Disappearing Glaciers: Exposing Vulnerabilities in the Rio Santa Basin Water Supply

LWS 548 Major Project

By: Cole Dinsdale

Master of Land and Water Systems

Faculty of Land and Food Systems

University of British Columbia

Vancouver, British Columbia

15 August 2021

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to Dr. Hans Schreier for his guidance and insightfulness throughout the development of this project along with his endless knowledge and interest in my work. Furthermore, I would like to thank Dr. Les Lavkulich, Autumn Watkinson and our program assistant Megan Bingham for helping me navigate my academic interests towards taking on a topic like this. I am grateful for all of their support throughout this past year while tackling the challenges of online education.

Lastly, I would like to thank all of my MLWS colleagues that made this past year unforgettable. Everyone has been very supportive and encouraging as we have ventured into our own projects in these unprecedented times, and I thank you all.

EXECUTIVE SUMMARY

Climate change drastically impacts regions worldwide, with some being more vulnerable to changing climatic conditions than others. The Rio Santa Basin contains the largest glaciated mountain range in Peru, the Cordillera Blanca, and these glaciers are experiencing rapid retreat. The glacierized mountains are the main water source for the basin by providing meltwater for agriculture, industrial, and domestic use throughout the year.

Climate projections consider both high and low emissions and population scenarios. Each case estimates significant warming in the tropical Andes between three and four degrees Celsius. With significant warming in the region, the high mountains may be increasingly vulnerable due to the ice-albedo feedback loop, therefore increasing the rate of glacial melt in the area. Most glaciers in the Cordillera Blanca have passed or are near the "peak meltwater" stage, meaning decreased flows are predicted into the future and, depending on the extent of glacier recession, annual flows in the Santa River may decrease by up to 30%. The impact during the dry season would be more severe, with estimated flow reductions ranging from 50 to 84%. A downward trend in water supply has already been reported in the basin, along with increased seasonality.

Future increases in population in conjunction with a swelling of inbound and domestic tourism at rates of 1.23%, 5.99% and 2.44% respectively will lead to increases in water consumption. Positive trends in export agriculture and mining result in greater water consumption and quality issues in an already water stressed basin. For example, fruit exports have grown by $3 billion USD in Peru from 2010 to 2020, with many crops being highly water intensive.

Consequently, the Rio Santa Basin should focus on transitioning away from water intensive crops such as mangos, artichokes, asparagus, and avocados and switch to low water use options. Crops like pineapple, tangerines, green beans, and other vegetables have much lower water use, but still maintain a relatively high export value. Furthermore, government support in educating and funding smaller scale farmers to install efficient infrastructure or learn better irrigation methods will effectively reduce unnecessary water usage.

1.0 INTRODUCTION

It is common knowledge in the water resource community that mountains are considered earth's water towers due to their yearly cycle of snow accumulation and melt. During warmer seasons glacial ice and snow will melt, releasing water downstream to overcome seasonal dry spells or long-term droughts. This meltwater originates from high mountain glaciers and is often the sole water source for many high mountain communities. Without meltwater contributions buffering dry season stream flow, growing season will be drastically shortened, hydropower generation will be reduced and drinking water availability will be minimized. This is the reality of the Rio Santa Basin in Peru. The Santa River originates in the Peruvian Andes, more specifically the Cordillera Blanca Range in the arid western part of the country, as noted in figure 1. This basin includes large population centers both upstream and downstream including Huaraz, Chimbote, and Trujilo which gives rise to water competition and various conflicts between communities in the basin.

The region relies heavily on meltwater contributions during the dry season from May to September, when minimal rainfall occurs. Most precipitation occurs in the wet season from October to April when snow accumulation occurs in the glacierized mountains of the Cordillera Blanca. These glaciers buffer runoff by releasing meltwater throughout the year. Meltwater is a crucial aspect in this region because there are no formal seasons and snow accumulations do not happen outside of the glaciated locations, meaning there is no seasonal snowmelt to aid in seasonal runoff (Vuille et al., 2008).

