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Addressing water availability and climate change issues in the Cordillera Blanca, Peru through technical analysis and community building strategies

by

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Addressing water availability and climate change issues in the Cordillera Blanca, Peru through technical analysis and community building strategies

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Thesis

Presented to the Faculty of the Graduate School of

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Dedication

This work is dedicated to my family for their boundless support and encouragement, to my friends for the spirit they add to my life, and to everyone I have met whose passion for their work has inspired me to keep learning.

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I would like to acknowledge the students and faculty of the Environmental and Water Resources Engineering Program for their technical and emotional support. I would like to thank my advisor, Dr. Daene McKinney for his guidance and encouragement of my research and studies, as well as the McKinney research group for their help with my model and language translation. I would also like to acknowledge the CRWR graduate student research group for their moral support and programming expertise.

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December 3, 2010

Abstract

Addressing water availability and climate change issues in the Cordillera Blanca, Peru through technical analysis and community building strategies

Laura K. Read, M.S.E.

The University of Texas at Austin, 2010

Supervisor: Daene McKinney

Accelerated tropical glacial melt on the order of 15-18 meters per year since the 1980's in Peru's Cordillera Blanca region is alarming rural communities and urban authorities, causing them to seek technical support for risk management and adaptation actions. Melting glaciers coupled with changing seasonal rainfall patterns has left many rural communities in the upper Rio Santa basin lacking sufficient fresh water supply to support livestock, irrigation and human consumption. In response to these concerns, a Water Evaluation And Planning (WEAP) model was created by the Stockholm Environmental Institute for simulating glacial melt and flow in the Santa River. Through input parameters of climate, glacial runoff, water use, crop acreage, soil type and groundwater interactions, WEAP has the flexibility to model scenarios for different

operation schemes. These schemes allow users to determine the most effective ways to regulate their resources and explore adaptation actions (e.g. altering farming practices and building reservoirs) for future planning.

This project improved the existing model by including observed water demand data for irrigation, and evaluating the Climate Forecast System Reanalysis (CFSR) dataset to serve as a potential source for filling gaps in the historic climate record. These improvements added robustness to the model and correlated well with historic stream flow at La Balsa (R^2 = 0.78 , Nash = 0.68). Two scenarios were explored where (1) a 50% reduction in potato crop was replaced with maize for each sub-basin, and (2) a 10% reduction in precipitation was applied over the upper basin. Results show that the WEAP model is sensitive to changes in crop type and rainfall at the sub-basin scale, an encouraging finding for future exploration. This investigation enables communities to base future decisions on technical evidence and provides a basis for educating citizens on the importance of evaluating their available resources under climate change projections.

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“Look at me from the depths of the earth,
Tiller of fields, weaver, reticent shepherd,
Groom of totemic gaunacos,
Mason high on your treacherous scaffolding,
Iceman of Andean tears,
Jeweler with crushed fingers,
Farmer anxious among his seedlings,
Potter wasted among his clays—
Bring to the cup of this new life
Your ancient buried sorrows.”
-Pablo Neruda, from Canto XII: The Heights of Macchu Picchu

Chapter 1: Introduction

As science and technology move toward information sharing and multidisciplinary research, no longer is it taboo to discuss climate change as a real phenomenon affecting environmental processes and communities around the world. The Earth’s surface is heating, sea level is rising, species are altering migration patterns, crop production is finding new ground, and people are taking notice of subtle changes they once cast aside as business as usual (IPCC 2007). With the development of interest groups, research based organizations and government policies focused on addressing climate issues, climate change has opened important lines of communication between scientists, engineers and policy makers, encouraging them to develop interdisciplinary frameworks.

Society can benefit from interdisciplinary partnerships as they foster holistic decision-making and information sharing to the public. For example, research on the effects of anthropogenic carbon dioxide emissions on temperature have led renewable energy enthusiasts, habitat ecologists, glaciologists and policy makers to join forces, conduct field studies and implement mitigation and adaptation practices. This process has occurred in Central Peru, where glacial melt in the tropical Cordillera Blanca mountain range has sparked research collaboration in science, engineering, and human geography in the region. Since water is a need across all disciplines, a central focus of these studies has been to understand how water availability and future development in the region will affect life in the Cordillera Blanca.

Increased attention to the severe climate change crisis in Peru has inspired international researchers to take a unique approach to solving these issues by which teams have funded new field monitoring instrumentation and spent significant time in the villages visiting and surveying indigenous members of the mountain communities. This research thesis strives to incorporate scientific assessment with elements of culture, community and practical application in order to convey the importance of approaching climate change issues with a range of perspectives and sustainable solutions.

1.1 A BRIEF HISTORY OF CLIMATE CHANGE

Although geologists have been monitoring large-scale changes in climate cycles for decades, concern over climate change began to increase when scientists separated recent history—since the Industrial Revolution—from the geologic time scale. From this, they observed accelerated trends in global temperature increase and a strong direct correlation between temperature and carbon dioxide concentrations in the atmosphere since measurements started in 1959 (Keeling, et al. 1976). Atmospheric carbon dioxide concentration has increased from 316 ppm in 1959 to 387 ppm in 2010, and increased by 1.90 ppm in 2010 (Earth System Research Laboratory 2010). The 2007 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) publication reports that mean surface temperature has increased by 0.65°C ± 0.2C from 1901 to 2005, the fastest increase since the 11th century; and, alarmingly, 11 of the 12 hottest years since 1850 occurred between 1995 and 2006, suggesting that the warming rate is accelerating even further (IPCC 2007). Figure 1 shows the temperature anomalies from 1880-2005 against the 1960-1991 mean as recorded by the Hadley Centre in the UK.

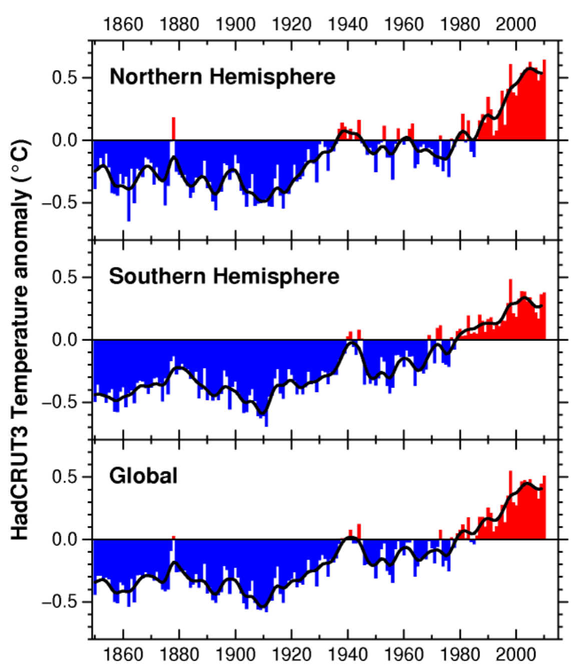

Figure 1: Air temperature anomalies (°C) from 1880-2005 based on 1961-1990 CRUT3 model (IPCC 2007)

As a driving mechanism for weather processes, increases in temperature cause changes in atmospheric moisture content, ocean circulation and seasonal cycles (IPCC

2007). Projections for carbon dioxide emissions show no sign of decline as fossil fuel usage is expanding to developing countries, implicating a continuation of temperature increases and positive feedbacks in albedo and weather cycles.

The primary source for climate related research is the Intergovernmental Panel on Climate Change, a consortium formed by the United Nations to report on "the scientific, technical and socio-economic information relevant for the understanding of human-induced climate change" (IPCC 2007). Since their inception in 1988 the IPCC has evolved into an extensive international collaborative effort, reporting on the physical science, impacts and adaptations, and mitigations related to climate change with contributions from over 800 authors. A significant contribution of their work is interpreting results from general circulation models (GCMs) for future prediction of temperature and precipitation on a regional scale. Figure 2 shows the projected mean temperature (top panel) and precipitation (lower panel) changes from 1980-1999 to 2080-2099 averaged by 21 models over South America for annual, summer (DJF) and winter (JJA) seasons (IPCC 2007). The models clearly indicate a positive trend for both annual and seasonal mean temperatures throughout Peru, and especially warmer winter months (JJA). Mean precipitation is projected to slightly increase during the rainy season (DJF) and slightly decrease in the dry season (JJA).

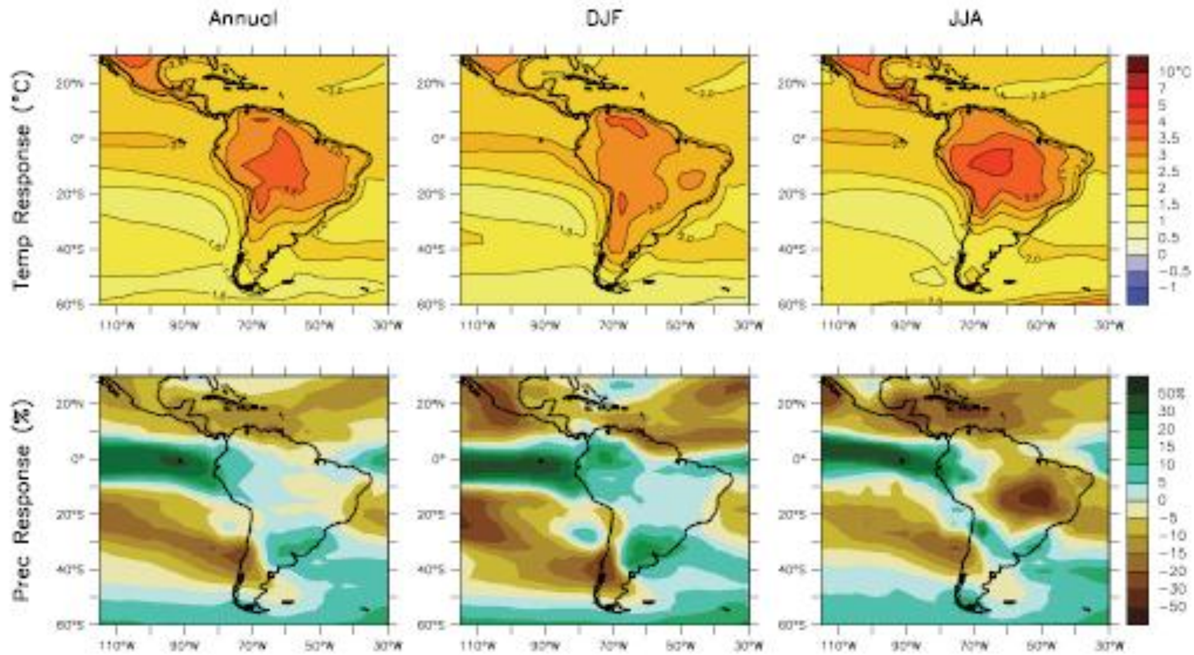

Figure 2: Projections of mean temperature (top panel) and precipitation (lower panel) percent changes from 1980-1999 to 2080-2099 by 21 GCMs over South America (IPCC 2007) for annual, summer (DJF) and winter (JJA) time periods

While the spatial resolution of GCMs are currently too coarse to be without considerable uncertainties, the IPCC puts forth great effort to account for sources of error resulting from instrumentation and resolution limitations. However, it should be noted that many scientists believe that the IPCC's estimates on risks and vulnerability are understated, and since governmental actions and international policies regarding climate change are largely based on findings by the IPCC, it is important to consider worst-case scenarios. In particular, processes driving microclimates in the high-altitude, low-latitude tropics are not well understood, especially in glacierized basins. As a response the IPCC's next technical report will have greater emphasis on results from regional climate models with higher spatial resolution to capture local phenomena that have been dampened on the global scale models.

1.2 The nature of tropical glaciers

The paradoxical nature of tropical glaciers is noted first in their namesake, where generally the tropics are associated with dense forests and beaches with rainy and humid weather. In contrast, tropical glaciers are found in low equatorial latitudes (mostly between ± 20°) providing mountain ecosystems in South America, Asia and Africa, and form/melt by different mechanisms than those in the mid-latitudes. Studies indicate that tropical glaciers are disappearing faster than their mid-latitude counterparts as increases in tropospheric carbon dioxide concentration have a greater impact on high altitude environments (Bradley, Vuille, et al. 2006).

Local climate in Peru's high elevation, low latitude tropical region is governed by two atmospheric circulation patterns: the El Niño Southern Oscillation (ENSO) and annual cycling of the Inter Tropical Convergence Zone (ITCZ). The ENSO cycles have been strongly correlated to bring warmer, drier conditions during El Niño years and colder, wetter conditions during La Niña years, affecting the glacial mass balance (Vuille, et al. 2008). Movement of the ITCZ causes a dry season (May to September) when the zone is away, leaving the Cordillera Blanca range to act as the separation barrier between the dry Pacific coast and wet Amazon rainforest. As the ITCZ approaches, winds mix and circulate humid air to cause seasonal shifts in precipitation and cloud cover (Kaser, et al. 2001). Historically, temperatures in this region are relatively steady and vary by less than 1°C annually, but recently climate scientists are concerned about how temperature increases due to anthropogenic forcing will affect the local energy budget and balance of the tropical atmosphere.

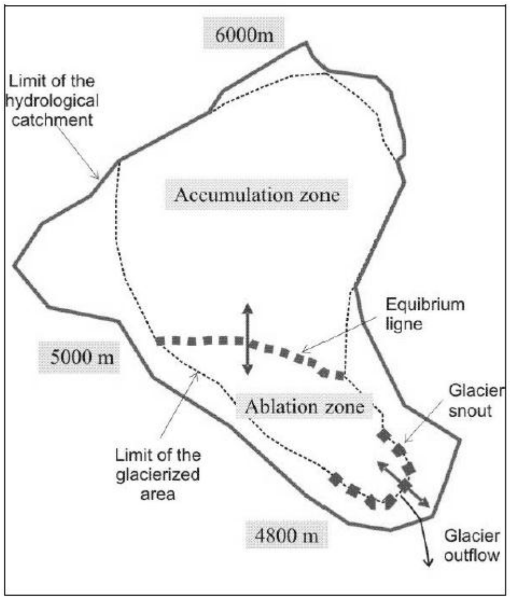

Figure 3: Schematic of a typical tropical glacier showing the zones and ELA (Chevallier, et al., 2004)

In the simplest description, glaciers are divided into two zones: the accumulation zone and the ablation zone. Figure 3 illustrates the schematic of a generic tropical glacier as found particularly in Peru. The accumulation zone is located higher in elevation and is defined as the area where precipitation falls as snow and glacial growth exceeds losses, whereas the ablation zone is defined as the region where annual losses exceed the gain due to snowfall (Encyclopedia Britannica, 2010). Between these two zones, the equilibrium line altitude (ELA) marks the latitude where the net balance of growth and loss is equal to zero (Braithwaite and Muller 1980). Since tropical climate cycles experience little temperature variation between the wet and dry seasons, glaciers accumulate and lose mass according to annual fluctuations in the ELA. When precipitation falls in the ablation zone, processes like radiation, temperature and latent heat contribute to melting in the tropics (Kaser and Osmaston 2002). Air temperatures in Peru's high Andes have increased by 0.1°C per decade over the past 70 years (Bradley, et al. 2009), and regionally scaled models indicate an even more rapid temperature increase of 0.35-0.39°C/decade from 1951 to 1999 (Mark and Seltzer 2005). These consistent increases in temperature cause a rise in atmospheric moisture, affecting cloud cover and ultimately long-wave radiation emissions back down to the surface. An albedo positive feedback mechanism reinforces this temperature rise in two ways: more ice is directly exposed as the snow cover melts, and as the snow extent melts and exposes darker surface areas, surface reflectivity decreases, enhancing absorption of the Sun's shortwave radiation (Bradley, Vuille, et al. 2006). The implications of these sensitivity characteristics are that minor perturbations in temperature and the energy budget can lead to large reductions in glacial mass causing a direct impact on stream flow and downstream processes.

1.3 Glacial impacts in Peru

Peru houses 70% of the world's tropical glaciers, making them especially prone to the adverse effects of climate change (Kaser and Osmaston 2002). Peru is ranked third in countries most at risk for climate change related disasters largely due a dramatic 25% reduction of the total glacial area from 1930-1990 with 11% of this loss from 1990-2000 (Vuille, et al. 2008). Peru's unique contrast between geography and natural resources also contributes to its vulnerability, where over 70% of Peru's population lives in areas where only 1.8% of the country's resources are accessible, adding political and social stresses to the system (McDevitt 1999). The loss of ice pack on tropical glaciers in Peru means the loss of a primary freshwater source during the dry season for communities dependent year-round on glacial base flow for drinking water and crop irrigation.

Figure 4: Overview of the Santa River basin, Peru; Image from: TMI, 2010

Availability of fresh water resources is inextricably linked to climate in Peru, as perennial glacial melt provides a vital base flow for the urban populations and farmers to use during the dry season. As such, changes in temperature, relative humidity, precipitation and radiation have already impacted the glacial mass balance and thus growth and shrinkage of glaciers in Central Peru. Higher global temperatures and shifts in seasonal rainfall patterns on the regional scale have contributed to accelerated melting, and trickled down to affect mountain ecosystems and local populations living among the glaciers (Mark and Seltzer, 2005).

Evidence of melting can be linked with the growing number of lakes formed at the bases of glaciers in the Cordillera Blanca, which have increased in number from 223 lakes in 1953 to a startling 374 in 1997 based on survey data (Carey 2005). Local engineers and glaciologists speculate that a number of undocumented lakes exist in the area, but due to terrain difficulty and limited equipment resources are unable to survey the entire region (Cesar Portocarrero, personal communication, July 2010). Besides indicating significant melting, these lakes pose a tremendous threat to the half million residents of the Callejon de Huaylas (Santa River valley) as flash floods and avalanches are enhanced by these large-volume reservoirs sitting above population and agriculture centers.

Figure 5: Glacial Lake Llaca located east of Huaraz in the Cordillera Blanca (left); The view west from the Llaca valley toward Huaraz below (right). Photo by Laura Read, July 2010.

Concern for glacial lake disasters comes after five tragic historic events involving lake flooding, avalanches and earthquakes in the valley between 1941 and 1970 resulted in the complete destruction of several towns and the deaths of over 27,000 people in total

(Carey 2005). These events have residents of Callejon de Huayalas panicked for better security measures and an emergency plan from the government, while at the same time untrusting that the government will take the necessary steps to prevent further disasters if it means the loss of hydropower or economic gains (Carey 2005). Engineered structures have been built for known hazard lakes, but it is likely that further adaptation actions will be necessary as glacial melt continues at an accelerated pace; these actions should be considered in the context of other adaptation plans for water availability and sustainable crop production.

