6	142	514.1
1979	173	59.6	139.5	134.4	638.8
1980	212.6	125.2	166.6	60.4	587.6
1981	172.2	135.3	219.7	170.8	524.1
1982	167.3	44.6	141.4	69.4	292.7
1983	52.8	106.5	64	74.3	741.7
1984	212.5	160.3	294.6	159.1	876.3
1985	301.1	263.3	152.8	228.7	850.6
1986	105.2	327.8	188.9	***141.4***	492.4
1987	***217.5***	46.9	86.6	48.5	432.6
1988	164.2	56.9	163.0	137.5	414.0
1989	116.7	73.9	85.9	35.6	260.9
1990	113.6	84.4	27.3	104.2	466.6
1991	148.9	96.1	117.4	71.7	268.8
1992	99.6	64.7	32.8	62	372.3
1993	125.5	73.1	111.7	111.6	474.6
1994	100.6	154.9	107.5	95.5	432.2
1995	82.4	122.8	131.5	129.6	404.8
1996	155.7	38.7	80.8	92.8	557.7
1997	193.2	129.9	141.8	78.9	397
1998	78.9	107.6	131.6	33	335.4
1999	99.8	68	134.6	33.1	391.1
2000	187.8	102.2	68	89.9	638.7
2001	210	209.4	129.4	131.7	512.6
2002	90.4	198.8	91.7	107.3	514.9
2003	179.2	82.6	145.8	74.6	563.4
2004	219	144.4	125.4	70.6	399.2
2005	90	154.8	83.8	126.8	356.2
2006	131.8	42.4	55.2	67.6	353
2007	77.8	48.8	158.8	81.8	

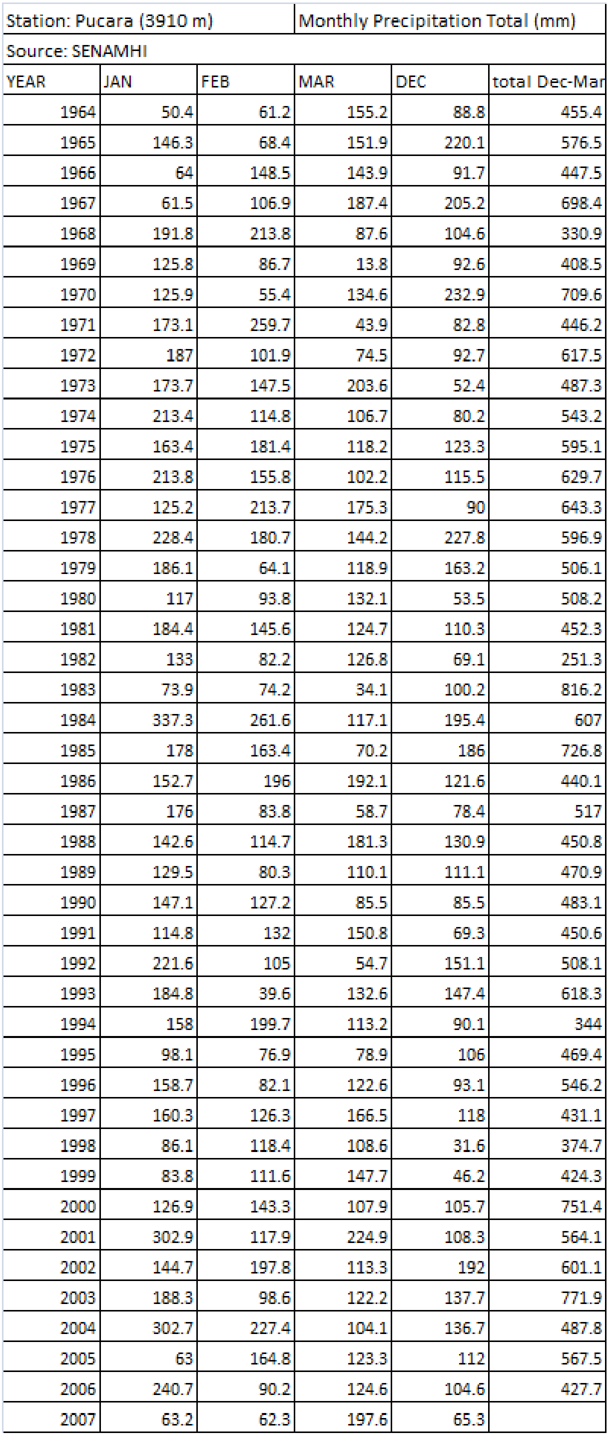
Station: Huancane (3890 m)			Monthly Precipitation Total (mm)		
Source: SENAMHI					
YEAR	JAN	FEB	MAR	DEC	Total Dec-Mar
1964	68	82	206	27.5	409.5
1965	173.5	108.5	100	184	539
1966	106	126	123	84.4	262.9
1967	27.5	73	78	166.5	585.3
1968	92.2	237.4	89.2	85.8	451.8
1969	121.2	148.8	96	40.4	362.8
1970	164.1	71.4	86.9	193	533.3
1971	108	183	49.3	46.5	345.3
1972	169.8	79	50	167	545.3
1973	151.6	63.2	163.5	56.5	401.2
1974	190.4	***103.3***	51.0	62.5	502.5
1975	127	209.5	103.5	155	288.7
1976	66	58	9.7	97.6	374.4
1977	31.6	150.6	94.6	91	572.8
1978	120.8	237.2	123.8	195.2	529.6
1979	191.8	99.5	43.1	107.9	491.3
1980	118.3	125.4	139.7	85.1	629.3
1981	326	103.6	114.6	106.6	417.6
1982	163	35.2	112.8	48.2	223.4
1983	102.4	48.4	24.4	84.8	401.5
1984	24.6	166.7	125.4	76.4	418.7
1985	168.7	66	107.6	163.8	646.8
1986	183.2	148.4	151.4	115.1	403.8
1987	191.1	20.1	77.5	57	632.1
1988	227.4	77.9	269.8	92.7	480.8
1989	156	120.3	111.8	83.6	310.5
1990	121.9	55.6	49.4	98.6	497.7
1991	123.4	137.7	138	148.2	402.5
1992	132	75.4	46.9	140	426.4
1993	127.3	47.9	111.2	143.9	510
1994	100.8	114.7	150.6	132.8	470.1
1995	133.3	124.1	79.9	67.2	420.1
1996	200.9	80.9	71.1	177.4	643.4
1997	171.8	110.8	183.4	51.7	317.9
1998	109.3	69.4	87.5	35.6	342.1
1999	88.8	65.9	151.8	41.2	296.1
2000	85.2	55.9	113.8	113.5	620.5
2001	205.1	142.2	159.7	123.6	541.5
2002	90.9	175.5	151.5	116.8	572.4
2003	216.5	107.8	131.3	105.9	503
2004	195.9	147.1	54.1	91.9	446.5
2005	109.4	148.6	96.6	94.2	426.3
2006	224.3	31.1	76.7	113.2	471.3
2007	137.9	97.4	122.8	119.4	