1.4 Advancement and Availability of Hydrologic Data

Hydrology-based models of real systems require observational data for calibration and validation, a difficult obstacle depending on the location of a project. One of the greatest challenges in working in Peru is the lack of historic data record and observational gauges in place to measure hydrologic variables. Without reliable and consistent sources of measured data, scientists have struggled to fully address many of the climate-related concerns facing Peru today as the tools necessary to assess these issues have fallen behind the number of analyses needed. The globe's interdependency regarding food and material production has reached the point where a potential climate threat to Peru's food security will affect markets in other countries. This concern has been a positive factor in creating international awareness and collaboration between scientists and governments, a necessary step in building infrastructure for projects with organizations like the U.S. Agency for International Development and the World Bank. In addition, academic research institutions have responded to these hydrologic data accessibility disconnects by creating the Consortium of Universities for the Advancement of Hydrologic Science, Inc (CUAHSI), which promotes web-based data sharing for parties interested in projects involving multiple data sources. By building these frameworks to host hydrologic and climate data, scientists are setting the stage for a revolution in how information is organized and distributed remotely worldwide.

Recently, vast advances in remote sensing data technology and land-surface models have opened doors for large-scale datasets to provide reasonable resolutions for river basin and regional assessment of hydrologic processes. Funded by the U.S. government, the National Climatic Data Center has built the National Operational Model Archive and Distribution System (NOMADS) to organize and disseminate climate related data projects run by NCEP and NOAA. With the need to understand global climate change on a regional scale for predicting future climate in both developed and developing countries, scientists have pushed for not only more emphasis on numerical weather prediction, but also wide-spread accessibility to such data. Climate change has crossed the lines from being a scientific question to a subject critical in policy and development decisions, making it crucial for scientists to have the available tools to present to results for governmental and international organizations. In short, these efforts by government and academic institutions have encouraged more interdisciplinary research, which can only benefit projects like climate change adaptation strategies and river basin modeling.

1.5 Research objectives

The central focus of this work is to create a scientific tool for communities in the Andean mountain villages of Peru (particularly in the Santa River valley) to use for support in making decisions for sustainable development and adaptations under climate change. Significant data collection, organization and comparisons comprise much of the effort for this research and serve as the backbone for achieving all other goals. I am personally connected to this project after visiting the research site in Peru during summer 2010, talking with local villagers and seeing first-hand the risks and challenges this region faces regarding water availability and climate change. The objectives for this research are the following:

- To collect and process climate and water use data from the Santa River basin in Peru via a summer 2010 field visit in coordination with The Mountain Institute and the Autoridad Nacional del Agua in Peru;
- To build on an existing Water Evaluation and Planning (WEAP) model created for the Santa River (Condom et al., 2010) to include water demands for irrigation and municipal water use in the upper basin for calculating available water (stream flow);
- To verify WEAP's representations of physical processes occurring in the Santa River Basin by validating the original and modified irrigation model with historic climate data;
- To test the validity of a new global climate re-analysis dataset that could be used to fill in data gaps in the historic record in the Santa basin; and
- To develop scenarios for future crop development in the upper Santa River basin based on temperature and precipitation projections as a means for guiding adaptations to climate change

Chapter 2: Background Research in Peru

2.1 Project location: Cordillera Blanca, Ancash, Peru

The Cordillera Blanca mountain range located in Peru's Central Andes is home to ancient traditions and stories of the indigenous Andean civilization. Ancient tales describe the Cordillera Blanca to the east (mountains with white glaciers) and the Cordillera Negra to the west (dark mountains). The Cordillera Blanca is one of the most extensively studied glacier regions in the world as it contains the greatest area of tropical glaciers in the world with a total area of 14,954 km^2 (Mark, et al. 2010), and feeds high-elevation ecosystems and populations inhabiting the Santa River basin. Economically, the Cordillera Blanca glacial melt waters provide an essential source for hydropower in the region year-round and drain to one of Peru's most fruitful agriculture valleys at the downstream section of the Santa River basin. Glaciers in the Cordillera Blanca range of Central Peru (8°-10° S) have shown significant retreat since the Industrialized era and an accelerated shrinkage rate of 15-18 meters per year since the 1980's (Vuille et al., 2008).

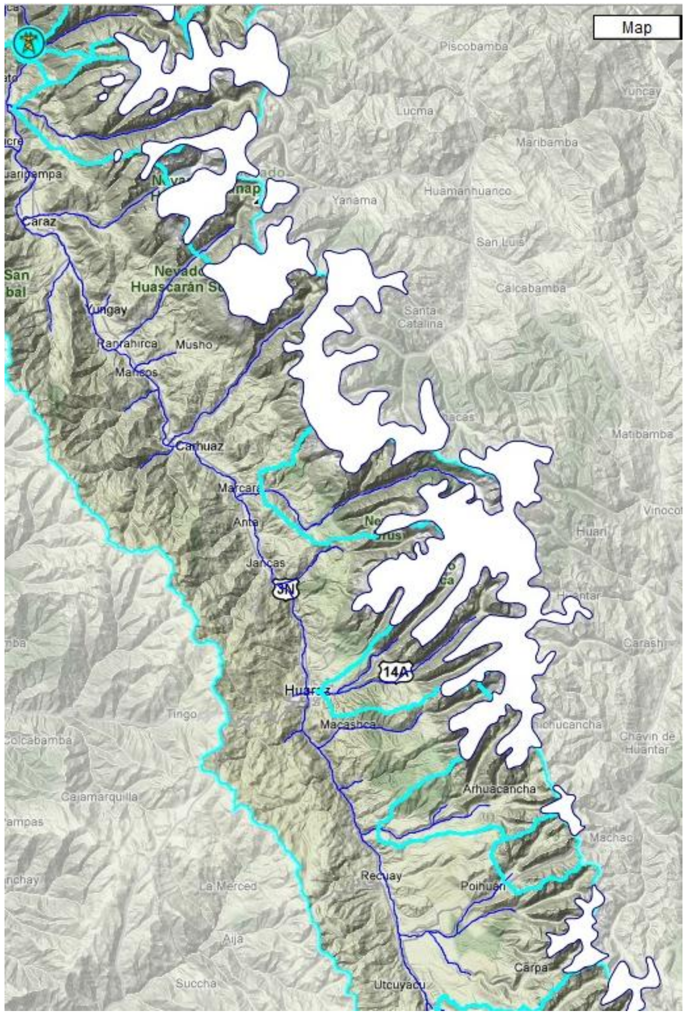

Figure 6: View of the upper Santa River basin and Cordillera Blanca glacier peaks. Source: http://www.mpl.ird.fr/divha/aguandes/peru/santa/map.htm.

The Cordillera Blanca mountains lie on a major fault line where a 7.7 magnitude earthquake in 1970 struck and caused a glacial avalanche resulting in the destruction of 65,000 km^2 of land, injured 50,000 and killed 70,000 inhabitants of the Yungay area (Carey 2010). Risk of catastrophic events (especially when they can combine to cause further damage) adds exponential risk and susceptibility to infrastructure and rural populations of the region. Population growth in the Santa River basin has increased at a rate of 23% in the urban areas and decreased by 6.3% in the rural areas from 1993 to

2007 (INEI 2009); the total Ancash province population is projected to increase by 12.62% over the next 5 years (Badatur Peru 2010).

With perennial snow-covered peak summits above 6,000 m, the Cordillera Blanca is one of the world's most famous ice climbing and mountaineering destinations. As such, the region relies heavily on an austral-winter tourism season for economic stimulation from outdoor enthusiasts. From 1988-2009, tourism in the Cordillera Blanca increased by 22.39% at a rate of 7.85% per year (Observatorio Turistico Del Peru 2010), drastically changing the industrial makeup of the local residents, as the need for taxi drivers, tour guides and other service jobs grew quickly. As further indicated by the negative rural population growth, the younger generation is moving more toward technological and small business careers instead of remaining in the rural communities and inheriting the farm practices of their parents.

During his presidency from 1990-2000, Alberto Fujimori pushed through a series of economic reforms in a movement now referred to as *Fujishock*, coined after his three terms as president became one of the most infamous eras in Peru's modern history. One outcome was that privatization policies were relaxed, opening the country to international business and inviting mining companies to lay claim to the slopes of the Cordillera Blanca and neighboring Negra (Carey 2010). While mining for precious metals including gold, silver and zinc helped stimulate Ancash's economy, the companies were not held accountable for environmental regulations or cleanup procedures. As the Cordillera Blanca populations took notice of the environmental degradation to their land and river, they banded together and forced the companies to cease operations, unfortunately leaving abandoned mine tailings to naturally erode into the Santa River basin, as shown in Figure 7 (Carey 2010). The Ancash province contributed 29.2% to the total mining industry in Peru in 2009, a decrease of about 1% since its peak in 1987

(INEI 2009); however, mines are no longer operating directly on the banks of the Santa River.

Figure 7: View of an abandoned mine in the Cordillera Blanca, Santa River banks; Photo by Laura Read

The importance of ecology and biodiversity in the Cordillera Blanca is illustrated best through Huascaran National Park, the world's largest protected area of tropical mountain ecosystem covering 340,000 ha at elevations above 4,000 m in the Cordillera Blanca (Young and Lipton 2006). Many rare species are under protection in the park, including the Andean condor and the puya raimondii (Figure 8) with strict protocols for implementing habitat conservation practices (Young and Lipton 2006).

Figure 8: View of a puya raimondii tree, a species only found in Peru's Central Andes; Photo by Laura Read

The park is visited by local and international tourists, promoting eco-tourism practices by highlighting conservation efforts and offering organized tours to sites like the famous Pastoruri glacier, which was recently closed due to "adverse climate change effects" and is expected to disappear completely by 2015 (Mark, et al. 2010). As tourism increases and more visitors experience the unique landscape and culture of the Cordillera Blanca, environmentalists and rural residents hope that more programs will be implemented to protect the region.

2.2 The Santa River Basin, Peru

The Santa River flows northwest from its origin at Lake Conochoca (4020 m) for a total of 294 km before emptying into the Pacific Ocean, draining an area of 12,289 km^2 (Duke Energy International, Egenor 2004). As the river moves north through the upper basin with the Cordillera Negra range to the west and Cordillera Blanca to the east, glacial runoff from the Blanca contributes year-round to the base flow, providing water to rural populations dispersed in the valleys. A 30-m resolution digital elevation map of the Santa River basin is shown in Figure 9, where the dramatic changes in elevation are illustrated (from 6722 m at the peak of Huascaran to 2 m at the coastal outlet). The valleys cutting in from the east contain significant tributaries that drain large percentages of glacial melt.

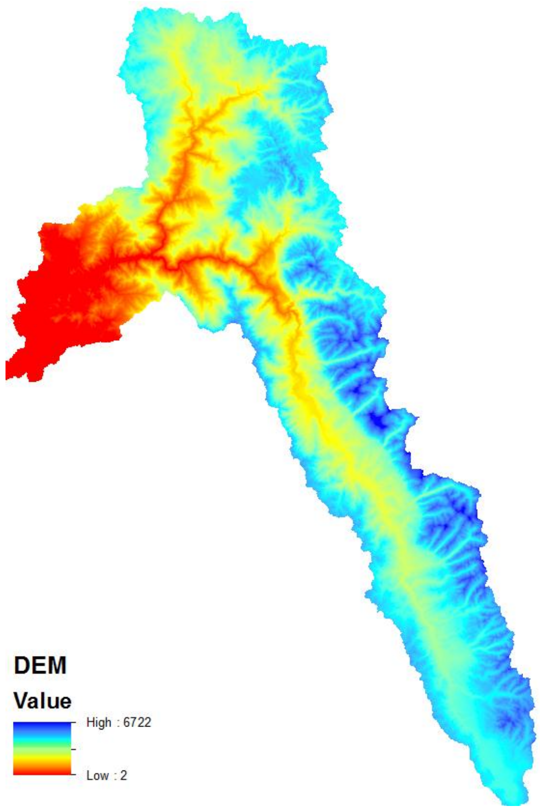

Figure 9: Digital elevation map of the Santa River basin at 30-m resolution; Image by Marcelo Somos

The lower basin is characterized by a flat, fertile landscape as the river turns west and heads down through two of Peru's most important agricultural regions: Chimbote and Chavimochic before reaching the Pacific. Most of the water downstream of Cañon del Pato is diverted for irrigation and subsequently used to serve the city of Trujillo on the Pacific Coast year-round as glacial melt supplements flow during the dry season by an estimated 40% (Mark and Seltzer, 2005).

The upper basin drains an area of 4,900 km^2, stretching from Lake Conochoca to the La Balsa gauge station directly upstream of Ancash's most productive hydropower plant, Cañon del Pato (3940 m). Water demands in the upper Santa River basin are divided among hydropower production (91.7%), agriculture (7.6%), municipal (0.48%), mining (0.03%) and fish flow (0.24%) sectors (Figure 10). This balance calculating hydropower production requirements does not include a return flow, rather it simply measures total water needs.

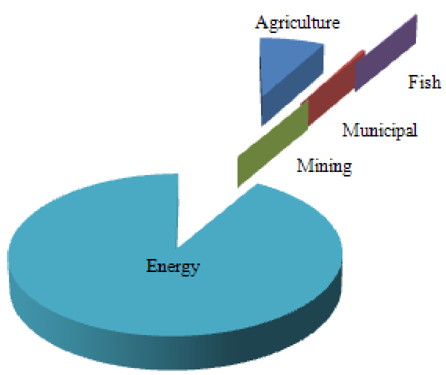

Figure 10: Demands by sector of the upper Santa River basin downstream to the hydropower station at Canon del Pato in 2007; Data source: ALA

According to a water balance study by the Autoridad Local del Agua (ALA), the monthly demands fluctuate between a surplus and deficit of flow depending on the season, where for example from June to November in 2007, Santa River flow at the La Balsa station was not sufficient to meet the demands (Figure 11). One serious issue this flow distribution illustrates is the need for water storage capabilities during the dry (low flow, high demand) season so that farmers and cities are not solely reliant on climate to meet needs.

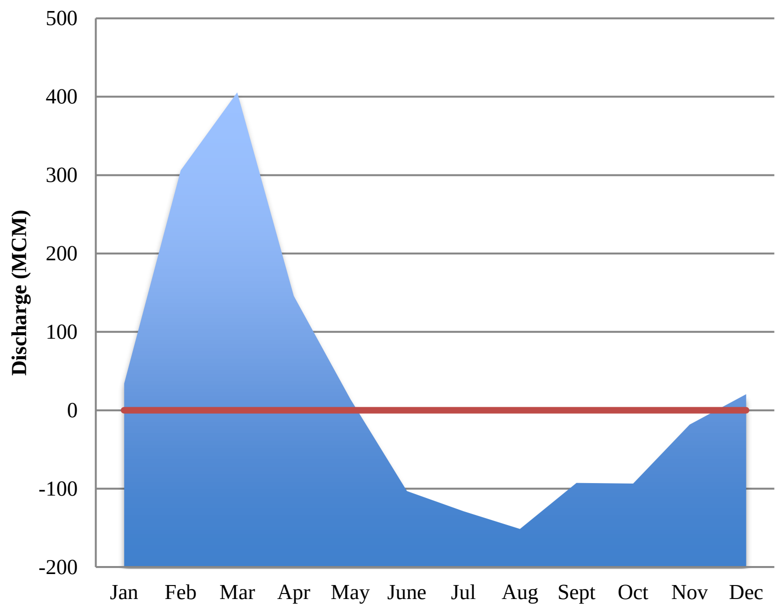

Figure 11: Monthly stream flow surplus and deficit for Santa River at the La Balsa station in 2007; Source: Autoridad Local del Agua

In 1992 the Fujimori government signed the Electric Power Concession Law paving the way for Duke Energy International to buy out the locally owned Cañon del Pato facility from Electroperu. Currently about 80% of Ancash's electricity consumption is derived from hydropower with 264 MW produced from Cañon del Pato alone (Duke Energy International, Egenor 2004). Concerns for meeting hydroelectric demands are high as Duke Energy's acquisition led to a decision to increase Cañon del Pato's outflow from 1 m/s to 4 m/s in 2007. The company also attempted to build more reservoirs in the upper basin to maximize capacity (Carey 2010) and in 2009 drained 50% of Lake Paron to maximize power production sending farmers into protest (Aiello 2009). Expected population growth and development has led the current national government to approve an international consulting company, GDF Suez, to invest $600 million in two hydroelectric plants, one in Ancash with a 112 MW capacity (Whitehouse and Emery 2010).

The vitality of electricity production through Cañon del Pato is heavily dependent on steady stream flow throughout the year, as it is a run-of-the-river plant, meaning that production levels rely on natural elevation to generate power. In the past this has been very efficient, however flow reduction during the dry season due to glacial mechanics has resulted in plant operation at less than capacity and is expected to decrease the effective runoff rate into the plant by 50% if melting continues at current rates (Vergara, Deeb, et al. 2009). To account for this potentially devastating loss in energy production, two reservoirs were built to secure emergency storage (Figure 12), but a question of longevity looms in the distance for when glaciers melt to a hypothetical equilibrium leaving hydropower vulnerable to droughts and increased irrigation and municipal needs within the basin.

Figure 12: One of two reservoirs built just upstream of Cañon del Pato for storage; Photo by Laura Read

2.3 Community and social description of Ancash, Peru

Census data from 2005 indicate that the Ancash province has a higher percentage of the population living in extreme poverty (20.8%) than the national average (16.8%) (INEI 2009). In 2007, 73.2% of the total population in Ancash had access to electricity, with 87.1% urban residents reporting access compared to a low 49.7% in the representative rural areas. A similar trend for sanitation shows that 73.5% of the Ancash population has access to sanitation services—latrine, septic tank, separation between kitchen and washroom—however 52% of the rural population lacks any of these types of sanitation and of the 48% that do have access to sanitation, 37% are latrines (INEI 2009).

According to the Ministry of Education in Peru, science curriculum is uniform for all K-12 students. The same textbook is produced and distributed from Lima to all the provinces throughout the country for each subject. By this centralized system, students living in dramatically different environments (Andes mountains, Amazon rainforest and desert coast) all learn the same concepts about science and nature without attention to regional specialization. With field trips limited to one or two per year for 6-8 graders in the Ancash province (location of Santa River), and the majority of class time spent listening to teachers or working from a textbook, students are led to under-appreciate their surroundings (Magistrate Eddy Valderrama Espinoza, personal communication, July 2010). Perhaps the greater concern is that students will not develop a personal connection to their natural environment without engaging in hands-on experience and active learning. Recently, the national government has responded to concerns of falling education standards by agreeing to decentralize textbooks and allow regional Ministry offices to exert influence over the curriculum. These changes will take effect in the 2011-2012 academic year in Huaraz and are expected to include more opportunities for experiments, although not necessarily directed toward environmental awareness

(Magistrate Eddy Valderrama Espinoza, personal communication, July 2010). While several international non-profit organizations send volunteers to teach English and mentor school-aged children, there has not been a push to improve science field experiences for students or funding available to organize trips to the mountains or water sources. The security of water resources in Ancash and Peru in general will likely depend on local residents taking interest in these issues and pursuing related careers.

Although advances in farming technology hit the global market during the Green Revolution in the 1970's and have since been implemented around the world, the relatively isolated rural Andean communities have largely been unexposed to modern equipment and kept with their traditional techniques. While these cultivation practices are worth continuing, preserving and passing down to future generations, improvements in irrigation efficiency and crop maximization would allow farmers to conserve water during the stressed dry season.

Household survey results from the Catac region (population ~3,250) in the upper Santa River basin indicate that the dominant livelihood activities are livestock (85%) and agriculture (68%), with 90% of households owning and/or accessing land resources (Bury et al., 2010). Interviews conducted in Catac also show that residents are most concerned about climate change affecting family and livestock health (44%), agriculture development (42%) and future water availability (25%) (Bury, et al. 2010). This suggests that at least 85% of the community relies on farming in some form, since hay and feed for the livestock (predominantly cows and sheep) primarily originate from local cultivation. This type of interconnectedness within communities in the Cordillera Blanca is as much a part of their unique culture as it is a contributor to the fragility of their infrastructure. Because the majority of their subsistence farming processes is local, small disruptions in the ability to grow crops, provide drinking water for families and livestock, and ensure a sufficient energy supply could have devastating consequences for entire rural communities.

A Peru-based non-profit organization, The Mountain Institute (TMI), works in *campesino* (or small farming) communities in the Cordillera Blanca to promote conservation through education and community-wide improvement projects. Through a project funded by USAID, TMI is working on the ground to understand how communities in the Cordillera Blanca can "adapt to a world without glaciers," specifically regarding changes in water availability, and enlisting international experts to evaluate the most effective strategies. At a TMI workshop held in Peru in 2009, participants identified institutional weaknesses, a lack of funding, a limited historic climate data record, and gaps between urban and rural populations as challenges to adaptation (Recharte, et al. 2009). Research recommendations for evaluating water availability include improving weather-monitoring stations, exploring financial resources, developing communication mechanisms and preparing scientific models (Recharte, et al. 2009). One TMI project in the upper Santa River basin is testing different native grasslands to understand how grassland management techniques can conserve water more efficiently. Overall, this grass-roots effort is adhering to an approach that others can follow by enlisting communities to take a proactive role in their own development, and to ensure that the improvements and changes are in accordance with cultural rites (Recharte 2010).

One of the largest obstacles limiting sustainable development in the Cordillera Blanca is the lack of funding sources for these communities, as local municipalities are usually too impoverished to build or maintain anything more than basic infrastructure. Recently, the national government has opened up grants for communities to receive money for updating old systems and developing new access to water and electricity;

however, the rural communities most in need of the funds are also the most isolated and either lack assistance in application process for the money, or are not able to provide proof of a technically sound project (Recharte, 2010).

Interviews and accounts of land hardships from residents of the Cordillera Blanca also reveal an economic and social incongruence that plays a large role in progress and development. Projects that consider these barriers and work to incorporate regional differences rather than ignoring them are able to understand the over-arching issues, their overlap, and thus develop solutions for other areas with similar hardships.

2.4 Climate change adaptations in the Cordillera Blanca

With the acceptance that climate change is occurring, governments and communities are investigating possible adaptation avenues to accommodate expected (and already observed) changes in water availability and thus crop production. Studies at the regional level are helpful for identifying adaptation strategies, since minute changes in temperature and the energy budget have such a significant influence on local hydrology in the high-altitude tropics. Local governments and non-profit organizations—from education and conservation to technical projects and structural improvements—have implemented a range of adaptation actions over the past decade.

The Autoridad Nacional del Agua (ANA) has an office for glaciology and water resources (INRENA) in Huaraz that researches glacial risk, conducts field measurements, and makes recommendations for water projects in the Cordillera Blanca. Recently, efforts to include local municipal leaders and citizens in brainstorming ideas for climate change adaptations have proven popular, and verified the widespread concern over this issue. In July 2010 Carhuaz (pop. ~15,000) hosted an international forum entitled

"Cambio Climatico y Gestion de Riesgos de Desastres[1]," where two expert glaciologists[2] led an assessment field visit to Laguna 513 and publically discussed possible avenues for reducing downstream risk due to glacial outburst flooding. Laguna 513 experienced an avalanche in April 2010 where a 100,000 m^2 area of ice from the Hualcan glacier (Figure 13) fell into the lake and caused flooding downstream including the destruction of 50 homes, death of six people and ruin to a waste water treatment plant serving 60,000 residents (Carroll 2010). While this event was significant, it would have likely caused even more severe damage to Carhuaz below had drainage tunnels not been installed to maintain a low volume of water in the lake. This event raised local awareness of the instability of such lakes among residents, scientists, academics and politicians, as evidenced by the group of 30 people in attendance, including the mayor of Carhuaz, for the field assessment hike (Figure 14).

Figure 13: Image of Hualcán glacier highlighting the 100,000 m^2 ice block from April, 2010 event; Lake 513 is located below this glacier's tongue. Photo by Laura Read

[1] Climate Change and Disaster Risk Management

[2] Dr. Wilifried Haeberli (Univ. of Zurich) and Dr. Stephen Evans (Univ. of Waterloo)

Figure 14: The mayor of Carhuaz, Oscar R. C. Gomez, and his assistant enjoy a view of the valley on the way to Laguna 513. Photo by Laura Read

The forum presented measures to ensure the safety of Laguna 513 and consisted of the following improvements: build a retention wall in the zone downstream of the lake in the flat pampa, increase pipe capacity to drain more water from the lake to maintain its low level, destroy a large block of ice just above the lake so that big events will be mitigated, and avoid future development in the extended flood path of the lake. Most importantly, the need for a regional emergency notification system was discussed as residents are scattered within the basin, often isolated, and outside the realm of modern-day communication. These recommendations can serve as a prototype for similar glacial lakes that have formed upstream of population centers and valuable agricultural fields.

While fears of natural disasters loom over the Cordillera Blanca, life continues on the mountains where communities are struggling with lower flows in the dry season, while at the same time experiencing a slight increase in flow during the rainy season due to glacial melting (Bury et al., 2010). Farmers have adjusted their crop planning in response to these higher flows (Perez, et al. 2010)—which are predicted to decrease sharply after glacial melt peaks in the near future (and may already be decreasing in sections of the basin) (Mark et al., 2010). This situation illustrates the need for sustainable adaptation methods and education of the basic science to the communities.

Agricultural adaptations need to consider changes in seasonal precipitation, length of the tundra/frost season, availability of glacial melt in the dry season, higher minimum daily temperatures and changes in evaporation losses. These climatic variations will result in physical changes on the farm regarding soil erosion, planting and harvesting times, and crop efficiency. Strategies for facing these challenges include improved land use management, continuation of ancestral knowledge, modifications to production systems, coping mechanisms and improved farming technologies (Perez, et al. 2010). For example, in the past 15 years farmers report that a disease called "late blight" has affected more of the annual highland potato crop than previously, as the equilibrium line altitude has receeded and left more fields exposed to higher temperatures for longer periods of the year allowing late blight to infect (Perez, et al. 2010). Since late blight is responsible for damaging over $5 billion USD in potatoes worldwide and native Andean species are less resilient than commercial types, some farmers are looking to switch to a hardier and more profitable commercial crop but at the cost of discontinuing their traditional varieties (Perez, et al. 2010). While this decision may be economically beneficial for the impoverished small-scale farmers, educating them in crop rotation and modifying planting schedules may also work to minimize disease and help preserve the native species.

2.5 Background on the Water Evaluation And Planning (WEAP) model

The WEAP21 Integrated Water Resources Management model was developed for the purpose of combining hydrologic river modeling with planning and management scenarios. A detailed description of the model's origins, fundamental equations and theory can be accessed online at www.weap21.org/downloads/WEAP_User_Guide.pdf or in Yates et al. (2005). WEAP's flexible user interface allows programmers to let the data and desired level of detail guide the model, whereby options for including groundwater, irrigation and soil moisture elements are available but not required. This facilitates international use of the model since data for many regions are often not available to the same degree as in the United States.

WEAP uses a geographic representation layout compatible with ArcMap shape files and allows users to build on this framework by adding supply and demand objects that are spatially linked to catchments. The basic required inputs for the Soil Moisture Method used to calculate rainfall runoff used in this model are listed in Table 1. This method assumes two soil layers (root and deep) for water to infiltrate, allowing land use and soil type to influence sub-surface processes (Figure 15).

Table 1: Fundamental WEAP parameters

Parameter	Resolution	Sensitivity
Land Use		
Area	Catchment	High
Soil Water Capacity	Soil	Moderate
Deep Water Capacity	Soil	Moderate
Leaf Area Index	Land Use	High
Crop Coefficient, Kc	Land Use	High
Climate		
Precipitation	Catchment	High
Temperature	Catchment	Moderate
Wind	Catchment	Low
Humidity	Catchment	Low
Melting Point	Catchment	N/A
Freezing Point	Catchment	N/A
Initial Snow	Catchment	N/A
Latitude	Catchment	N/A

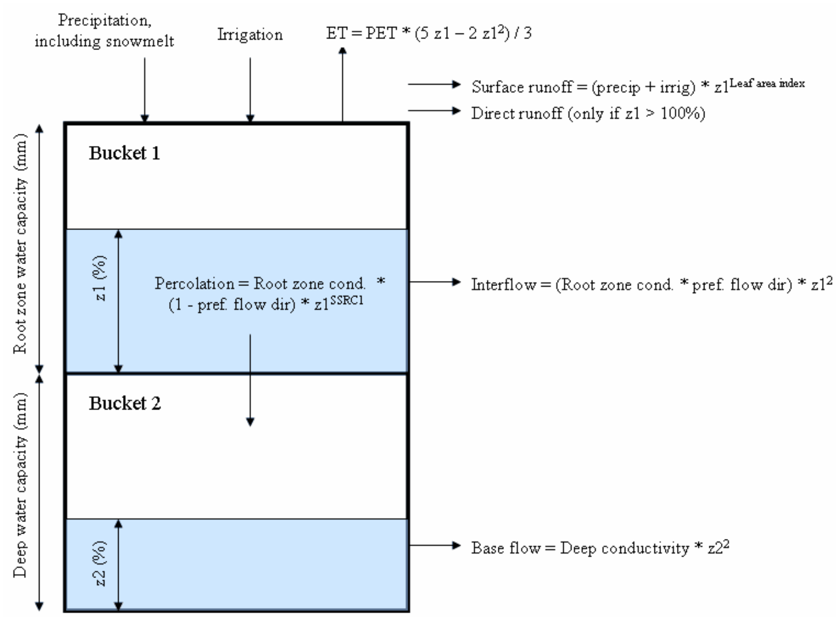

Figure 15: Schematic of WEAP's Soil Moisture Method, two-bucket layers

The river management aspect of the model comes into play when information is known about specific user supplies, demands and diversions on the river. These data are entered as single constants or time-varying values depending on the detail required, and can be associated with a catchment or made general for the entire river. Examples pertaining to this work include irrigated land areas, varying crop coefficients, reservoirs, municipal water demands.

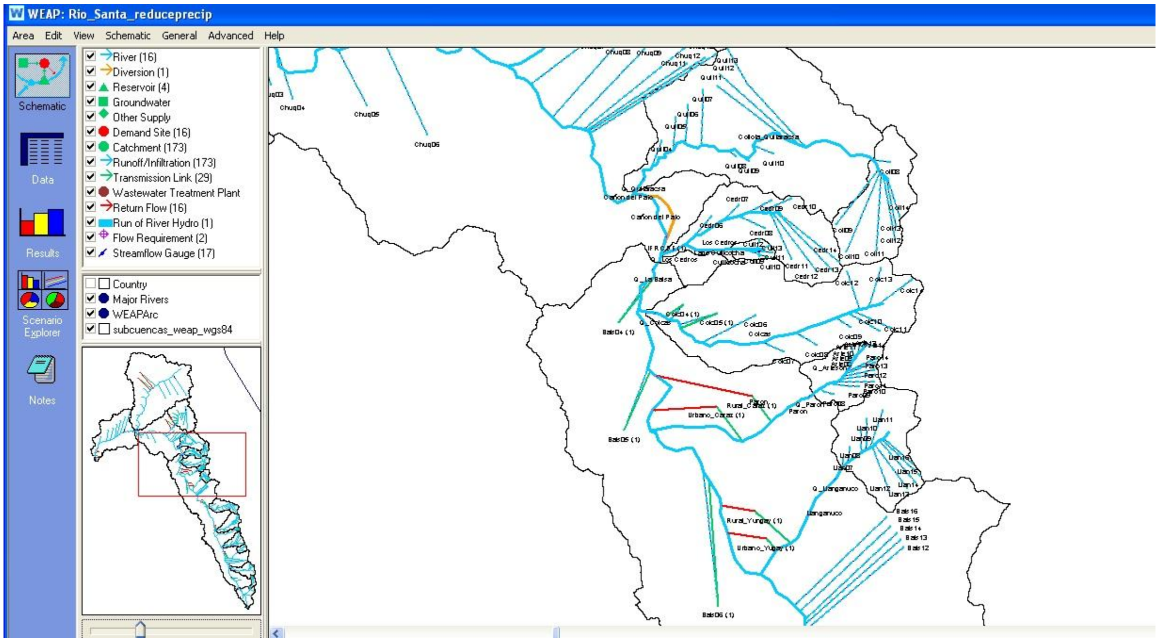

Figure 16: WEAP screenshot of the Santa River basin showing catchment elements

WEAP's stream flow calculations can be calibrated against historic flows or manually inserted algorithms based on data availability. Once calibration is satisfactory, the user can develop scenarios to test the sensitivity of different parameters such as variations in climate or demands. Scenarios are a useful way to present plausible options for city planners or government agencies looking to implement policies related to water availability and use. With climate change expected to greatly influence future regional water resources, modelers can run scenarios based on IPCC projections and develop worst-case scenarios for their rivers.

Figure 17: The Santa River basin with sub-watersheds labeled

Chapter 3: Methods

This section contains an exploration of the Peru WEAP glacier model and descriptions of modifications made to the original model. A new global climate dataset was introduced and tested as a possible substitution for gaps in the historic record. Calibration, validation and statistical assessments were conducted for simulations on the original and modified model for stream flow and irrigation flows. Scenarios were built from the modified irrigation model to explore possible different crop portfolios.

3.1 Introduction to the Peru WEAP glacier model

The model used for this research was developed by the Stockholm Environmental Institute, Davis CA office and is detailed in Condom et al. (2010). Their addition of a glacial mass balance model is a new component in WEAP and currently unique to the Cordillera Blanca, Peru model used in this project. A brief description of the model parameters and basic assumptions are provided in this section.

The Santa River basin sub-watersheds were delineated from a 1:100,000 digital elevation map provided by the Insituto Geologico Minero y Metalurgico, and elevation bands at 700 m (and 300 m in the higher regions) intervals were delineated to the define catchments (Appendix). Climate data and the annual glacial mass balance are calculated on a monthly time step for each elevation band area to account for the effect of elevation on glacier accumulation and melting. This setup is illustrated with the Paron sub-watershed as an example (Figure 18), where elevation bands can be thought of as contour line areas.

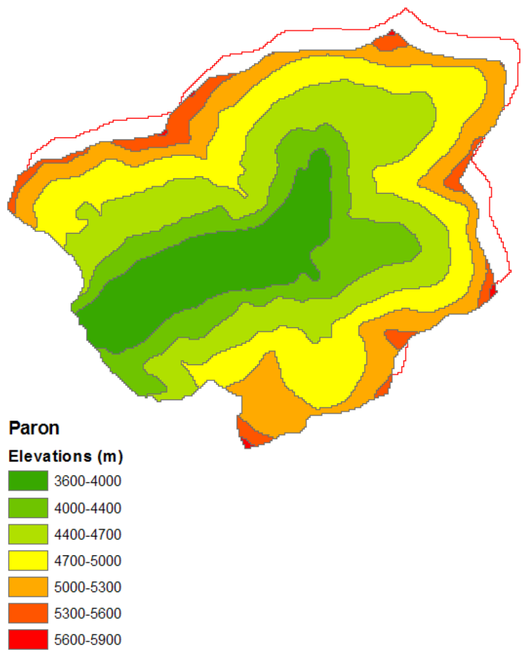

Figure 18: Image of the Paron sub-watershed with elevation band areas

Due to lack of a consecutive time series and complete spatial representation of historic climate data in the basin, assumptions were made to compute the climate data from 1968-1999 in the original model. Temperature was computed on a monthly time step using the degree-day model and assuming a 0.6°C/100 m temperature decrease (Suarez, et al. 2008). Monthly average humidity and wind speed were taken from the Recuay station for the period 1968-1999 and assumed to apply to all catchments. Monthly average wind speeds were assumed to have no annual variation over the 30-year period and applied to each catchment over the entire basin. From 39 precipitation gauges in the Santa River basin, monthly values were extrapolated to each catchment based on the inverse distance-weighting tool in ArcGIS. In order to correct for differences in precipitation due to elevation, a set of empirical equations were used (World Bank 2009) to yield corrected precipitation values. Land use data sets were collected from the

Chavimochic project run by the Institute of National Development (Condom, et al., 2010); land is classified into three types: tundra; shrub ("matorral"); or arable land ("cultivos"). A summary of the key assumptions kept constant in space and time in WEAP are shown in Table 2.

Table 2: Key Assumptions Regarding Parameters Constant in Space or Time in WEAP

Parameter	Value
Soil water factor (mm)	80
Deep water capacity (mm)	500
Runoff resistance factor, Rf	1
Rf factor	0.8
SW conductivity factor (mm/mon)	500
Deep conductivity (mm/mon)	50
Preferred flow direction	0.68
Initial Z1 (%)	35
Initial Z2 (%)	35
Urban growth rate (%)	1.6
Rural growth rate (%)	1.2

Parameters of the glacial model were not changed for the research reported here since the previous version was sufficiently calibrated with observational data from the well-studied Artesoncocha glacier and sub-watershed. The model captured seasonal flows and monthly averages well (R^2 = 0.67) and was able to reproduce the glacial retreat anomaly experienced from 1970-1987 (Condom et al., 2010).

3.2 MUNICIPAL WATER DEMANDS AND POPULATION DATA

In the original WEAP model, municipal water demands for the urban centers in the Santa River basin were calibrated based on 2005 census data from Peru's National Institute of Statistics and Informatics (INEI) where annual growth rates of 1.6% in the urban centers and 1.2% in the rural areas were applied to calculate annual populations back to 1968 (Condom et al., 2010). These general assumptions are not completely applicable on a sub-regional scale since more recent census data from INEI shows that the populations in rural areas of Ancash actually decreased from 1993 to 2007 at a rate of 0.45% (INEI 2009). Separated by province, the movement of people in Ancash over the last 17 years is presented in Table 4. The most recent census data (Table 3-4) indicates a noticeable exodus from the rural areas to the urban centers, supporting data collected in one Ancash province showed 87% of the male residents between 27-33 leaving the family farms and migrating to urban areas (Young and Lipton 2006).