Station: Lampa (3892 m)			Monthly Precipitation Total (mm)		
Source: SENAMHI					
YEAR	JAN	FEB	MAR	DEC	Total Dec-Mar
1964	43	118.4	127.6	50.1	401.5
1965	154.8	97.5	99.1	155	346
1966	31	107	53	97.1	405
1967	67.6	111.7	128.6	168.5	539.2
1968	97.9	199.4	73.4	67.6	340.6
1969	164.4	75.7	32.9	63.4	440.2
1970	142.9	107.6	126.3	112.7	430.9
1971	97.8	184.4	36	144.4	622.3
1972	239.3	89	149.6	60.3	552.6
1973	213.1	158.1	121.1	61.6	451.8
1974	222.4	107.2	60.6	78.9	528.5
1975	157.7	178.1	113.8	82.9	393.8
1976	187.2	68.5	55.2	111.3	560.8
1977	71	170	208.5	163.7	896.4
1978	414.2	176	142.5	209.6	640.9
1979	192.5	76.9	161.9	136.5	495
1980	86.5	95.5	176.5	54	526.1
1981	190.5	145.5	136.1	173.5	581.5
1982	166.5	101.5	140	39.5	119.3
1983	23	***32.3***	24.5	47.5	443.3
1984	223.8	127.1	44.9	263.7	999.6
1985	156.1	433.3	146.5	158.4	618.8
1986	131.3	186.7	142.4	122	430.9
1987	215.5	76.3	17.1	101.4	512.9
1988	194.5	56.5	160.5	146.2	471.1
1989	131.4	82	111.5	49.7	232.4
1990	89.7	61.7	31.3	91.8	428
1991	138.7	107	90.5	82.9	279
1992	86.4	76.2	33.5	111.1	424.7
1993	155.3	18.2	140.1	135.7	552.9
1994	164	148.2	105	85.2	382.1
1995	107.8	94.9	94.2	61.8	466.8
1996	196	100.6	108.4	149.3	623.6
1997	149.4	177.8	147.1	95.6	458.7
1998	104.7	154.4	104	62.1	456
1999	152.7	97.8	143.4	63.5	481
2000	173.7	113.5	130.3	114.2	666.8
2001	249.7	188.3	114.6	73.7	411.4
2002	121.8	76.5	139.4	177.4	656
2003	203.3	136.2	139.1	132.1	643.8
2004	266.6	144.1	101	100	595.4
2005	100.6	278.3	116.5	164.6	585.2
2006	188.2	109.5	122.9	95.7	503.4
2007	81.5	67.8	258.4		

Station: Pampahuta (4400 m)			Monthly Precipitation Total (mm)		
Source: SENAMHI					
YEAR	JAN	FEB	MAR	DEC	Total Dec-Mar
1964				72	
1965	124.1	163.1	123.1	***132.15***	482.3
1966	89.4	178.5	63.5	103.4	463.6
1967	77.2	94	211.1	128.7	485.7
1968	179.5	213.3	112.8	83.9	634.3
1969	152.6	89.6	57.4	111.4	383.5
1970	157.4	140.5	169.6	209.1	578.9
1971	151.7	259.4	117.7	191.1	737.9
1972	244.3	79.1	168	93.2	682.5
1973	279.6	210.4	124.7	142.5	707.9
1974	208	262.6	109.5	110.6	722.6
1975	232.5	237.2	144.7	171.3	725
1976	207.2	110.4	162.5	72.8	651.4
1977	106.8	182.5	150.4	85	512.5
1978	310.2	98.7	83.6	145.7	577.5
1979	188.3	123.1	100.9	103.3	558
1980	115.1	73.7	245.5	41.4	537.6
1981	204	212.5	159.7	152.8	617.6
1982	168.2	81.8	139.8	28.7	542.6
1983	83.6	53	53.8	86.1	219.1
1984	259.1	254.3	201.3	181.4	800.8
1985	81.8	210	168.1	162.5	641.3
1986	168.3	276	189.9	196.5	796.7
1987	229.1	25	54.2	45.5	504.8
1988	186	69.9	214	105.5	515.4
1989	175.2	100.5	131.8	78.1	513
1990	160.5	75.2	59.9	91.4	373.7
1991	205.6	119.3	146.2	102.4	562.5
1992	96.5	142.3	23.4	81.6	364.6
1993	246.2	62	138.2	175.1	528
1994	224.8	168.1	127.6	165.4	695.6
1995	115.4	151.5	120.9	142.8	553.2
1996	254.5	164.2	73.5	228.3	635
1997	220.1	185.5	100.3	103.7	734.2
1998	154.6	159.8	103.4	45	521.5
1999	153.5	163.9	204.9	118	567.3
2000	202.1	258.8	181.6	136.1	760.5
2001	299	248.1	149.3	68.1	832.5
2002	152.6	240.7	111	170.5	572.4
2003	222.2	194.8	201.4	155.6	788.9
2004	226.8	162.8	55.8	102.1	601
2005	111.5	267.5	97.7	136.1	578.8
2006	179.4	165	163.7	89.4	644.2
2007	149.6	147.9	260.9	116.8	647.8