Table 3: Differences in population distribution in Ancash from 1993 to 2005

Province	Urban (%)	Rural (%)
Huaraz	3.19	-1.06
Carhuaz	2.51	0.189
Recuay	0.032	-1.04
Yungay	3.21	0.205
Corongo	-0.910	-1.14
Santa	1.42	-0.393
1993 to 2005 total	**1.10% growth overall**	

Source: INEI census data, www.inei.gob.pe

Table 4: Differences in population distribution in Ancash from 2005 to 2007

Province	Urban (%)	Rural (%)
Huaraz	4.30	-7.34
Carhuaz	4.14	-1.58
Recuay	4.71	1.80
Yungay	6.70	-2.57
Corongo	8.22	5.32
Santa	1.12	-7.70
2005 to 2007 total	**0.39% growth overall**	

Source: INEI census data, www.inei.gob.pe

Combining the dataset collected in summer 2010 from the agriculture and regional water authority, ALA, for total municipal water demand in rural and urban provinces per month for 2007-2008 with INEI census population data from 2007, consumption rates per month were calculated to be approximately 300 [+/- 1%] L/person/day. Assuming that the average daily consumption rate per person does not change significantly over time, these values were applied for the 1967-1999 simulation period.

3.3 Adding Irrigation to the Peru WEAP glacier model

Significant changes to the existing model were made in the land use (irrigation) data section. The majority of these data were collected on a field visit during summer 2010 to Peru where meetings with the Autoridad Nacional del Agua (ANA), The Mountain Institute and Ministry of Agriculture (ALA) led to the acquisition of data specific to water use, cultivated land areas and crop types in the Rio Santa Basin.

The catchments containing "cultivos" areas in the upper Rio Santa basin are located between 1900-3800 m in the La Balsa, Colcas, Chancos, Quillcay catchments (Figure 19).

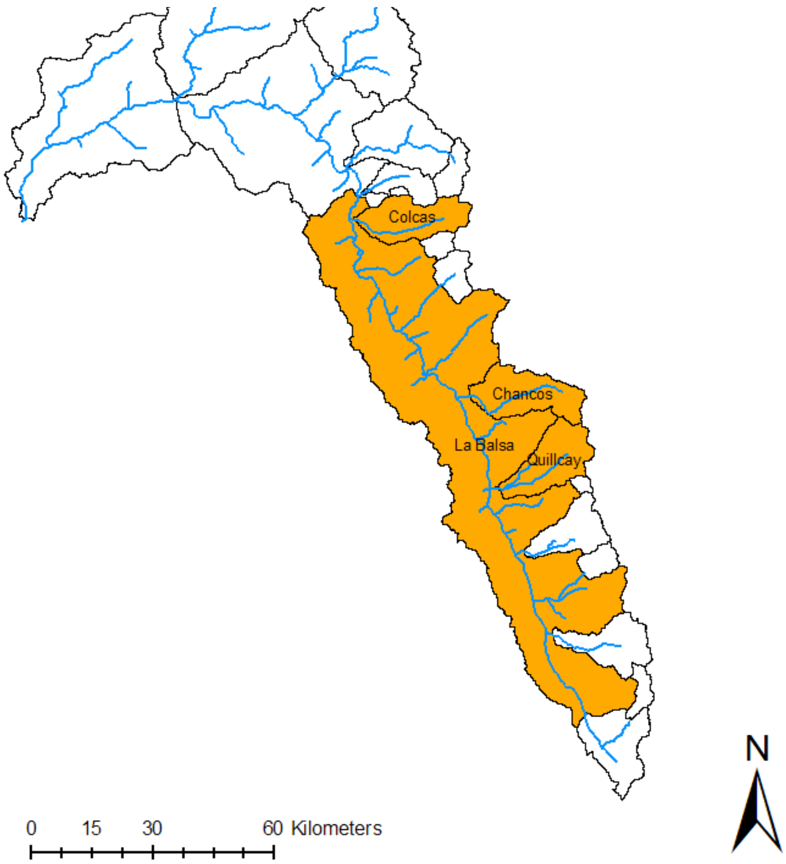

Figure 19: Sub-basins that contain cultivated land and require irrigation

The crop mosaic in the high Andes is diverse and highly location specific since most farms are small-scale and grown for a cluster of communities. Cultivation in the previous WEAP model was generalized to produce a single crop with a constant crop coefficient (Kc) throughout the year. Research indicates that crop coefficients vary significantly depending on the time of year and the growth stage of the particular crop (Farm and Agriculture Organization 1998). The previous model did not include irrigation as a demand on the Santa, whereas this research assumes irrigation based on the Soil Moisture Method in accordance with the Farm and Agriculture Organization method

(FAO, 1998): The land is irrigated when soil moisture drops below 35% and is not irrigated when soil moisture is above 50%. A list of the most common crops grown in the Santa River basin from 2007-2009 is presented in Table 5 with their associated growth (yellow) and harvest (green) seasons, and these cropping areas are assumed to be relatively constant over the past several decades. From this, monthly Kc values indexed by FAO were assigned for each crop based on data from Peru's agriculture association (ALA) on cultivation and harvest seasons in Ancash.

Table 5: Growth and harvest seasons for crops grown in Ancash

Crop Types	**Veg. Period**	**Au**	**S**	**Oc**	**N**	**De**	**Ja**	**Fe**	**Ma**	**Ap**	**May**	**Jun**	**Jul**
Forest	Perm												
Fruits	Perm												
Pasture	Semi-perm												
Alfalfa	Semi-perm												
Vegetable	Semi-perm												
Artichoke	Semi-perm												
Olluco-native pot.	7												
Soy beans	5												
Green Peas	5												
Maize	6												
Potatoes	5												
Coca leaf	7												
Wheat	6-7												
Grain	6-7												
Oats	6-7												
Beans	4												

Source: Autoridad Local del Agua (ALA), 2007

Crop area percentages were assigned to the catchment elevation bands based on the following process:

- Catchments with land area classified as "cultivos" in the original WEAP model were identified as having irrigation demands
- These catchments' locations were compared with proximity to field data collected from an ANA dataset on hectares of farmed land in each region
- Altitude limitations on crop growth restricted the selection to elevation bands lower than 4,000 m
- Crop areas in hectares were converted to percents of catchment since the available cultivated land area is dependent on annual calculations of the total glacier mass balance

3.4 Catchment site selection for calibration and comparison

Five locations in the upper basin were chosen to compare monthly WEAP-computed stream flow with historic gauge data (Figure 20). A brief description of each catchment and rationale for its selection follows.

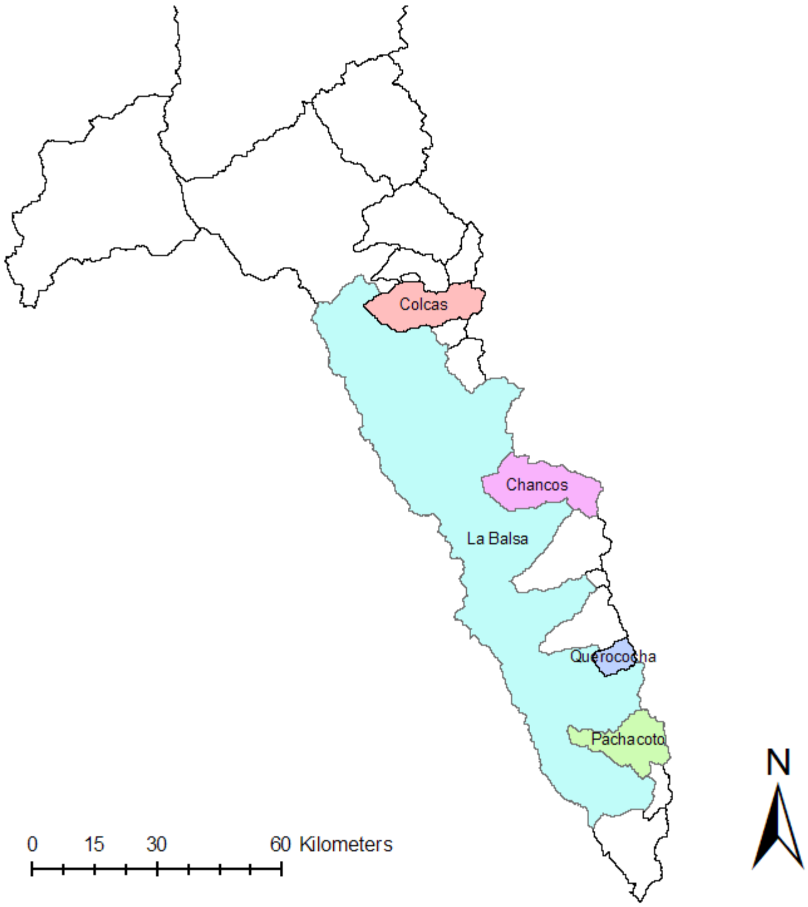

Figure 20: Locations of selected catchments for calibration and validation

- The La Balsa station is located just upstream of the Cañon del Pato hydroelectric station and is the largest sub-watershed in the Santa basin; it has served as the major comparison point for previous studies in Peru and the recent WEAP model reports (Condom et al., 2010)
- The Colcas sub-basin is located at the downstream end of the upper basin and has two irrigated land areas and thus serves as an indicator of how changes in crop production may affect flow in the sub-watershed
- Pachacoto is one of the furthest upstream sub-watersheds in the basin, draining a valley that cuts in from the east. This region is one of the Cordillera Blanca's

most popular tourist destinations as it contains the famous Pastoruri glacier, one of the most accessible to visitors (and one of the fastest shrinking glaciers). This region is a prime access point to the Huascaran National Park and for viewing the rare *puya raymondii* trees

- The Chancos sub-basin is located in the central-east region of the upper basin draining to the valley feeding the towns of Carhuaz and Marcara; this region has been highlighted as an area of concern to residents based on risk assessments of glacial lakes and potential seismic activity in the glacier regions
- Querococha is a small sub-basin located downstream of Pachacoto and feeding into La Balsa from the east; this region was chosen in order to get an idea of how data resolution limitations and scale may affect modeling the hydrology and stream flow.

Table 6: Sub-basins selected for model calibration

Catchment	Area (km^2)	Irrigation area
La Balsa	3159	Bals4, Bals5, Bals6, Bals7
Pachacoto	198	N/A
Querococha	54	N/A
Chancos	270	Chan6
Colcas	234	Colc4, Colc5

3.5 Incorporating Climate Forecast Systems Reanalysis data

NOAA's National Climatic Data Center completed a Climate Forecast Systems Reanalysis (CFSR) project in January 2010 to provide satellite-coupled data from ocean and land systems over the entire earth at high resolution (Saha, Suranjana and Coauthors 2010). This dataset is available for downloading on an hourly or monthly time series at 0.5 degree (~38 km) grid cell resolution at this URL: http://nomads.ncdc.noaa.gov/data.php#CFSR-data. In order to calibrate the model with water demand and historic climate data over the same time period, new climate data (2007-2008) was needed to run simulations. The new ANA water use dataset covered the period 2007-2008 and the previous WEAP model used data from 1968-1999. Until January 2010, accessing climate data (e.g., precipitation and temperature) at useful resolutions for the Santa basin has been extremely difficult, since the historic weather record was interrupted in 1999 and many gauges and observational stations remain nonoperational.

In order to validate the CFSR climate input variables with historic data and model output, three stations from sub-basins in the upper Santa basin—Llanganuco, Querococha and Paron—were selected to compare with historic precipitation from 1995. The Llanganuco and Paron sub-basins are located next to each other on the east side of the basin, both with areas reaching above 6,000 meters. Both sub-basins also have a tumultuous past of natural disasters causing damage to residents downstream, as the Paron sub-basin drains to the closely monitored Lake Paron above the city of Caraz, and Llanganuco drains to Yungay (buried in the 1970 earthquake and avalanche).

Table 7: Variable names from CFSR in netCDF format

netCDF variable name	Units
Total_precipitation	mm/day/month
Temperature_surface	Degrees K
Relative_humidity_entire_atmosphere	%
U-component_of_wind_maximum_wind	m/s

Monthly averages of the four fundamental climate input variables listed in Table 7 for 1995, 2007 and 2008 were downloaded for input into WEAP. Maximum wind speed was chosen due to lack of data on average wind speed; corrections for this are described in a later section. The CFSR data were downloaded as netCDF files for each month with the four variables included, where the "pgbh" series was used for high-resolution data. In order to obtain monthly averages for each catchment in the Santa River basin, ArcGIS was used in the following procedure shown schematically in Model Builder (Figure 21).

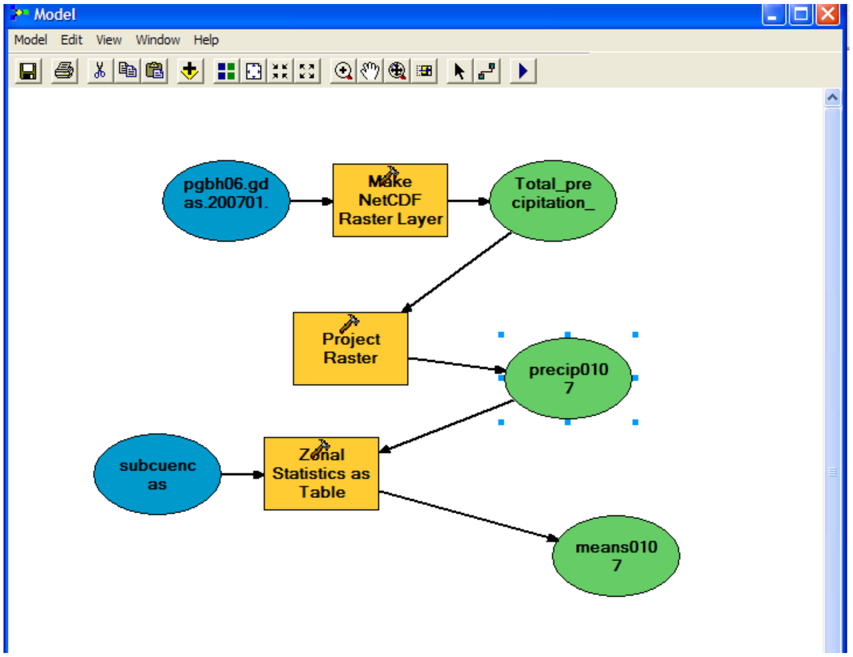

Figure 21: Model Builder view of extracting monthly means from netCDF files

The netCDF file was converted to a raster using ArcToolbox → Multidimensional tools. The variable of choice was selected from the netCDF file and a raster was created for each month and saved into a Peru geodatabase. The resulting raster files at 32 km resolution are shown in Figure 22 to give a sense of the span and potential spatial interpolation errors associated with this dataset. In order to make calculations between the raster file and Santa River catchments as feature class polygons ("subcuencas"), both files had to be projected in the same coordinate system.

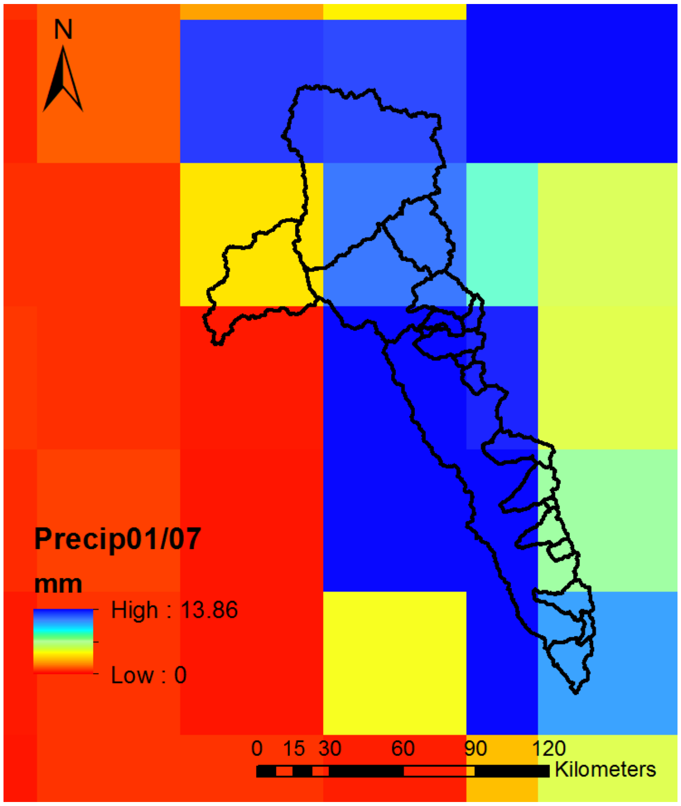

Figure 22: Original raster processed from 2007 CFSR precipitation over the basin

The Peru Central Zone projection was chosen for the Santa River basin. Each raster was projected into this coordinate system using ArcToolbox → Data Management Tools → Projections and Transformations → Raster → Project Raster. Since the grid cell resolution was larger than most of the catchment sizes, the raster was re-sampled to reduce the cell size from 0.5 degrees (38 km) to 30 m using the nearest neighbor sampling method: ArcToolbox → Data Management Tools → Rasters → Resample. This technique minimizes interpolation and in this case created ~10 new grid cells per original cell by sampling the value of the nearest cell (Figure 23).

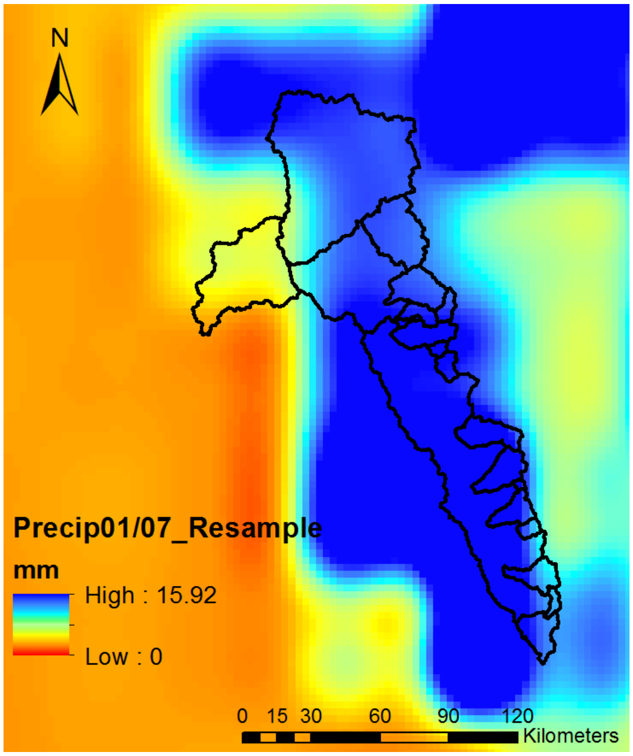

Figure 23: Re-sampled raster processed from 2007 CFSR precipitation over the basin

With the projected and re-sampled raster, zonal statistics were computed for each catchment in the basin giving the monthly means, minimums, maximums and standard deviations for temperature, precipitation, relative humidity and maximum u-wind speed. A simple model using ArcMap's Model Builder tool was created to automate this three-step process; the model was then exported to a Python script to loop over the two-year period for each variable (Appendix). The results were converted to dbf files and imported into Excel and combined into a single .csv file per variable to read into WEAP.