Station: Progreso (3970 m)			Monthly Precipitation Total (mm)		
Source: SENAMHI					
YEAR	JAN	FEB	MAR	DEC	Total Dec-Mar
1964	77.7	66.5	218.0	60.8	457.7
1965	150.4	130.5	116.0	122.1	292.6
1966	50.1	74.5	45.9	70.7	345.8
1967	66.9	81.2	127.0	89.9	397.7
1968	50.7	158.4	98.7	44.2	318.3
1969	143.1	83.5	47.5	56.4	403.6
1970	141.5	82.2	123.5	139.5	453.7
1971	133.1	158.3	22.8	79.8	481.0
1972	155.2	166.7	79.3	104.2	471.6
1973	162.6	101.0	103.8	89.8	400.8
1974	107.1	117.5	86.4	55.1	370.0
1975	104.7	88.4	121.8	90.3	430.0
1976	167.6	80.1	92.0	117.7	439.1
1977	84.4	92.0	145.0	83.9	469.1
1978	150.6	110.3	124.3	184.6	452.8
1979	146.4	41.3	80.5	131.0	436.1
1980	117.2	80.4	107.5	81.3	431.8
1981	146.7	101.1	102.7	109.9	450.5
1982	191.7	53.4	95.5	48.3	262.8
1983	82.3	58.8	73.4	63.1	289.0
1984	108.7	37.9	***79.3***	***138.3***	584.1
1985	***170.1***	***152.7***	***123.0***	154.4	620.2
1986	134.3	168.7	162.8	102.3	383.7
1987	119.8	78.7	82.9	144.8	533.4
1988	148.8	85.0	154.8	67.5	447.4
1989	151.6	119.8	108.5	69.7	313.5
1990	131.5	75.6	36.7	18.0	351.1
1991	154.3	73.7	105.1	131.7	398.0
1992	***116.5***	***100.6***	49.1	78.6	452.8
1993	191.5	79.1	103.6	98.3	431.1
1994	120.1	110.7	102.0	116.6	366.9
1995	69.5	79.1	101.7	98.2	397.2
1996	141.5	62.9	94.6	125.4	637.9
1997	179.8	135.8	196.9	60.2	299.0
1998	113.8	72.2	52.8	32.6	403.1
1999	108.3	125.6	136.6	65.7	411.8
2000	126.9	114.1	105.1	99.6	498.3
2001	151.8	111.5	135.4	57.4	363.4
2002	117.0	107.0	82.0	134.6	547.7
2003	163.4	114.9	134.8	80.6	536.6
2004	234.0	160.2	61.8	134.2	440.4
2005	52.5	199.0	54.7	81.6	329.8
2006	137.7	46.9	63.6	79.5	420.3
2007	130.1	58.1	152.6	51.0	