Further processing was necessary for the CFSR values precipitation, temperature and wind speed to prepare them for input into WEAP. Since temperature variation drives the glacial calculations in WEAP, the high sensitivity of temperature with elevation was accounted for by applying the linear trend of -0.6°C per 100 m elevation increase. This procedure was implemented within the multiple elevation bands in each catchment (refer back to Paron figure), where the CFSR temperature value was assumed to occur at the second lowest elevation band in each catchment. This assumption was made after comparing temperatures from the CFSR gradient at each elevation band at the Olleros station with values extrapolated from the Recuay site in the original model and finding the best agreement (Figure 24). The Olleros station was chosen for this validation based on its proximity to the Recuay station compared with the other possible locations. The CFSR data shows a notable decrease in temperature during September followed by an increase in October, where October is the warmest month according to CFSR data. Without a historic record to compare with for 1995 (or any substantial continuous record), it is difficult to speculate whether this pattern is experienced on the small regional scale or whether the coarse grid cell size has created this effect.

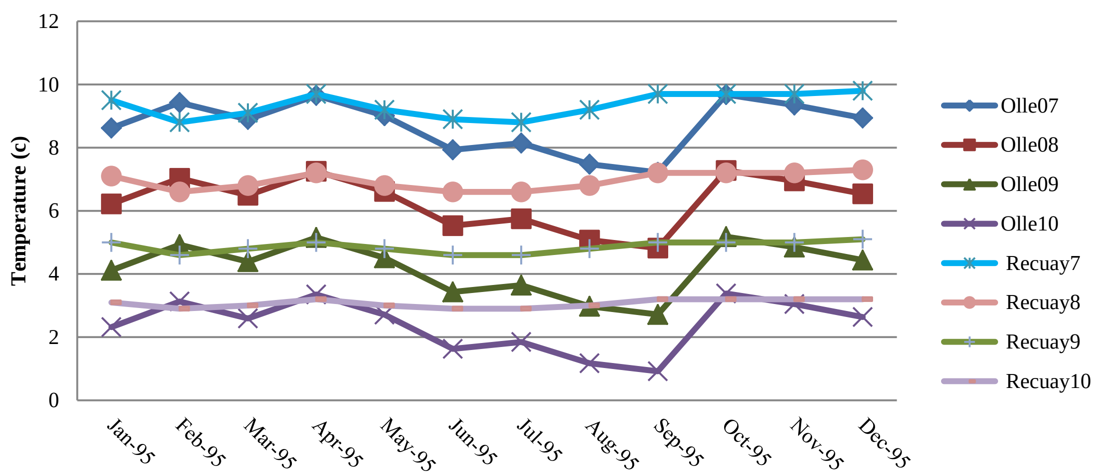

Figure 24: Comparison between 1995 monthly temperatures for elevation bands 7-10 used in the original model at Recuay (light) and CFSR values processed at Olleros (dark)

Maximum wind speeds were considered to have an annual variation and scaled down to represent averages using the historic monthly values as a correction factor:

$$U_{wind(mon)} = \frac{AnnAvg}{CFSRvalue} * HistoricMonAv \quad (1)$$

The validity of the CFSR dataset for use in the Santa River basin was evaluated based on comparing precipitation and stream flow in the following ways:

- Precipitation: monthly averaged CFSR precipitation totals for the three catchments—Llanganuco, Querococha and Paron—were compared with historic gauge precipitation from the three catchment stations from 1967-1999
- Stream flow: WEAP-computed flow at La Balsa, Querococha, Colcas, Chancos, Pachacoto using CFSR precipitation and temperature data were compared with calculated flows using the original climate data

3.6 Statistical analysis

In order to quantify how changes in water demands and population affect stream flow in the Santa River and its glacial sub-basin tributaries, several statistical tests were applied at four stations in the basin. The coefficient of determination (R^2), coefficient of efficiency (Nash) and index of agreement have been documented as appropriate tests for hydrologic data (Legates and McCabe Jr. 1999) and were thus computed for flows at the La Balsa, Chancos, Pachacoto, Querococha and Colcas stations in both the original and modified WEAP models. These same statistical parameters were used to validate CFSR climate and flow values with historic data for 1995 and 2007-2008 simulations.

3.7 Scenario exploration

In accordance with future projections of development in the upper Santa River basin, two alternate scenarios were simulated in WEAP and compared on a sub-watershed scale:

- A 50% reduction in the total potato crop and a corresponding increase in maize production within each sub-basin; as temperatures increase in the high altitudes, potatoes will become more susceptible to disease while maize will be grown at higher altitudes in the warmer climate; and
- A 10% reduction in monthly precipitation for catchments located above -9° latitude in the upper Santa basin; this corresponds to hypothesis that regional climate models will show a decrease in atmospheric moisture in the inner-tropics

Chapter 4: Results and Discussion

4.1. WEAP GLACIER MODEL WITH IRRIGATION DEMANDS

Initially the WEAP model was run with the aforementioned changes in irrigation and municipal water consumption rates. Results from five historic stream gauges at catchment outlets were compared to model outputs for 1969-1997. The five stream flow gauges at La Balsa, Colcas, Pachacoto, Chancos and Querococha were selected to represent comparison points for the upper Santa basin as established in the Methods section.

Three statistical tests were computed comparing both the original WEAP model and the irrigation model to historic stream flow gauge data. The coefficient of determination (R^2) is a parametric test that quantifies correlation strength between observed (O) and predicted (P) datasets (scale of 0 to 1) and is analogous to Pearson's r:

$$R^2 = \left\{ \frac{\sum_{i=1}^{N}(O_i - \bar{O})(P_i - \bar{P})}{\left[\sum_{i=1}^{N}(O_i - \bar{O})^2\right]^{0.5}\left[\sum_{i=1}^{N}(P_i - \bar{P})^2\right]^{0.5}} \right\}^2 \qquad (2)$$

The index of agreement (d) compares the mean squared error to the potential error on a scale from 0-1, where higher values correspond to better agreement between the datasets (Legates and McCabe Jr. 1999):

$$d = 1.0 - \frac{\sum_{i=1}^{N}(P_i - Pi)^2}{\sum_{i=1}^{N}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \qquad (3)$$

The Nash-Sutcliff coefficient of efficiency (E) is one minus the ratio of the mean squared error to the variance of the observed data, with a range from negative infinity to one (Nash and Sutcliffe 1970). A zero value indicates that the model is as good a predictor as the observed values, and positive values indicate that the model is a better predictor than the observed means:

$$E = 1.0 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2} \quad (4)$$

The original model performed well over the 28-year period for four of the five selected catchments, especially at the most important La Balsa point (E = 0.70), but had a lower correlation ($R^2 = 0.59$) and a negative Nash coefficient (E = -0.64) for the Chancos sub-basin as compared with gauge flows (Table 8).

Table 8: Statistics for stream flow comparisons between original model and gauge data

Station	R^2	d	E
La Balsa	0.78	0.89	0.70
Pachacoto	0.65	0.87	0.62
Chancos	0.59	0.63	-0.64
Querococha	0.75	0.80	0.29
Colcas	0.67	0.67	0.80

Similarly, the modified irrigation model performed well at La Balsa (E= 0.68), and also at Querococha, Pachacoto and Colcas, but, as in the original model, the monthly average flows in Chancos (R^2=0.59, E = -0.66) were not well reproduced over the 32 year period (Table 9). Since this establishes the irrigation model as a reasonable tool relative to the original model using historic data, further simulations are focused on the modified model and since the additions are improvements to the robustness of the model. Figure 25 shows stream flow at La Balsa from 1967 to 1999 comparing the irrigation model (blue) to gauge flow (orange). Seasonal flow variation is well captured throughout, however extremely high flows due primarily to El Niño/La Niña interference are not reproduced, and modeled low flows during the 1990's drop below observed values.

Table 9: Statistics for stream flow comparisons between modified model and gauge data

Station	R^2	d	E
La Balsa	0.78	0.90	0.68
Pachacoto	0.68	0.81	0.38
Chancos	0.59	0.64	-0.66
Querococha	0.75	0.91	0.69
Colcas	0.48	0.67	0.099

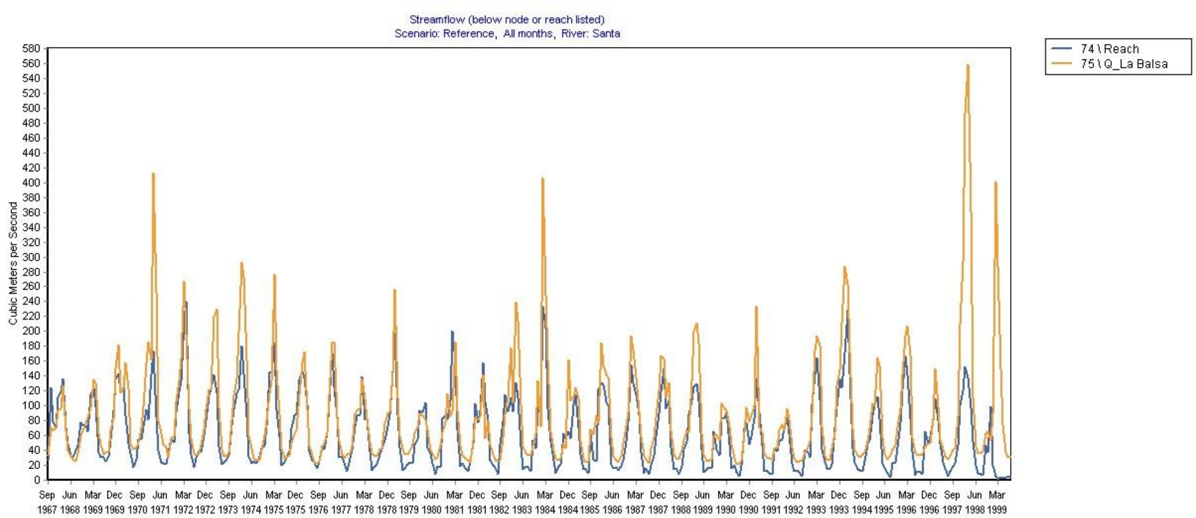

Figure 25: Monthly stream flows (1967-1999) at the La Balsa station comparing modified model (blue) to the historic gauge (orange)

Comparing observed and modeled flows on a per-month basis over the 32-year time period indicates that the model is generally more successful during the wet season than the dry season at reproducing the flow magnitudes (see La Balsa in Figure 26 for example), and that the general flow pattern is recreated for all months even if the magnitudes are not. This may indicate that the glacial melt magnitudes are not well calculated in the model or that groundwater is a factor not accounted for in the dry season since both the irrigation and original models show this pattern. As expected based on the sub-basin statistics, modeled flows at Chancos are substantially lower than the observations; however, the correct seasonal shape is maintained (Figure 26).

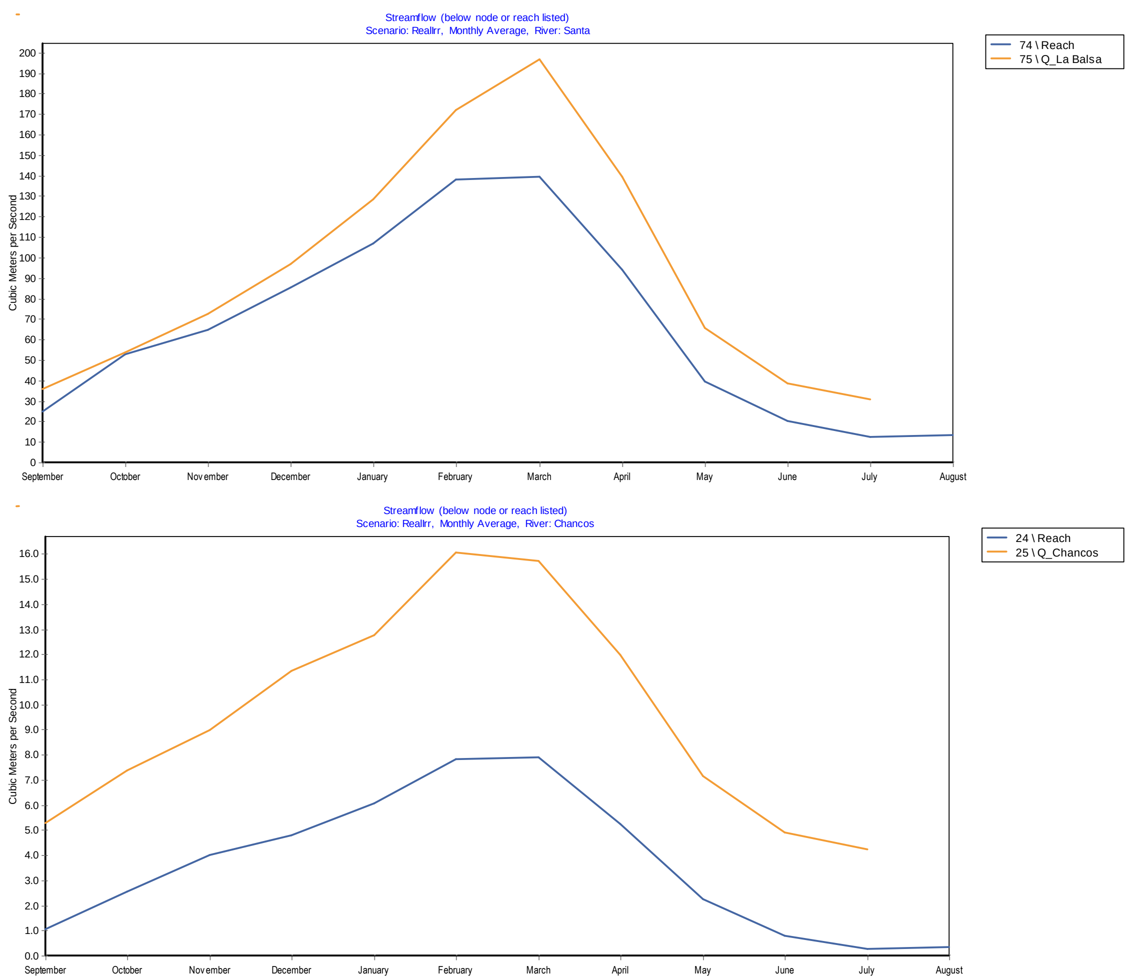

Figure 26: Monthly averaged stream flow distribution (1968-1999) at La Balsa (top) and Chancos (bottom) comparing the model (blue) and observed gauge flows (orange)

By analyzing a single month over the entire time period, this phenomenon of poorer representation of the austral winter months (May – Oct) is again illustrated, for example in July and August at La Balsa (Figure 27), a trend also seen in the original model. In addition, monthly comparison for July, August and September shows a diverging trend between model and observed flow over the years suggesting that the model performed better in the first 10-15 years closer to the calibration start time. Since this pattern is seen exclusively in the austral-winter, it indicates that the model is either not capturing a change occurring during the dry season in the upper basin, or that some hydrologic process in the glacial component contributing to melt in the dry season (or perhaps more recent accelerated melting) is not well understood. Since the glacier model does not include a radiation balance and historic data is currently unavailable, scientists can only speculate at this point about changes in the energy budget and the effects on melting. The wet season does not see this diverging trend; rather, the flows are reproduced well over the entire time period in shape and magnitude as seen for example during February (Figure 28).

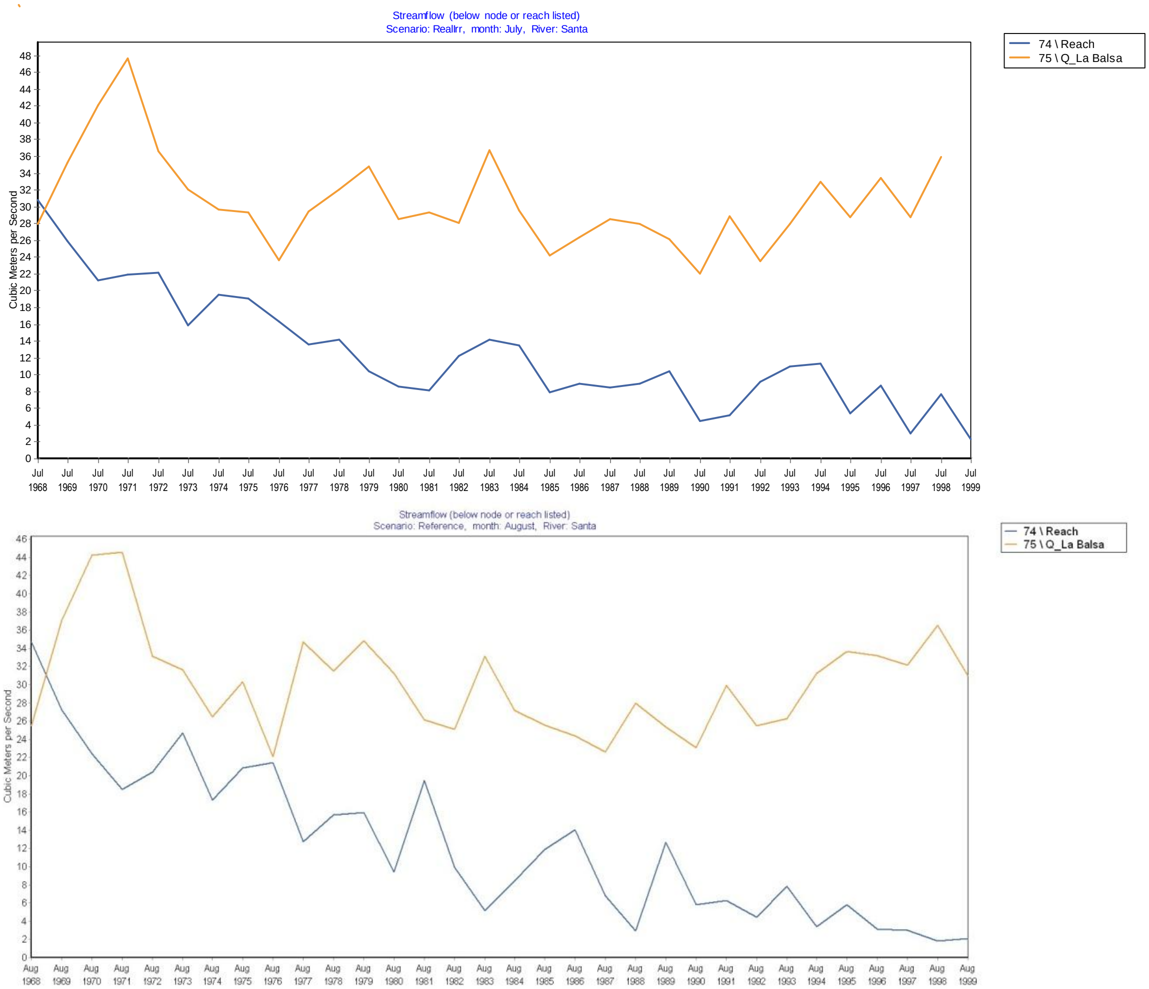

Figure 27: Monthly stream flow for July (top) and August (bottom) at La Balsa from 1968-1999, comparing the model (blue) to the observed gauge flow (orange)