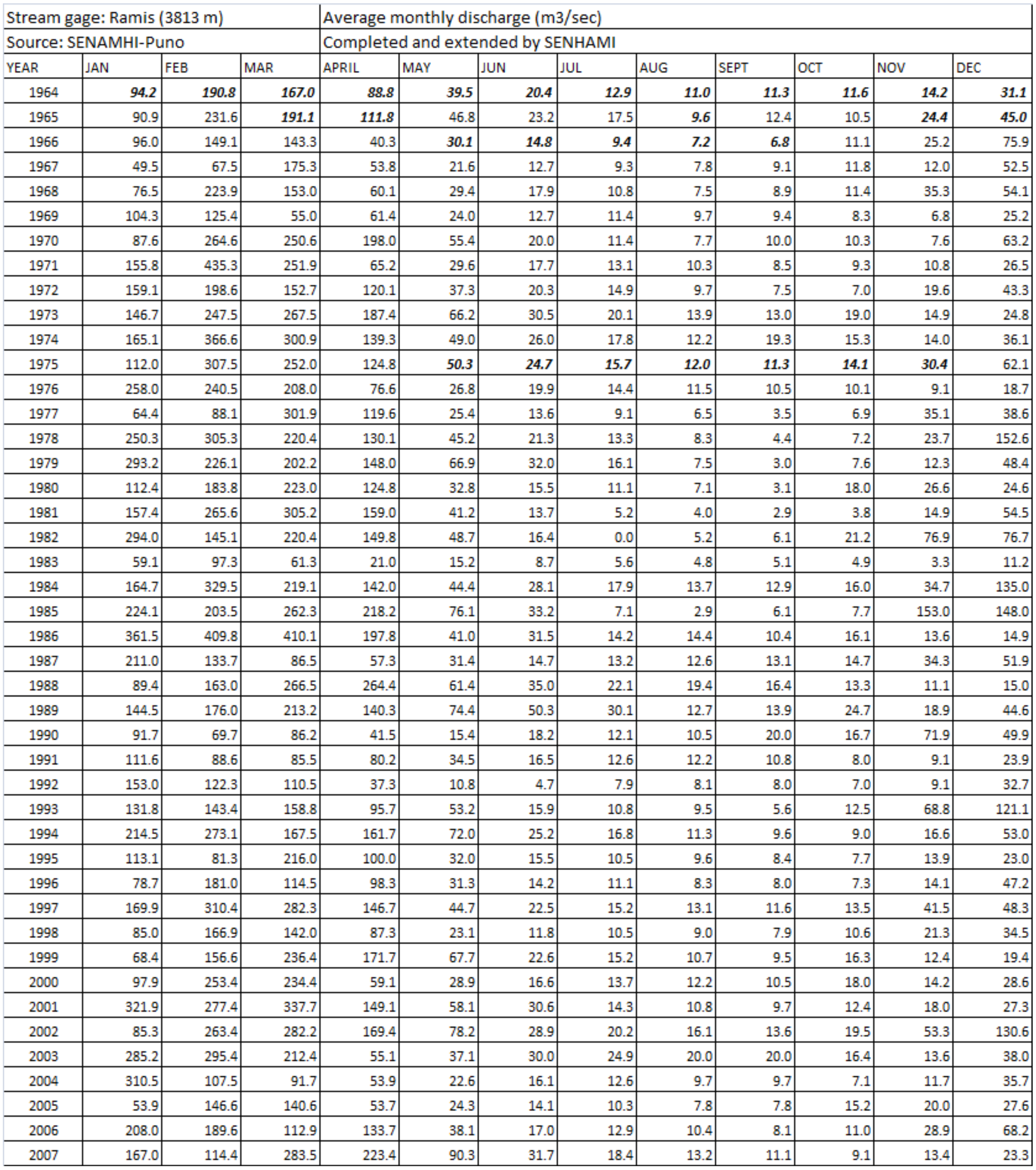
Station: Pucara (3910 m)			Monthly Precipitation Total (mm)		
Source: SENAMHI					
YEAR	JAN	FEB	MAR	DEC	total Dec-Mar
1964	50.4	61.2	155.2	88.8	455.4
1965	146.3	68.4	151.9	220.1	576.5
1966	64	148.5	143.9	91.7	447.5
1967	61.5	106.9	187.4	205.2	698.4
1968	191.8	213.8	87.6	104.6	330.9
1969	125.8	86.7	13.8	92.6	408.5
1970	125.9	55.4	134.6	232.9	709.6
1971	173.1	259.7	43.9	82.8	446.2
1972	187	101.9	74.5	92.7	617.5
1973	173.7	147.5	203.6	52.4	487.3
1974	213.4	114.8	106.7	80.2	543.2
1975	163.4	181.4	118.2	123.3	595.1
1976	213.8	155.8	102.2	115.5	629.7
1977	125.2	213.7	175.3	90	643.3
1978	228.4	180.7	144.2	227.8	596.9
1979	186.1	64.1	118.9	163.2	506.1
1980	117	93.8	132.1	53.5	508.2
1981	184.4	145.6	124.7	110.3	452.3
1982	133	82.2	126.8	69.1	251.3
1983	73.9	74.2	34.1	100.2	816.2
1984	337.3	261.6	117.1	195.4	607
1985	178	163.4	70.2	186	726.8
1986	152.7	196	192.1	121.6	440.1
1987	176	83.8	58.7	78.4	517
1988	142.6	114.7	181.3	130.9	450.8
1989	129.5	80.3	110.1	111.1	470.9
1990	147.1	127.2	85.5	85.5	483.1
1991	114.8	132	150.8	69.3	450.6
1992	221.6	105	54.7	151.1	508.1
1993	184.8	39.6	132.6	147.4	618.3
1994	158	199.7	113.2	90.1	344
1995	98.1	76.9	78.9	106	469.4
1996	158.7	82.1	122.6	93.1	546.2
1997	160.3	126.3	166.5	118	431.1
1998	86.1	118.4	108.6	31.6	374.7
1999	83.8	111.6	147.7	46.2	424.3
2000	126.9	143.3	107.9	105.7	751.4
2001	302.9	117.9	224.9	108.3	564.1
2002	144.7	197.8	113.3	192	601.1
2003	188.3	98.6	122.2	137.7	771.9
2004	302.7	227.4	104.1	136.7	487.8
2005	63	164.8	123.3	112	567.5
2006	240.7	90.2	124.6	104.6	427.7
2007	63.2	62.3	197.6	65.3	

Station: Taraco (3820 m)			Monthly Precipitation Total (mm)		
Source: SENAMHI					
YEAR	JAN	FEB	MAR	DEC	Total Dec-Mar
1964				33.5	
1965	128.3	100.1	129.3	118.7	391.2
1966	80.5	106	46.4	84	351.6
1967	34.9	118.2	64.7	126.1	301.8
1968	21.1	110	74.5	79.1	331.7
1969	100.5	49.6	43.3	71.6	272.5
1970	128.5	79.9	83.6	85.6	363.6
1971	92.1	118.7	45.5	34.9	341.9
1972	200.5	78.7	81.3	81.1	395.4
1973	149.3	68.2	103.4	51.4	402
1974	225.8	98.8	101.8	84.1	477.8
1975	102	87.3	139	148.3	412.4
1976	163.4	80.3	40.8	49.3	432.8
1977	86.3	200.8	120	78	456.4
1978	183.7	135.9	72.2	128.2	469.8
1979	198.7	75.4	119.8	77.4	522.1
1980	56.2	79	84.9	40.5	297.5
1981	148.5	160.1	135.3	77.9	484.4
1982	166.1	65.6	55.8	46.6	365.4
1983	126.1	25.4	26.3	71.2	224.4
1984	256.7	207.6	123.1	178.4	658.6
1985	151.3	177	95.3	220.8	602
1986	194.5	217.9	233.8	140.9	867
1987	285.4	38.5	40.8	67.8	505.6
1988	119.2	49.8	177.3	108.3	414.1
1989	126.4	69.1	76	54.5	379.8
1990	166.4	79.8	24.8	192.1	325.5
1991	168.7	102.6	126.9	63.7	590.3
1992	137.7	116.4	26.6	79	344.4
1993	149.5	50.7	98.9	123.8	378.1
1994	140.6	196.4	76.6	98.4	537.4
1995	135.7	179.8	129.1	107.1	543
1996	74.2	51	79.1	98.2	311.4
1997	190.2	146.4	109	92	543.8
1998	123.6	98.6	58.4	34.3	372.6
1999	99.6	96	115.8	38.6	345.7
2000	135	73.4	74	54	321
2001	111.8	109.8	14.4	79.6	290
2002	93.6	126.2	63.8	53.6	363.2
2003	197	100.2	102.4	78.2	453.2
2004	157.2	127	107	47.2	469.4
2005	78.4	110.6	105.4	108.2	341.6
2006	187.6	47.8	66.2	125.6	409.8
2007	89.2	46.2	123.5	69.8	384.5