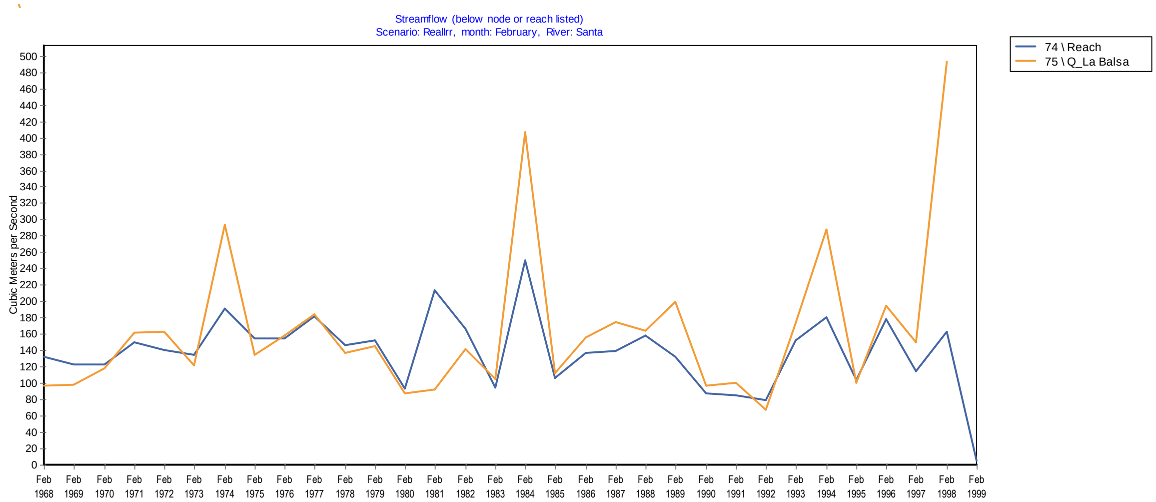

Figure 28: Monthly stream flow for February at La Balsa from 1968-1999, comparing the model (blue) to the observed gauge flow (orange)

4.2 COMPUTED IRRIGATION FLOWS

The 2007 irrigation demand for agriculture in the upper Santa basin was 250 million cubic meters (MCM) of water based on crop type, growth period and field data collection as reported by ALA (Instituto Nacional de Recursos Naturales 2008). Since the areas and crop types were derived from this ALA dataset, it was expected that the model would set aside for irrigation about the same amount of water, based on calculations within WEAP of soil moisture and potential evapotranspiration. Figure 29 shows the annual totals for irrigation in the upper basin as calculated by WEAP using original climate data over 1967-1999 with the Corongo sub-basin added (despite being downstream of Canon del Pato) since it was included in ALA's dataset for total irrigation of the upper basin. Results show that the average annual irrigation flow for the upper basin as is 150 MCM, about 40% less than the ALA total for 2007-2009. There are several possible reasons for this outcome, one is that more water per acre on average is being used to irrigate presently (2007-on) as compared with the past 30 years, but without having irrigation data available to compare, or climate data from 2007-2009 it is difficult to isolate the cause of this disparity. However, this explanation is rather counter-intuitive since the traditional ditch and canal irrigation systems have not changed significantly, and if anything irrigation efficiency would be more likely to improve rather than digress as technology and conservation methods press forward. Based on the ALA data, the required irrigation per hectare decreased slightly from 4,811 m^3/ha in 2007 to 4,745 m^3/ha in 2008. While it is also possible that the total irrigated land area may have increased over time since 1967, data do not show significant changes from 2007 (52,140 ha) to 2008 (50,864 ha). Since there is no clear trend in the irrigation data time series, it may be that the irrigation demand calculations in the model are too sensitive to calibrated soil moisture parameters such as upper and lower thresholds for irrigating, flow direction and conductivity factors.

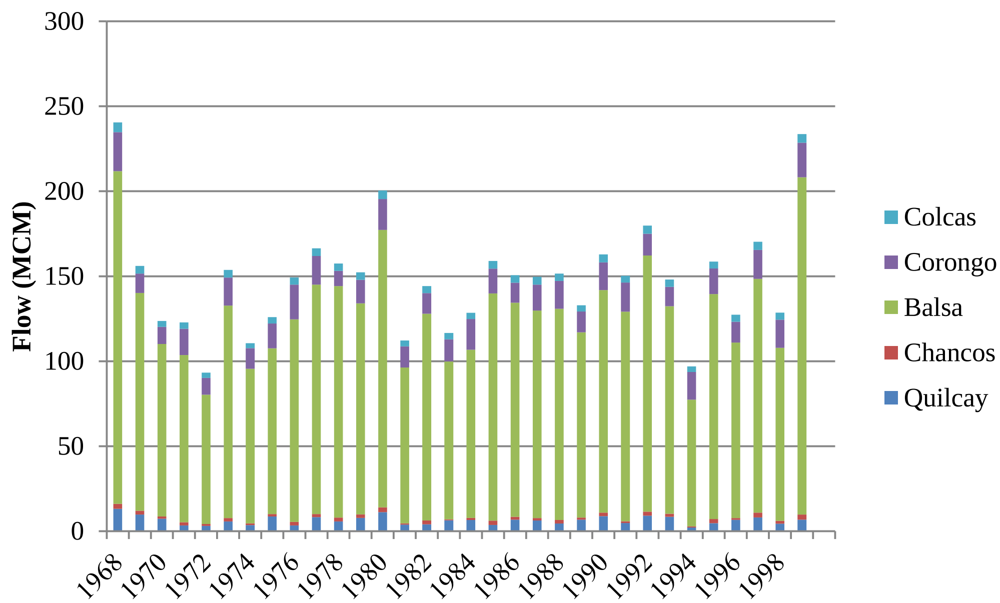

Figure 29: Total annual irrigation flow (MCM) calculated by WEAP and separated by sub-basin demands for 1968-1999

As indicated by the stacked bars in Figure 29, most of the irrigation in the upper basin is in the La Balsa region (81.5%) with Corongo comprising 10%, Quillcay with 4.5%, Colcas with 2.8% and Chancos with 1.2%. The La Balsa sub-basin contains the largest population centers as well as irrigation areas, two sectors that can be expected to be in competition for land and water resources in the future if growth and development continue to increase. The modeled irrigation demands for each month in La Balsa show peak needs during the dry season (up to 23 MCM/month in September) and falling to near zero in the wettest months (Figure 30). Glacial melt base flow in the dry season has enabled these demands to be met, a situation that is changing and expected to stress perennial water supply in the Santa basin.

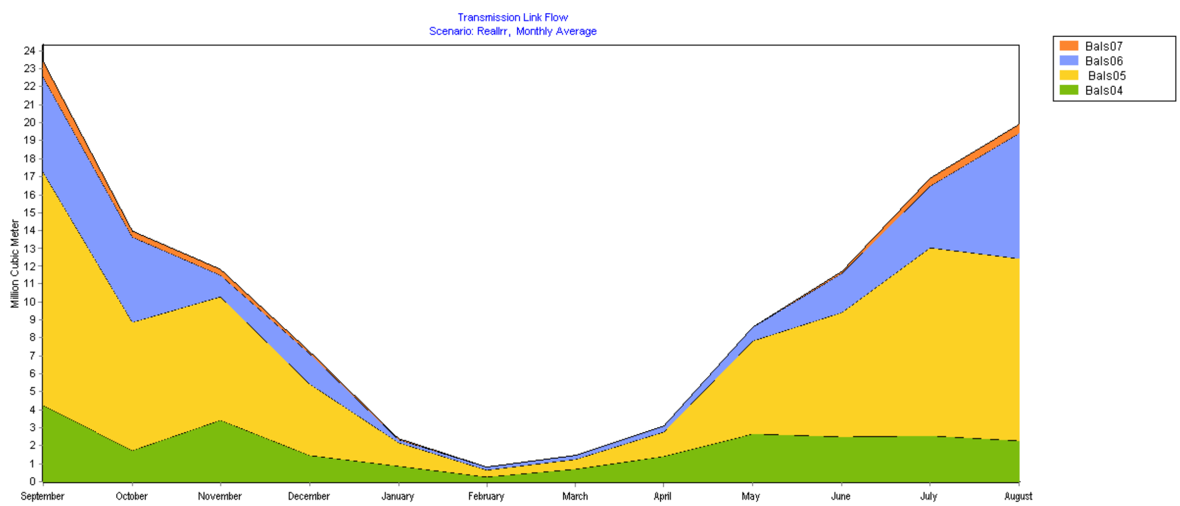

Figure 30: Monthly irrigation flows for La Balsa sub-basin averaged over 1968-1999

4.3 Evaluating CFSR data for the Santa River basin

In order to get a sense of the accuracy of the CFSR dataset compared with the historic observational data, a statistical comparison of CFSR data versus historic gauge data was conducted for monthly averages of precipitation, temperature and humidity in

1995. Monthly average precipitation values from Querococha, Paron and Llanganuco were compared against observed data and results show that the seasonal precipitation pattern is captured throughout the year by the CFSR data, however the magnitude of the peak precipitation in January and February is not well reproduced (Figure 31a,b,c).

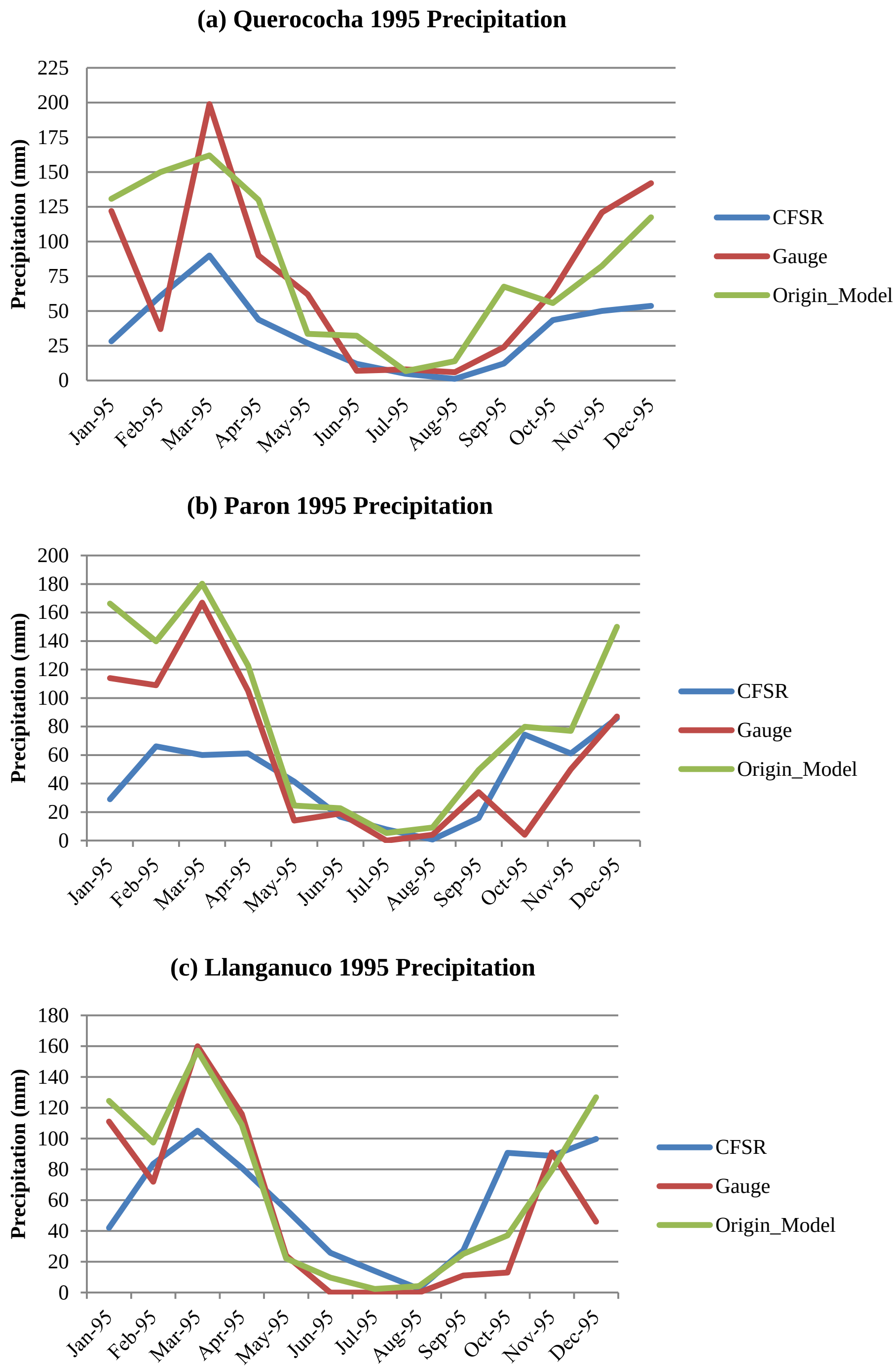

Figure 31: Comparison of monthly precipitation in 1995 between gauge (red), CFSR processed data (blue) and the original model (green) for the (a) Querococha sub-basin; (b) Paron sub-basin; (c) Llanganuco sub-basin

As illustrated in Figure 31, the original model captures the overall shape and magnitude of the monthly precipitation in pattern quite well. Statistical analysis indicates good agreement between the observed and CFSR precipitation data for all three catchments using the non-correlation based tests, but shows relatively low R^2 values (Table 10).

Table 10: Statistical summary of CFSR and historic gauge precipitation

Station	Pearson's r	R^2	d	E
Querococha	0.816	0.667	0.820	0.640
Paron	0.492	0.242	0.840	0.610
Llanganuco	0.639	0.409	0.910	0.695

Figure 32 provides a closer look at temperature differences for each elevation band and shows that the CFSR data has a greater monthly variation than the observed and interpolated Recuay station data; light colors represent Recuay temperature and the dark colors represent CFSR data for four selected elevation bands, where ideally the Pach7/Bals7 temperatures should align with Recuay7. An important discovery is that Recuay is not a great proxy for distributing temperature uniformly throughout the basin, as was done in the original WEAP model. CFSR temperatures at Olleros and Pachacoto show good agreement with the Recuay station; however, La Balsa CFSR temperatures are all about four degrees lower than the corresponding Recuay stations, suggesting that the bands should be shifted to find better agreement (e.g., change Bals7 to Bals9 to match Recuay9).

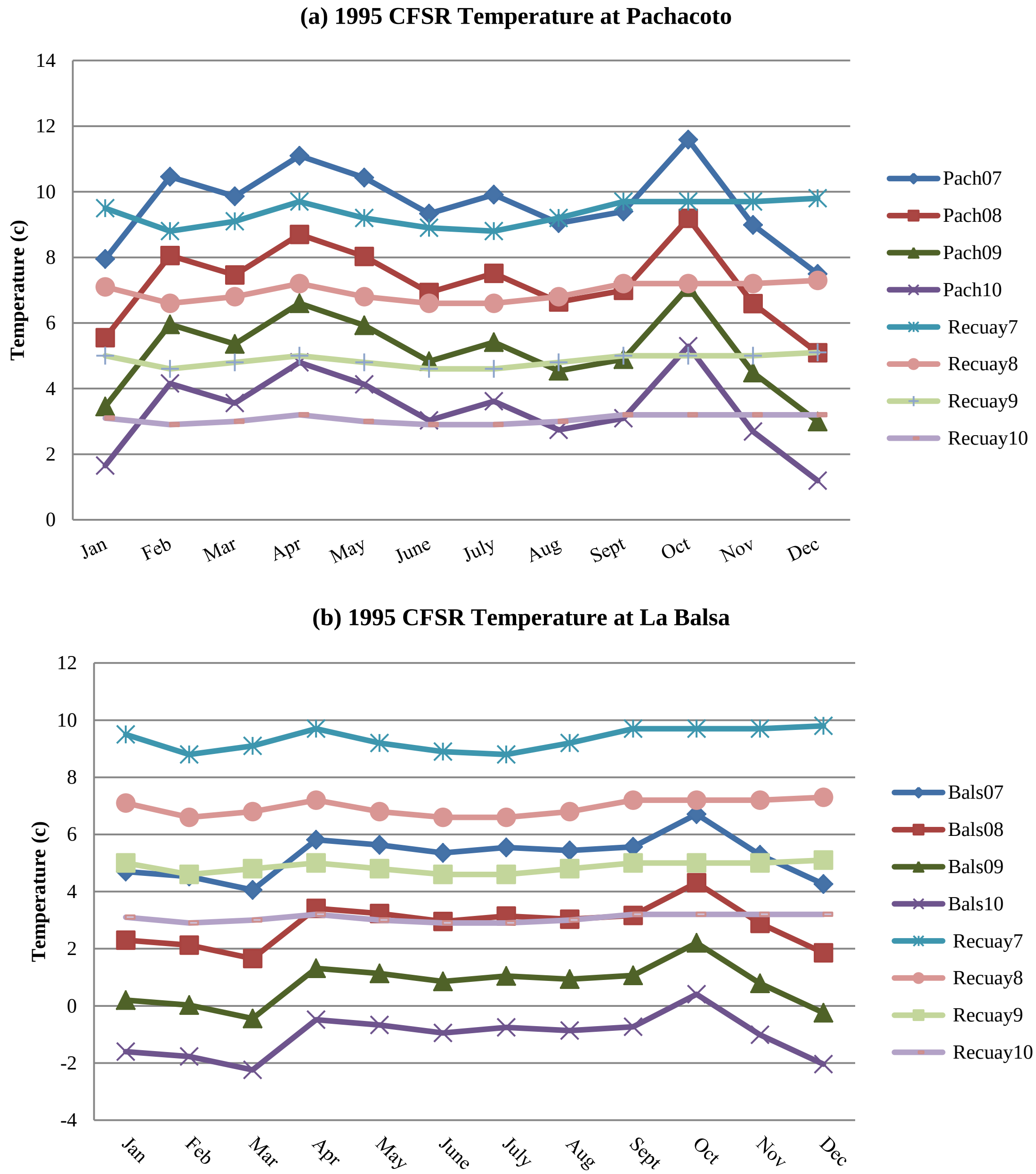

Figure 32: Comparison of 1995 monthly temperature input data at elevation bands 7-10 from CFSR (dark colors) to the existing model temperature derived from the Recuay weather station (light colors) at (a) Pachacoto (Pach), and (b) La Balsa (Balsa)

This situation raises questions of validity in the CFSR dataset and also with the processing methods at the Recuay station used in the original model. It seems there is a discrepancy that needs to be reconciled here as the CFSR data accounts for spatial temperature variability across the basin while the Recuay-processed data accounts for local elevation differences, but there is no overlap between them to consider both effects. With some catchments showing good agreement in temperature and others not, and no historic record to support one approach over the other, comparing stream flow may indicate how severe these discrepancies translate in the model.