Station: Munani (3948 m)			Monthly Precipitation Total (mm)		
Source: SENAMHI					
YEAR	JAN	FEB	MAR	DEC	Total Dec-Mar
1964				***63.9***	227.0
1965	106.6	56.5	0	85.1	311.0
1966	78.8	92.2	54.9	26.7	146.3
1967	17.7	43.3	58.6	230.4	449.6
1968	75.7	123.9	19.6	31.6	315
1969	135	86.6	61.8	86.7	435.6
1970	213.3	66.1	69.5	175.6	637.8
1971	135.5	252.4	74.3	38.8	250.6
1972	148.6	47.2	16	84.4	313.6
1973	81.8	88.2	59.2	38.4	259.6
1974	100	96	25.2	69.8	281
1975	61	76	74.2	185.6	1202.2
1976	337.9	366.4	312.3	132.2	478.1
1977	96.4	128.9	120.6	95	554.5
1978	186.5	157.3	115.7	254.8	604
1979	226	45.9	77.3	133.3	438
1980	114.5	77.7	112.5	49.6	467.4
1981	195.8	90.4	131.6	93.6	362
1982	120.3	70.1	78	22.4	240
1983	89.2	83.3	45.1	53.9	582
1984	249.3	188.3	90.5	154.6	511.7
1985	122.8	137.5	96.8	223.1	666.4
1986	88.6	192.2	162.5	111.6	471.4
1987	199.6	101	59.2	33	345.7
1988	118.7	112.7	81.3	123.2	511.3
1989	112.8	186.1	89.2	57.1	281.6
1990	136.8	63.7	24	67.9	419.9
1991	129.2	83.6	139.2	116.3	441.8
1992	188.3	91.4	45.8	111.7	408.7
1993	157	56.3	83.7	104.3	394.4
1994	104	94.3	91.8	110.2	556.6
1995	154.5	181.8	110.1	96.2	389
1996	153.9	70.1	68.8	61.4	569.4
1997	181.6	109.2	217.2	32.5	297.8
1998	62.5	96.4	106.4	41.6	290.9
1999	83.6	40.5	125.2	92.9	392.2
2000	119.8	98.1	81.4	108.6	554
2001	173	109.2	163.2	87	397.7
2002	90.3	115.9	104.5	125.7	561.3
2003	225.1	102.3	108.2	117.4	645.4
2004	281.7	129.1	117.2	133.5	540.9
2005	98.6	224.2	84.6	68.2	391
2006	203.9	61.9	57	144.1	382.8
2007	104	15.6	119.1	55.4	

APPENDIX B

STREAMFLOW DATA



Stream gage: Ramis (3813 m)				Average monthly discharge (m3/sec)								
Source: SENAMHI-Puno				Completed and extended by SENHAMI								
YEAR	JAN	FEB	MAR	APRIL	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
1964	***94.2***	***190.8***	***167.0***	***88.8***	***39.5***	***20.4***	***12.9***	***11.0***	***11.3***	***11.6***	***14.2***	***31.1***
1965	90.9	231.6	***191.1***	***111.8***	46.8	23.2	17.5	***9.6***	12.4	10.5	***24.4***	***45.0***
1966	96.0	149.1	143.3	40.3	***30.1***	***14.8***	***9.4***	***7.2***	***6.8***	11.1	25.2	75.9
1967	49.5	67.5	175.3	53.8	21.6	12.7	9.3	7.8	9.1	11.8	12.0	52.5
1968	76.5	223.9	153.0	60.1	29.4	17.9	10.8	7.5	8.9	11.4	35.3	54.1
1969	104.3	125.4	55.0	61.4	24.0	12.7	11.4	9.7	9.4	8.3	6.8	25.2
1970	87.6	264.6	250.6	198.0	55.4	20.0	11.4	7.7	10.0	10.3	7.6	63.2
1971	155.8	435.3	251.9	65.2	29.6	17.7	13.1	10.3	8.5	9.3	10.8	26.5
1972	159.1	198.6	152.7	120.1	37.3	20.3	14.9	9.7	7.5	7.0	19.6	43.3
1973	146.7	247.5	267.5	187.4	66.2	30.5	20.1	13.9	13.0	19.0	14.9	24.8
1974	165.1	366.6	300.9	139.3	49.0	26.0	17.8	12.2	19.3	15.3	14.0	36.1
1975	112.0	307.5	252.0	124.8	***50.3***	***24.7***	***15.7***	***12.0***	***11.3***	***14.1***	***30.4***	62.1
1976	258.0	240.5	208.0	76.6	26.8	19.9	14.4	11.5	10.5	10.1	9.1	18.7
1977	64.4	88.1	301.9	119.6	25.4	13.6	9.1	6.5	3.5	6.9	35.1	38.6
1978	250.3	305.3	220.4	130.1	45.2	21.3	13.3	8.3	4.4	7.2	23.7	152.6
1979	293.2	226.1	202.2	148.0	66.9	32.0	16.1	7.5	3.0	7.6	12.3	48.4
1980	112.4	183.8	223.0	124.8	32.8	15.5	11.1	7.1	3.1	18.0	26.6	24.6
1981	157.4	265.6	305.2	159.0	41.2	13.7	5.2	4.0	2.9	3.8	14.9	54.5
1982	294.0	145.1	220.4	149.8	48.7	16.4	0.0	5.2	6.1	21.2	76.9	76.7
1983	59.1	97.3	61.3	21.0	15.2	8.7	5.6	4.8	5.1	4.9	3.3	11.2
1984	164.7	329.5	219.1	142.0	44.4	28.1	17.9	13.7	12.9	16.0	34.7	135.0
1985	224.1	203.5	262.3	218.2	76.1	33.2	7.1	2.9	6.1	7.7	153.0	148.0
1986	361.5	409.8	410.1	197.8	41.0	31.5	14.2	14.4	10.4	16.1	13.6	14.9
1987	211.0	133.7	86.5	57.3	31.4	14.7	13.2	12.6	13.1	14.7	34.3	51.9
1988	89.4	163.0	266.5	264.4	61.4	35.0	22.1	19.4	16.4	13.3	11.1	15.0
1989	144.5	176.0	213.2	140.3	74.4	50.3	30.1	12.7	13.9	24.7	18.9	44.6
1990	91.7	69.7	86.2	41.5	15.4	18.2	12.1	10.5	20.0	16.7	71.9	49.9
1991	111.6	88.6	85.5	80.2	34.5	16.5	12.6	12.2	10.8	8.0	9.1	23.9
1992	153.0	122.3	110.5	37.3	10.8	4.7	7.9	8.1	8.0	7.0	9.1	32.7
1993	131.8	143.4	158.8	95.7	53.2	15.9	10.8	9.5	5.6	12.5	68.8	121.1
1994	214.5	273.1	167.5	161.7	72.0	25.2	16.8	11.3	9.6	9.0	16.6	53.0
1995	113.1	81.3	216.0	100.0	32.0	15.5	10.5	9.6	8.4	7.7	13.9	23.0
1996	78.7	181.0	114.5	98.3	31.3	14.2	11.1	8.3	8.0	7.3	14.1	47.2
1997	169.9	310.4	282.3	146.7	44.7	22.5	15.2	13.1	11.6	13.5	41.5	48.3
1998	85.0	166.9	142.0	87.3	23.1	11.8	10.5	9.0	7.9	10.6	21.3	34.5
1999	68.4	156.6	236.4	171.7	67.7	22.6	15.2	10.7	9.5	16.3	12.4	19.4
2000	97.9	253.4	234.4	59.1	28.9	16.6	13.7	12.2	10.5	18.0	14.2	28.6
2001	321.9	277.4	337.7	149.1	58.1	30.6	14.3	10.8	9.7	12.4	18.0	27.3
2002	85.3	263.4	282.2	169.4	78.2	28.9	20.2	16.1	13.6	19.5	53.3	130.6
2003	285.2	295.4	212.4	55.1	37.1	30.0	24.9	20.0	20.0	16.4	13.6	38.0
2004	310.5	107.5	91.7	53.9	22.6	16.1	12.6	9.7	9.7	7.1	11.7	35.7
2005	53.9	146.6	140.6	53.7	24.3	14.1	10.3	7.8	7.8	15.2	20.0	27.6
2006	208.0	189.6	112.9	133.7	38.1	17.0	12.9	10.4	8.1	11.0	28.9	68.2
2007	167.0	114.4	283.5	223.4	90.3	31.7	18.4	13.2	11.1	9.1	13.4	23.3