Stream flow comparisons between simulations run with CFSR and historic climate data for 1995 continue to show that the model reproduces the seasonal pattern but not peak flows. Figure 33 shows comparisons for 1995 monthly stream flow at Querococha and La Balsa stations. Looking back at the precipitation comparison at Querococha, it is not surprising that the peak flow during March is not reproduced, and in fact verifies the direct effect of precipitation on stream flow without a noticeable storage time lag between rainfall and runoff. Interestingly, March is also a month of notable temperature decrease—much more pronounced in the CFSR data—which could explain why the peak flow is lower: if a portion of the precipitation and existing snow cover is calculated to remain frozen, less discharge will flow from the high elevations. In this way, discrepancies in input precipitation and temperature data build on one another and propagate into errors in stream flow output.

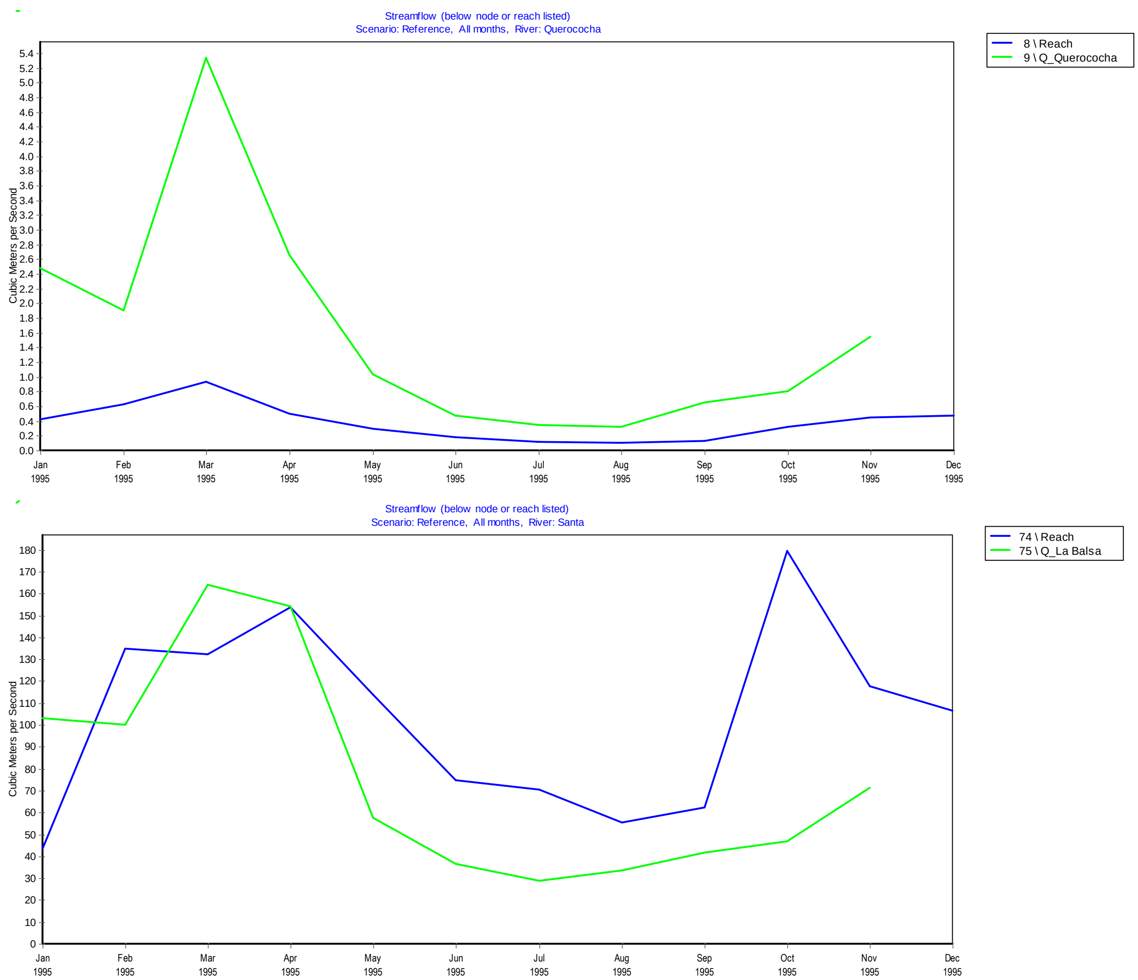

Figure 33: Monthly stream flow comparison over 1995 between the model (blue) and historic gauge data (green) at Querococha (top) and La Balsa (bottom) stations

According to the Nash coefficient (E in Table 11), the modeled stream flow using 1995 CFSR data is a poorer predictor of the mean than the observational data for all five sub-basins investigated. Large disparities in stream flow between the observations and the CFSR model must be due to differences in one or both of the CFSR variables for 1995: precipitation and temperature. One possible reason the flow values have such large discrepancies compared with the raw precipitation values is a result of internal processing of the glacier component in WEAP. Since the model is organized by elevation bands within catchments and precipitation falls as snow above a certain elevation depending on the temperature and location of the ELA, ultimately this model is constrained by the accuracy of temperature data at each band. A positive result of this comparison indicates that the zonal monthly averages of CFSR precipitation over these catchments provides reasonable representations of the historic data taken from a single station in each catchment, despite the relatively coarse resolution of the original grid cells.

Table 11: Statistics comparing observed flows to WEAP computed flows using CFSR data for 1995

Station	Pearson's r	R^2	d	E
La Balsa	0.429	0.184	0.63	-0.41
Pachacoto	0.177	0.031	0.45	-2.71
Chancos	0.234	0.055	0.42	-4.60
Querococha	0.797	0.635	0.39	-4.78
Colcas	-0.030	0.001	0.387	-4.776

A WEAP simulation was run for 2007-2008 using CFSR precipitations and the previously discussed temperature processing method, with irrigation demands activated. Results were compared at La Balsa using historic flows retrieved from Duke Energy (Figure 34). While the general shape is captured for 2007, the model does not reproduce 2008 well, as the wet season peak is shifted earlier (to Oct-Dec 2007) and flow in Oct-Dec 2008 is an order of magnitude larger than the observed flow values at La Balsa.

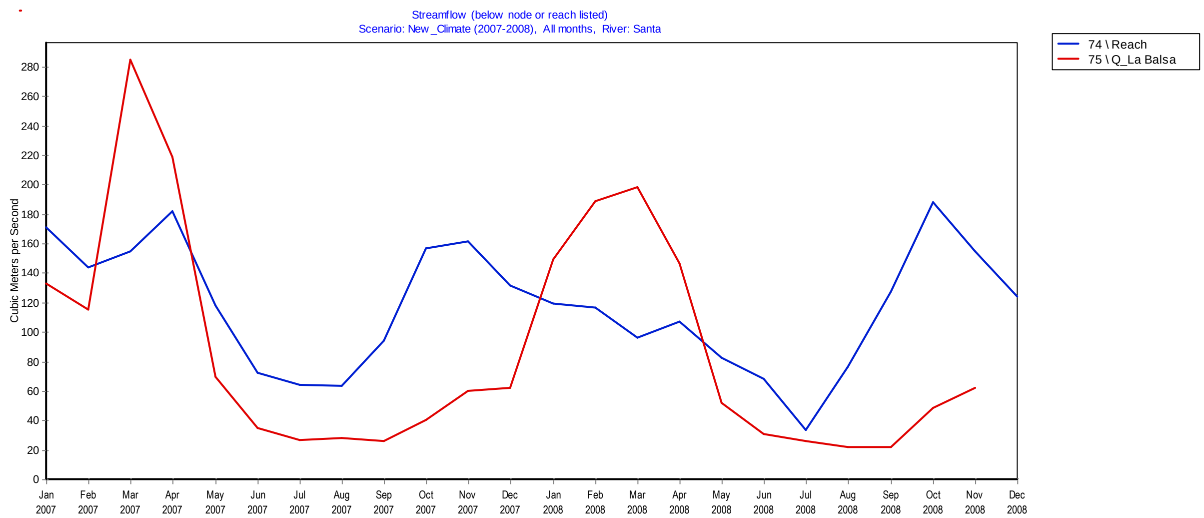

Figure 34: Comparison of stream flow for 2007-2008 between model (blue) and historic gauge data (red); CFSR precipitation and temperature were used in the model run

Statistics indicate that the model stream flow has a mean-squared error equal to that of the variance of the observed flow with a Nash coefficient of zero (Pearson's r = 0.421, R^2 = 0.178, d = 0.60). Since there is no observational data available to compare with CFSR precipitation and temperature values, it is difficult to narrow the source of error to any one of the four climate inputs (including humidity and wind speed). In both the 1995 and 2007-2008 CFSR simulations, stream flow results show a defined peak in October, one not seen in the gauge flows. This is likely due to a corresponding temperature spike in October that cannot be verified. The response of stream flow to temperature highlights the sensitivity of the model to changes in temperature and suggests that model stream flow may improve if this extra peak is removed or scaled.

4.4 Scenario results

As discussed previously, a strength of WEAP as a modeling application is the ability to define and simulate different scenarios in order to explore best management practices of a basin. Based on projections for future crop development in the Cordillera Blanca, farmers will look to replace a portion of their potato crop with maize for three reasons: market driven economic benefits, susceptibility of potatoes to diseases at higher temperatures, and the ability to grow maize at higher elevations due to extended warming periods. For this scenario, the potato crop was decreased by 50% in the sub-basins with cultivation, and subsequently added to the maize crop area. Results for simulating 1967-1999 over the upper basin indicate that replacing potatoes with maize increases water consumption per sub-basin compared to the original irrigation setup (Figure 35), mainly in the dry season. Comparing stream flow at the La Balsa outlet between the original irrigation model conditions and the 50% reduction in potatoes shows that on average (over 1967-1999) for 10 months out of the year, the irrigation requirement increased by up to 20 MCM per month on average during the dry season. While the changes overall are relatively minute (< 2 MCM per month on average) on a sub-basin scale, this trend can give communities a sense of how their actions can affect available resources. After working through this project and visiting the region, it seems that presenting a scientific assessment showing the potential consequences of a community's actions would encourage sustainable decision-making strategies.

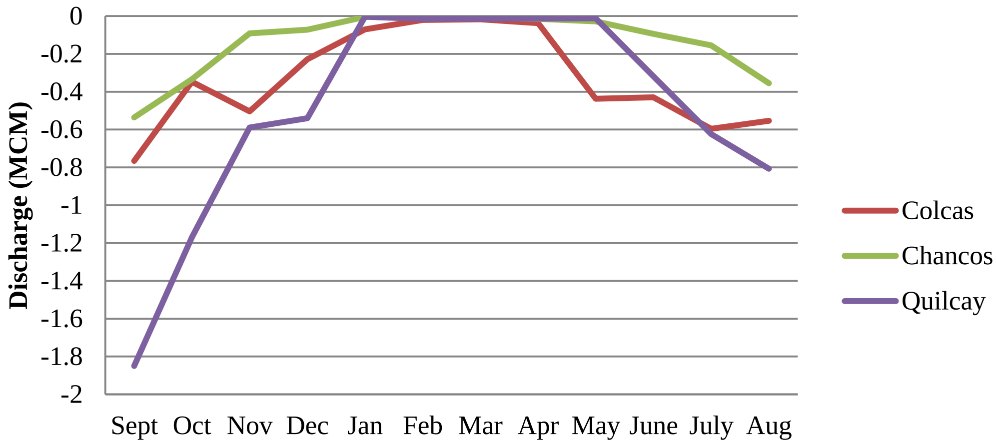

Figure 35: Average monthly discharge differences (1967-1999) between the irrigation model and a scenario of a 50% reduction in potato crop with a corresponding increase in maize crop area in the upper Santa River basin

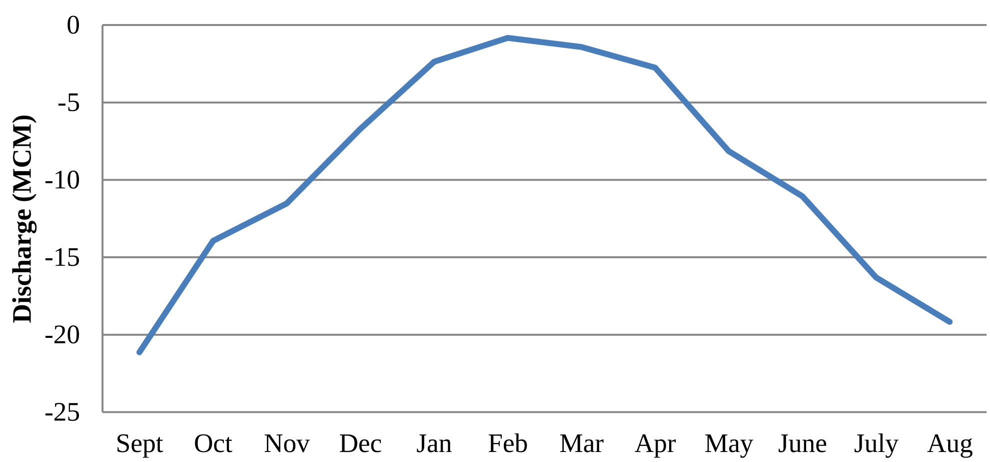

Figure 36: Comparison of monthly average stream flow data at La Balsa (1967-1999) between the original irrigation model and 50% potato crop reduction scenario

The second scenario explored was to analyze how a uniform monthly 10% reduction in precipitation at latitudes within -9° would affect stream flow in the upper basin. This scenario was inspired by the IPCC climate model projections that on average, annual rainfall will decrease on the west slopes of the Cordillera Blanca in future decades (IPCC 2007). The Japanese Earth Simulator shows an overall decrease in precipitation, but a slightly rainier wet season with simulations at nested (20 km) high resolutions (Vergara, Kondo, et al. 2007) suggesting that future work should examine seasonal precipitation scenarios. After selecting the catchments above -9° and applying a 10% reduction in precipitation to the 1967-1999 inputs, results were compared to the modified irrigation model at the La Balsa (Figure 37) outlet. Flow differences at Chancos, Querococha and Pachacoto indicate a reduction of about 0.9 m^3/s per month.

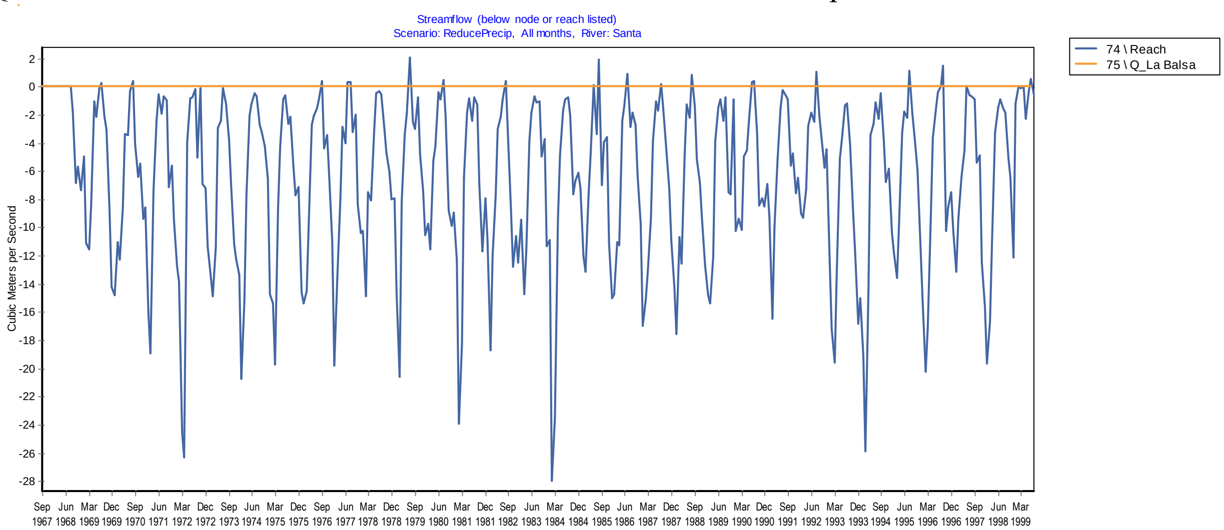

Figure 37: Differences in stream flow (m^3/s) for scenario with 10% decrease in precipitation to the modified irrigation model over 1967-1999 at La Balsa (yellow line indicates no difference)

Monthly averages over the 32-year time period were also compared to the irrigation model at La Balsa and indicate a reduction in stream flow all year, with up to a

26 m^3/s decrease in February and March, the wettest months of the year (Figure 38). This result further supports the theory that stream flow is dominated by glacial melt, especially in the dry season when a 10% decrease in precipitation only affects discharge by 2 to 3 m^3/s per month. From this, two concerns for the future water security of the basin arise: (1) a decrease in precipitation could translate to about 73 MCM in February and March alone (204 MCM per year on average), greatly reducing agriculture production and storage for municipal use and hydro-electric power; and (2) glacial melt is essential to providing water for economic and social services in the dry season, and these processes will be significantly impacted when melt is no longer occurring at the same rates.

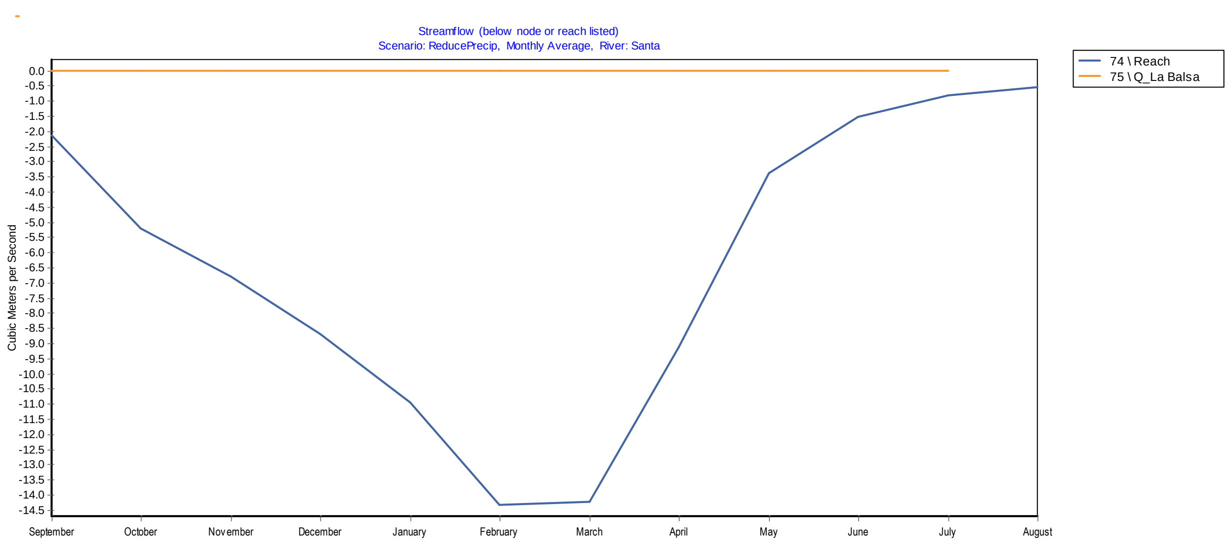

Figure 38: Change in average monthly stream flow at the La Balsa station when 10% decrease in rainfall is applied to catchments within -9° compared to the irrigation model

In terms of how this would affect irrigation in the upper basin, most catchments receiving irrigation would experience increased demand all year compared to the normal irrigation setup. Bals05 and Bals06 are affected most, requiring up to 0.85 MCM of additional water in October, June and July. The monthly distribution is presented in Figure 39, where the relatively minor differences in flow are another indication of the role glacial melt plays on maintaining stream flow levels year-round. Despite the small disagreement from October to December between each sub-basin, these differences are within the model's margin of error and so are not considered. However, this scenario shows that during the wet season changes in precipitation do not greatly affect irrigation stream flow simply because in these months precipitation is sufficient and extra water is not diverted for irrigation.

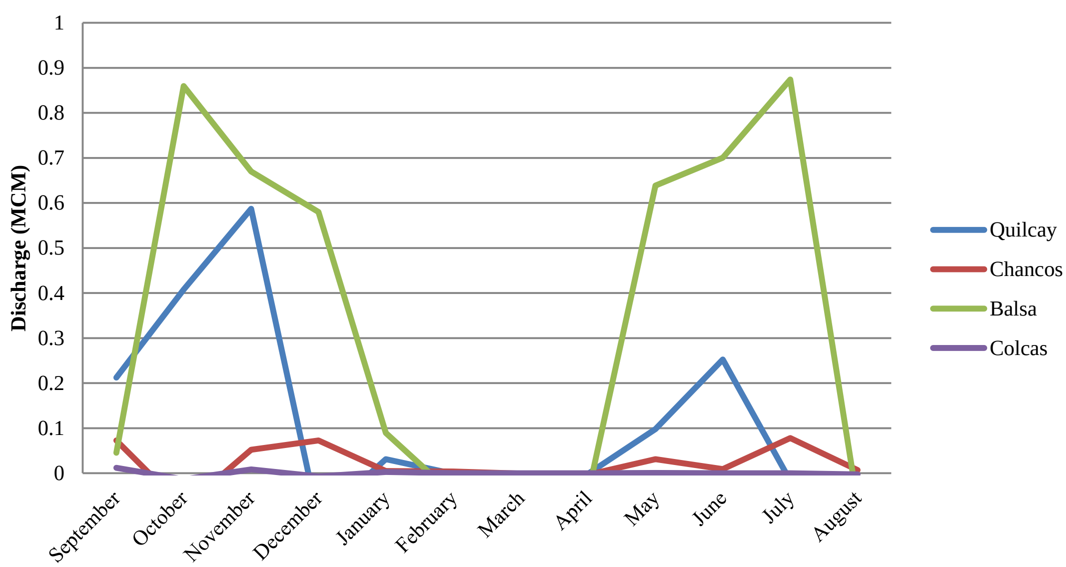

Figure 39: Monthly averaged irrigation flows (1967-1999) comparing the 10% decrease in rainfall scenario to the irrigation model for each sub-basin receiving irrigation

Changes in the La Balsa irrigation flows (Bals04-07) suggest that some months would actually require less water for irrigation if precipitation decreases by 10% (Figure

40). This result is counter-intuitive as, everything else being equal, a decrease in rainfall should add stress to water availability in the basin for irrigation or in the best case, cause no difference in required discharge. One explanation for this result could be that the irrigation calculations in WEAP are breaking down; potential evapotranspiration is calculated based on differences in the moisture levels between the top and bottom soil layer, so if these are considered to be both low or both saturated, the evaporation will be lower when in actuality the crops will still require this water delivery.

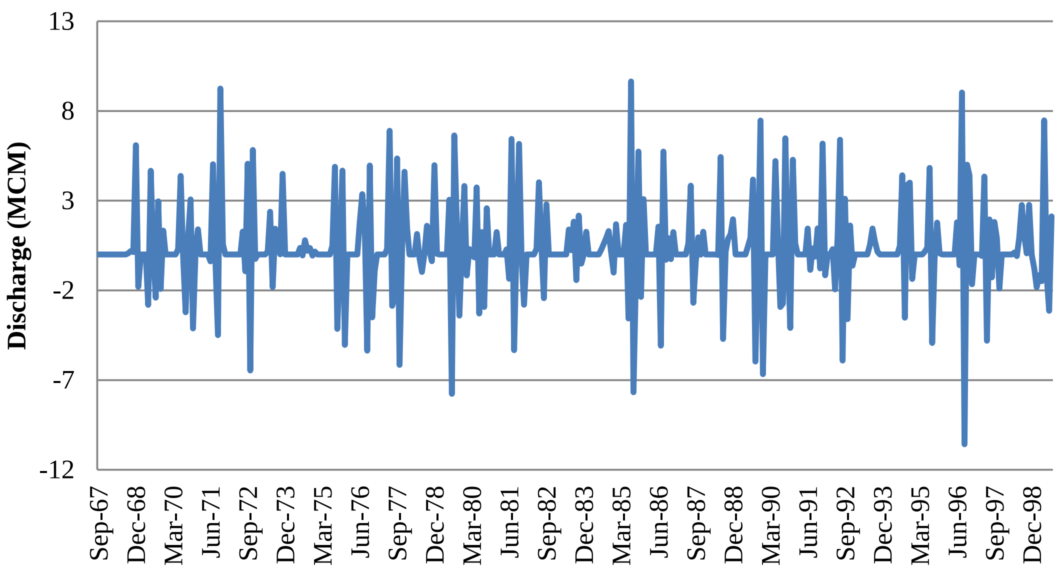

Figure 40: Monthly changes in irrigation water (MCM) due to a 10% decrease in precipitation (compared with irrigation model) for each elevation band at La Balsa

Chapter 5: Conclusions

5.1 Implications of WEAP simulation results

Accurately depicting the hydrologic processes and active user demands of a river basin is an arduous task even under ideal circumstances, as sources of uncertainty are inherent within every measurement and dataset. The Santa River is certainly no exception as the size, tropical location and data inconsistencies associated with the basin lead to more assumptions made overall in an attempt to smooth out unknowns. In general, the modified irrigation WEAP application improved performance slightly compared to the original model and provides users with more opportunities to explore future scenarios. While it is encouraging that adding additional observational data contributes to better results, the relatively low magnitude of differences in monthly stream flow on a sub-basin scale were surprising considering the enormous impacts irrigation has on the river's users and water availability. The inability to capture high flows during extreme events and La Niña years speaks to the predictor capacity of the model, as these almost decadal occurrences alter the groundwater, storage and flood risk within the basin. Further investigation into the specific reasons for these large events and their frequency classifications would be beneficial for expanding community-level mitigation strategies for glacial lake flooding and the expected increase in storm severity.

The current parameterizations in the WEAP glacier model emphasize temperature as the main driver of glacial melt and ultimately stream flow, as confirmed in this project by comparing two different temperature datasets. However, since the basin is located in tropical latitudes where temperature is relatively uniform throughout the year at a given elevation, there are certainly other influential climatic phenomena at play. This raises concerns regarding use of the Degree-Day model in WEAP as temperature dependence may be overstated, downplaying the importance of other climate variables (e.g., radiation). Moreover, if the Degree-Day model is continued for application in the Santa River basin, it would be beneficial to compare with other research from the tropics to refine the basic parameters to be suitable for the tropics since previous studies document difficulty with Degree-Day models in this region (Sicart, Hock, & Six, 2008); since and, the parameters in the current model are based on mid-latitude glaciers (Condom, et al., 2010).

Another unclear aspect in the glacial component of WEAP is how the model accounts for physical interactions between snow, ice and melted water. In the model, when snow covers a glacier the underlying ice is considered to stay frozen and not contribute to melting, and instead only exposed ice is included in melting. This insinuates that in the austral winter months little melting occurs on the glaciers, a conclusion supported by the results in this study from a scenario of a 10% reduction in precipitation. However, cloud cover effects, albedo and positive feedback melting mechanisms, and changes in humidity and ground flux are mechanisms that need consideration separate from temperature.

This discussion implicates the introduction of an energy balance component in WEAP to account for fluctuations in radiation intensity and potential evapotranspiration. This would be a viable addition to help address parameterization uncertainties and verify the validity of the glacier section and climate assumptions. Recently a model was introduced for tropical (specifically Central Andean) glaciers that treats sky long-wave irradiance as a proxy for seasonal variance in the energy flux, with results showing that changes in cloud cover are more influential than temperature (Sicart et al., 2010). Incorporating this model or one similar as the basis for calculating glacial mass balances will improve model performance and give confidence that the local physical processes dominating the region are well represented. With advancements and improved access to global datasets like CFSR (Saha, Suranjana and Coauthors 2010) and Moderate Resolution Imaging Spectroradiometer (MODIS), it may be feasible to greatly improve and update the model for the Cordillera Blanca region.

In terms of improving model through the CFSR dataset in the Santa River basin, using available hourly time-series data may provide a more accurate alternative to the monthly mean data used in this research. Unfortunately, to date there is no composite file available for the time series, rather each hourly increment must be downloaded individually, totaling 8760 files needed for one year. CFSR outputs are also available at the 700 hPa (~5500 m) level (as well as a number of other elevations relevant to the Santa Basin) on the hourly time-scale; this pressure level corresponds approximately with the elevation of Huaraz, making it easier and more accurate to appropriately scale the data to the elevation bands for use in WEAP. Since observational data are difficult to obtain in the Santa Basin, both in terms of variable selection and record length, exploring the capabilities of CFSR data is a worthy venture. Other remote-based sensory datasets like MODIS can provide cloud cover and radiation values helpful for including an energy balance in the future.

5.2 SCENARIO IMPLICATIONS

The two scenarios explored in this analysis serve as examples for future investigations that can address the needs and direction of development in the communities of the Santa River Basin. Since nearly all families in the rural Cordillera Blanca practice some scale of land cultivation, efficient water use and irrigation methods are of general concern to the public. The analysis from scenario 1 shows that the model is able to trace how alterations in crop selection will affect stream flow on a sub-basin scale. This finding supports a main goal of this research as it suggests that the model may be used as a tool within the communities for assessing best land management strategies. Future work in this area should verify the WEAP irrigation calculations with field work to quantify the uncertainty and error margin in the model. Once this has been established, the next step is to get input from the communities as to their future development goals and use WEAP to analyze these possible scenarios. This work becomes more feasible since communities in the upper basin are taking a pro-active approach to conservation and adaptation by getting involved with groups like TMI and organizing into action committees. Adding scientific assessment to the communities' proposals and decision-making processes will strengthen their cases when applying for regional and federal funds to build and maintain infrastructure.

Climate change affects regional weather in the Santa River basin non-uniformly from the upper to lower basin due to drastic geographic differences in the basin. In expectation of new IPCC results projecting rainfall to decrease in Andean tropical latitudes between 9º and -9º in the future decades, scenario 2 explored a 10% rainfall reduction over the appropriate sub-basins. The model results show that stream flow in the wet season was significantly reduced while flow in the dry season remained relatively constant, implying that enhanced storage will become an important adaptation even for use in the wet season. Once again, field testing is needed to validate WEAP stream flows since precipitation was derived for each elevation band instead of from observation; losses and ground water interactions are not understood adequately enough for application. This research can help support motivation for improving hydrologic measurement equipment in the basin by providing evidence that the current system leaves too many unanswered questions. An interesting direction for this line of work would be to involve the communities in a small sub-basin case study in the scientific process of gathering hydrologic data and operating instruments. This could be another way to foster community cohesiveness and encourage pro-active role taking for adaptation and mitigation strategies.

5.3 Lessons from the Field

A significant contribution of data and learning for this research occurred during summer 2010 while visiting the Cordillera Blanca region of Peru. In collaboration with The Mountain Institute and the National Water Authority, field visits to high mountain lakes and rural communities were made possible, adding a personal element to this experience that cannot be overstated. Reflecting on this trip, several cultural lessons stand out as crucial regional factors unique to working in Peru. Namely, visiting the research sites with seasoned experts and visually inspecting the lakes and distribution systems with local residents changed the motivation of this project from simply producing a river basin model to creating a useful tool for people to make educated decisions regarding their water supply and land development.

As alluded to in Chapter 2, Peruvian politics directly influence the maintenance and progress of hydrologic information and sharing. While in Peru, it became clear that Lima central government agencies like ANA are willing to work with students and professionals but require written documentation stating the goals of both entities before making exchange agreements. While this encourages personal communication and relationship building, it is inconvenient and inhibitory for online information sharing since traveling to Lima is not always within the scope of a project. Even with the letter of support, receiving data from the water agencies is not easy since there is no communication network setup between the SENAHMI weather agency, ANA, universities, and the smaller regional governments who oversee infrastructure construction and maintenance. This disconnect makes it extremely difficult to collect all the data needed for a water-related project as it entails personally meeting with each separate organization and obtaining support letters. While international interest has bridged this gap and helped connect these entities, the progress has not been sufficient to overcome the traditional data sharing customs. Part of this issue is likely related to the anxiety caused by the tumultuousness of the Peruvian government during Presidential elections, as the outcome can result in the closure of certain agencies as ANA was for several years in the late 1990's. With international pressure to act on climate change and address social issues it seems unlikely that future Presidents will choose to inhibit climate data collection; however, if a consortium of experts in the field banned together to provide support for organized teamwork between these entities, further progress may arise.

Along with communication issues related to data collection, another issue is that a large percentage of the historical records are hand-written and have not yet been translated into electronic form. This drastically reduces data accessibility to those able to visit the appropriate offices and take the time to transfer information. The threat of losing these historic data is also a concern as natural disasters or accidents could wipe out original copies of paper documents and devastate the already spotty historic record of certain climatic and hydrologic measurements in the region. Technology infrastructure improvements are needed to protect and share Peru's historic data records, potentially in an Open ML network or through a CUAHSI type system.

5.4 Future work summary

As detailed earlier in the context of this section, there is great opportunity for future work involving WEAP model improvements especially regarding assumptions and parameterizations of the glacier component. Currently, simulations with the CFSR climate variables show that the dataset is acceptable for representing temperature and precipitation in the upper Santa basin, but the model does not produce adequate results for stream flow in the selected catchments. A radiation balance addition and additional historic and field measurement data would allow better calibration and validation of WEAP stream flow calculations and better evaluation of the CFSR climate dataset.

Two elements not explored in this analysis are (1) the role of groundwater and (2) water quality in the Santa River basin. A recent study by Mark et al. (2010) points to the lack of groundwater characterization as a possible unexplored resource, especially since glacial melt can feed directly into the sub-surface given certain soil types. If groundwater resources prove to be abundant, future projects by the communities through support from groups like TMI and Engineers Without Borders may look to building wells and infrastructure to tap into this clean water supply. On a similar note, access to fresh groundwater might help solve the significant problem of poor water quality in the Santa River and several of its tributaries. Contamination from mine tailings, pollution and natural minerals in the water cause certain stretches to be void for any use besides hydropower. There has not been an overall assessment of the extent of pollution and its source in each sub-basin, a study that would benefit the communities in terms of educating residents on the safe uses for their water and for locating non-toxic future water sources. With knowledge of the contamination specifications, the government and non-profit organizations could identify and implement low-cost and low-maintenance solutions as have been tested in other analogous studies.

Working on a comprehensive river basin model has conjured more questions than can be addressed here, but which can be feasibly answered through development of communication strategies and improvements to the WEAP model. From this analysis, the rural Cordillera Blanca communities need technical guidance to supplement their decision-making on water supply and climate change issues. Implementing a management model like WEAP is a positive and holistic approach for addressing these concerns as it facilitates a way to translate from technical science and modeling into practical application for people to utilize.

Appendix

1: Defined ranges for elevation bands in the WEAP glacier model

Z bands	Elevation range (m)
1	0-500
2	500-1200
3	1200-1900
4	1900-2600
5	2600-3100
6	3100-3600
7	3600-4000
8	4000-4400
9	4400-4700
10	4700-5000
11	5000-5300
12	5300-5600
13	5600-5900
14	5900-6200
15	6200-6500
16	6500-6800

2: Example Python script for processing CFSR climate variables

```
# ---------------------------------------------------------------------------
# climate_testing.py
# Created on: Sat Oct 30 2010 11:50:55 AM
#   (generated by ArcGIS/ModelBuilder)
# ---------------------------------------------------------------------------

# Import system modules
import sys, string, os, arcgisscripting,glob

# Create the Geoprocessor object
gp = arcgisscripting.create()

# Check out any necessary licenses
gp.CheckOutExtension("spatial")

# Load required toolboxes...
```

```
gp.AddToolbox("C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Spatial Analyst
Tools.tbx")
gp.AddToolbox("C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Data Management
Tools.tbx")
gp.AddToolbox("C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Multidimension
Tools.tbx")
inputpath = 'C:\\lkr435\\perumaps\\cfsr'
for infile in glob.glob(os.path.join(inputpath,'pgbh06.gdas.*.nc')):
        print 'Current file processing is: '+infile
        pgbh06_gdas_199501_grb2_nc = infile
        #Get the file name date
        fileID = infile.title()
        dd = fileID.rsplit('\\')
        xx = dd[-1].split('.')[2]
        # Local variables...
        Total_precip = "Total_precip"+xx
        #pgbh06_gdas_200701_grb2_nc =
"C:\\lkr435\\perumaps\\cfsr\\pgbh06.gdas.199501.grb2.nc"
        precip0195 = "C:\\lkr435\\perumaps\\RioSanta.mdb\\precip"+xx
        precip0195_Resample =
"C:\\lkr435\\perumaps\\RioSanta.mdb\\precip0195_Resample"+xx
        means_precip0195 = "C:\\lkr435\\perumaps\\cfsr\\output\\means_precip"+xx
        subcuencas = "C:\\lkr435\\perumaps\\RioSanta.mdb\\Peru1\\subcuencas"
        # Process: Make NetCDF Raster Layer...
        gp.MakeNetCDFRasterLayer_md(pgbh06_gdas_199501_grb2_nc,
"Total_precipitation", "lon", "lat", Total_precip, "", "", "BY_VALUE")
        # Process: Project Raster...
        cs='C:\\Program Files\\ArcGIS\\Coordinate Systems\\Projected Coordinate
Systems\\National Grids\\Peru Central Zone.prj'
        gp.ProjectRaster_management(Total_precip,precip0195,cs, "NEAREST",
"29401.033885", "PSAD_1956_To_WGS_1984_1", "",
"GEOGCS['GCS_WGS_1984',DATUM['D_WGS_1984',SPHEROID['WGS_1984',6378
137.0,298.257223563]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433
]]")
        # Process: Resample...
        gp.Resample_management(precip0195, precip0195_Resample, "3000",
"CUBIC")
        # Process: Zonal Statistics as Table...
        gp.ZonalStatisticsAsTable_sa(subcuencas, "NAME", precip0195_Resample,
means_precip0195, "DATA")
        print 'file: ',infile,'is processed successfull'

print 'All files in the directory have been processed'
```

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