APPENDIX C

R SCRIPT FOR NDVI REGRESSION MODEL M.2 $NDVI_{CELL}$

```
#REGRESSION CALLS
fun_pvalue<- function (fstat){
    pf(fstat[1], fstat[2], fstat[3], lower.tail=FALSE)}

Fun4 <- function (x){
    lmf<- lm (x ~YearCE + PrecipCE + TempCE + JdayCE)
    c(lmf$coefficients[2],lmf$coefficients[3],lmf$coefficients[4],lmf$coefficients[5],
        summary(lmf)$r.squared,
        anova(lmf)$"Pr(>F)"[1], anova(lmf)$"Pr(>F)"[2],anova(lmf)$"Pr(>F)"[3],
anova(lmf)$"Pr(>F)"[4],
        fun_pvalue(summary(lmf)$fstatistic), summary(lmf)$fstat[3])
}

Final_regression2 = calc (Brick_crop, Fun4)

#DATA & STEPS IN FINAL REGRESSION
#1 Read data using Raster Package
library (raster)
filename =
("F:\\Meagan\\NDVI_Analysis_Full\\Full_Model_Analysis\\BIL_Files\\Nunoa_NDVI_BIL")
NDVI_Brick = brick (filename)
class(NDVI_Brick)
str(NDVI_Brick)

#2 Using calculate function to set values >20000 to NA
fun<- function(x) { x[x>20000] <- NA; return(x) }
NDVI_Brick_NA<- calc(NDVI_Brick, fun)

#3 Bring in CSV files
precipC =
read.csv("F:\\Meagan\\NDVI_Analysis_Full\\Full_Model_Analysis\\precip_10_crop.csv")
tempC =
read.csv("F:\\Meagan\\NDVI_Analysis_Full\\Full_Model_Analysis\\Temp_10_crop.csv")
jdayC =
read.csv("F:\\Meagan\\NDVI_Analysis_Full\\Full_Model_Analysis\\Julian_Day_10_crop.csv")
Year = precipC$Year

#4 Center data
PrecipCE = precipC$Log - mean(precipC$Log, na.rm= TRUE)
YearCE = precipC$Year - mean(precipC$Year, na.rm=TRUE)
TempCE = tempC$Log - mean(tempC$Log, na.rm= TRUE)
JdayCE = jdayC$Julian_Day - mean(jdayC$Julian_Day, na.rm= TRUE)
```

```
#5 Exclude 1992 and 1995 in brick with NAs
Brick_crop<- dropLayer (NDVI_Brick_NA, c(14,17))
```

 # WRITE RASTER TO GEOTIFF

```
writeRaster  (Final_regression2, filename = "Regress_NDVI.tif", format = "GTiff", overwrite = TRUE)
```

```
class       : RasterBrick
dimensions  : 3004, 2528, 11  (nrow, ncol, nlayers)
resolution  : 30, 30  (x, y)
extent      : 285795, 361635, 8353225, 8443345  (xmin, xmax, ymin, ymax)
coord. ref. : +proj=utm +zone=19 +south +ellps=WGS84 +datum=WGS84 +units=m +no_defs +towgs84=0,0,0
values      : F:\Meagan\NDVI_Analysis_Full\Full_Model_Analysis\Regress_NDVI.tif
minvalues  : -3.4e+03 -5.4e+05 -2.8e+05 -2.1e+03  2.4e-04  8.6e-11  1.1e-10  3.3e-06  2.2e-08  7.1e-10 ...
max values  :   2222 378645 286967   4628     1     1     1     1     1     1 ...
```

#RESULTS

Raster_1	coefficient YearCE
Raster_2	coefficient PrecipCE (log)
Raster_3	coefficient TempCE (log)
Raster_4	coefficient JdayCE
Raster_5	r-square
Raster_6	p-value (f-stat) YearCE
Raster_7	p-value (f-stat) PrecipCE (log)
Raster_8	p-value (f-stat) TempCE (log)
Raster_9	p-value (f-stat) JdayCE
Raster_10	p-value (f-stat) overall model
Raster_11	degrees of freedom (minus 4 for the variables)

```
##Re-run regression to get the output for intercept to make error maps (this was added on 12/5/2011)
Fun5 <- function (x){
    lmf<- lm (x ~YearCE + PrecipCE + TempCE + JdayCE)
    c(lmf$coefficients[1])
}

Final_regression5 = calc (Brick_crop, Fun5)
plot (Final_regression5)

#Write "Final_regression5" results to tiff for reading in ArcMAP
setwd ("F:\\Meagan\\NDVI_Analysis_Full\\Full_Model_Analysis\\GIS_regression")
writeRaster (Final_regression5, filename = "Intercept_NDVI.tif", format = "GTiff", overwrite = TRUE)

#Results:
```

```
class       : RasterLayer
dimensions  : 3004, 2528, 7594112  (nrow, ncol, ncell)
resolution  : 30, 30  (x, y)
extent      : 285795, 361635, 8353225, 8443345  (xmin, xmax, ymin, ymax)
coord. ref. : +proj=utm +zone=19 +south +ellps=WGS84 +datum=WGS84 +units=m +no_defs
+towgs84=0,0,0
values      :
F:\Meagan\NDVI_Analysis_Full\Full_Model_Analysis\GIS_regression\Intercept_NDVI.tif
min value   : -29423.55
max value   : 21882.21
```

APPENDIX D

COMMUNITY MAPPING QUESTIONAIRE GUIDELINE

A. <u>RECURSOS NATURALES: ID recursos naturales críticos, describir su función, la distribución y variación espacial y temporal</u>

1. Which natural resources are critical to the functioning of the herding system (for example humedales, rivers, springs (manantiales), and vegetation)?
   ¿Qué recursos naturales son fundamentales para el funcionamiento del sistema de pastoreo (por ejemplo, Bofedales (humedales), ríos, manantiales (ojos de Agua), vegetación)?

2. Why are these resources important? ¿Por qué son importantes estos recursos? What services do they provide? ¿Qué beneficios ofrecen?

3. What are the important vegetation species?
   ¿Cuáles son las especies vegetales más importantes?

4. How are these natural resources distributed spatially throughout the land?
   ¿Cómo se distribuyen espacialmente los recursos naturales en la tierra?
   a. Can you draw the bofedales (humedales) on the on the map and label them with a B? ¿Puede dibujar los humedales en el mapa y etiquetarlos con una B?

   b. Can you draw any springs on the map and label them with an M?
      ¿Puede dibujar los manantiales en el mapa y etiquetarlos con una M?

5. How do these resources vary from dry season to wet season?
   ¿De qué forma varían estos recursos de la estación seca a la estación húmeda?
   a. Please draw on the map the location of the wet season pastures.
      Por favor, dibuje en el mapa la ubicación de los pastos de estación húmeda.

   b. Please draw on the map the location of the dry season pastures.
      Por favor, dibuje en el mapa la ubicación de los pastos de estación seca.

   c. Are some resources, such as manantiales present only in the wet season? Algunos recursos como los Manantiales están solamente presentes en la temporada de lluvias?

   d. How does the quality of vegetation differ in the dry season from the wet season?
      ¿De qué manera difiere la calidad de la vegetación en la estación seca y la temporada de lluvias?

e. How do the humedales differ in the dry season from the wet season? ¿Cómo difieren los humedales de la estación seca de la temporada de lluvias?

B. Herds: Characterize herd demographics and health issues and resource needs for each species
Rebaños: Caracterice la demografía, la salud y los recursos necesarios para cada especie

1. Does the community have written records of the number of alpaca, llama, sheep and cattle in the community over time?
¿Hay registros en la comunidad del número de alpacas, llamas, ovinos y vacunos en la comunidad a lo largo del tiempo?

   May I see the records?
   ¿Podría ver los registros?

   May I record the information?
   ¿Podría grabar la información?

2. What are the main species of vegetation that sustain alpaca?
¿Cuáles son las principales especies vegetales que sustentan la alpaca?

3. What are the main species of vegetation that sustain llama?
¿Cuáles son las principales especies vegetales que sustentan la llama?

4. What are the main species of vegetation that sustain sheep?
¿Cuáles son las principales especies especies vegetales que sustentan las ovejas?

5. What are the main species of vegetation that sustain cattle?
¿Cuáles son las principales especies especies vegetales que sustentan el ganado?

6. Is any fodder (barley or alfalfa) grown for the animals?
¿Existen forrajes (cebada o alfalfa) producidos para los animales?

   What fodder and for what animals?
   Qué tipo de forraje y para qué animales?

C. Land Management: Ordenamiento Territorial

1. What are pasture use patterns and herd rotation practices throughout the year?
¿Cuáles son los patrones de uso de los pastos y los patrones de rotación de los rebaños a lo largo del año? Mapa.

2. Where do alpaca, llama, sheep, cattle graze in the wet season? Dry season?

¿Dónde alpaca, llama, ovejas, y vacas pastan en la temporada de lluvias? Estación seca? Mapa.

3. At the community level how do they manage the pastures (fertilization, burning, transplanting)?
   A nivel comunitario, ¿cómo se las gestionan los pastos (fertilización, quema, muda)?

4. When are these management activities performed?
   ¿Cuándo se realiza la gestión de estas actividades?

5. How does the community manage water resources?
   ¿De qué manera la comunidad gestiona los recursos hídricos?
   a. Do they use irrigation? ¿Utilizan riego?
   b. Do they withdraw water from the rivers? ¿Se retira agua de los ríos?
   c. Do they have wells? ¿Tienen los pozos?

6. How does the community manage humedales (maintaining, expanding, transplanting)?
   ¿Cómo gestiona la comunidad los humedales (mantenimiento, ampliación, muda)?

7. What is the seasonal cycle for managing humedales?
   ¿Cuál es el ciclo estacional para la gestión de humedales?

D. <u>Economic and Production Systems: Economía y Sistemas de Producción</u>

1. Does the community grow crops? If so which crops?
   ¿Tiene la comunidad cultivos? Si es así, qué los cultivos?

2. Are these crops grown on community land or private plots?
   ¿Dónde son estos cultivos? En las tierras comunitarias o en parcelas privadas?

3. How many “masas” are in the community?
   ¿Cuántas "masas" hay en la comunidad?

4. Which crops and what percentage of each of these crops are for subsistence (human use)?
   ¿Qué cultivos y qué porcentaje de cada uno de estos cultivos son para la subsistencia (uso humano)?

5. Which and what percentage of crops, if any is for market?
   ¿Cuáles y qué porcentaje de los cultivos, son para el mercado?

6. Does the community acquire seed, fertilizer, or pesticides from outside the community?

¿La comunidad necesita adquirir semillas, fertilizantes, plaguicidas fuera de la comunidad? Si es así,

   a. Are these products acquired at the community level or the individual level?
      ¿Se trata de productos adquiridos comunitariamente o individualmente?

   b. How do they acquire each product (purchase, barter)?
      ¿Cómo se adquieren los productos (compra, permuta)?

8. Animal products – what animal products are used for subsistence?
   Productos de origen animal - ¿Qué productos de origen animal se utilizan para la subsistencia?

9. What animal products are for market?
   ¿Qué productos de origen animal son destinados al mercado?

10. In what quantity? ¿En qué cantidad?
11.
12. Are these products sold? ¿Se venden los productos?

12. Does the community engage in other economic activities such as mining?
    ¿Participa la comunidad en otras actividades económicas como la minería?

13. Does the community receive financing for any of the activities?
    ¿La comunidad recibe financiación de ninguna de las actividades? If so, which activities? En caso afirmativo, en qué actividades?

E. <u>External Services:</u> <u>Servicios Externos</u>

   A. Are any NGOs currently working in the community?
      ¿Hay organizaciones no gubernamentales que trabajan en la comunidad?

      If so what NGOs and for what purpose? Si es así lo que las ONG y con qué fin?

   2. Are any government agencies working in the community?
      ¿Existen organismos gubernamentales que trabajan en la comunidad?

      If so, which and what are the activities? Si es así, ¿cuáles y cuáles son las actividades?

   3. Are any other outside services currently being provided to the community?
      ¿Hay otros servicios de fuera a la comunidad que se prestan actualmente a la comunidad?

F. <u>Characterize herders knowledge and perception of the environment</u>
   <u>Caracterizar el conocimiento y la percepción sobre el medio ambiente de los pastores</u>

Sustainability Aspects Aspectos de Sostenibilidad

1. Does the community use an RUO (Reducion unidad ovino) index?
   ¿Tiene la comunidad un uso RUO (unidad ovino Reducion) índice?

2. What density of alpaca can the community land sustain?
   ¿Qué densidad de alpacas la tierra de la comunidad puede sostener?

   What density of llama? ¿Qué densidad de llamas? Sheep? Cattle? De ovejas? De ganado?

   What number of alpaca, llama, sheep, cattle is considered ecologically sustainable. That is, what number of each species can be supported by the natural resources on their community lands with minimum degradation?

   ¿Qué número de alpacas, llamas, ovinos, bovinos se considera ecológicamente sostenible? Es decir, qué número de individuos de cada especie es soportable con los recursos naturales disponibles en la comunidad con un mínimo degradación?

3. Is there a difference in carrying capacity in the tiempo de lluvias (para pacha – DJFM) and the estacion de secas (ch'aki pacha – April-Nov.)?
   ¿Hay una diferencia en la capacidad de carga en la época lluviosa? (para pacha - DJFM) y la estacion de seca? (ch'aki pacha - April-Nov.)?

4. Currently (July) what does the community think of the total population of animals on community land?
   Actualmente (julio) qué piensa la comunidad de la población de animales en tierras comunitarias?

   Is this a “good” density for ecological sustainability? Is this a “good” density for economical reasons?
   ¿Es esta una "buena" densidad para la sostenibilidad ecológica?

   ¿ Es esta una "buena" densidad del punto de vista económico?

G. Changes in local weather, hydrology, land use/cover, and the herding and social systems
Los cambios en el clima local, la hidrología, el uso del suelo/cobertura y los sistemas de pastoreo y social

Is there less precipitation throughout the year?
¿Hhay menos precipitaciones a lo largo del año?

Is there a shift in the onset of precipitation?
¿Hay algún cambio al inicio de la precipitación?

Is there less streamflow? ¿Hay menos caudal?

Is there less surface water (related to the frosts)?
¿Hay menos agua superficial (relacionda con las heladas)?

Is there less water in the form of springs?
¿Hay menos agua en forma de manantiales?

Are humedales changing in quality/quantity?
La calidad o cantidad de humedales cambia?

What were the humedales like when the community first formed?
¿Cómo eran los humedales cuando se formó la comunidad?

What were they like before?
Cómo eran como antes?

What are they like now? ¿Cómo son ahora?

Are the vegetation species in the humedales changing?
¿La vegetación de los humedales está cambiando? Si es así, ¿cómo?

Are there differences in the seasons and other weather related phenomena such as winds and frost?
¿Existen diferencias en las estaciones y el clima y otros fenómenos relacionados como los vientos y las heladas?

Are there changes in the seasons?
¿Hay cambios en las estaciones?
tiempo de lluvias (para pacha – DJFM)
estacion de secas (ch'aki pacha – April-Nov)
estación de heladas – (qasa pacha, chirawa pacha –April-August)

What changes have occurred in land management practices? Burning, irrigation, pesticide use, etc.

¿Qué cambios se han producido en las prácticas de manejo del suelo?
Quemas, riego, uso de pesticidas, etc

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