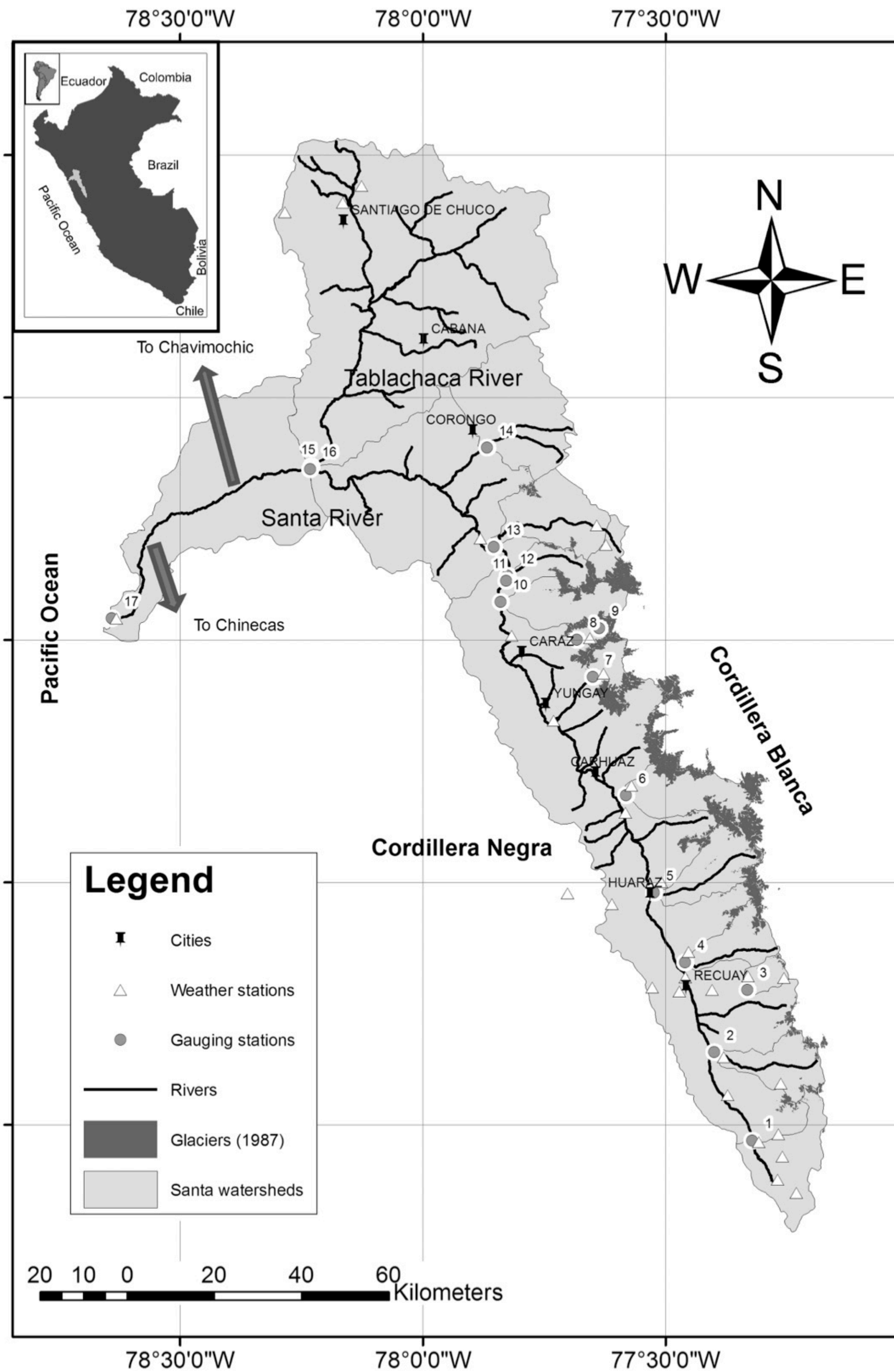

Figure 1: Overview of the Rio Santa Basin, location of glaciers, and significant population centers in the watershed (Condom et al., 2012).

Peru contains over two thirds of all tropical glaciers in the world and the Cordillera Blanca range is the most extensively glaciated mountain range in Peru (Vuille et al., 2008). This region is experiencing rapid retreat of its glaciers, which are no longer in balance. Therefore, these glaciers are permanently losing mass each year because of climate change. Due to the large population in the basin and the economic activities that rely on glacial meltwater there is growing uncertainty surrounding the future water supplies of both rural and urban communities if meltwater contributions dimmish throughout the 21st century. Based on community concerns and current climate trends, a review of glacier, climate, and water data, along with an analysis of population, economic, and water used trends will be conducted. This will aid in the presentation of recommendations which hope to overcome water scarcity issues or conflicts as they arise. The tropical Andes are experiencing rapid changes due to climate change that are more pronounced than other regions in the world, therefore water projections and analyses are a more pressing concern in the tropical Andes than in other glacierized watersheds.

2.0 TEMPERATURE PROJECTIONS

The recent acceleration of glacier recession globally can be linked to climate change and the overall warming of Earth. In 2013 the International Panel on Climate Change (IPCC) released an assessment report on long-term climate change projections, considering multiple greenhouse gas concentration pathways and the resulting global temperature increases (Collins et al., 2013). According to Berkeley Earth current global mean surface temperature has increased approximately 1.2 degrees Celsius above preindustrial levels, and the IPCC project this change could reach over 2 degrees Celsius by 2050 and over 4 degrees Celsius by 2100 according to the highest greenhouse gas scenario (Berkeley Earth, 2021; Collins et al., 2013). This warming varies drastically across regions with the Arctic expecting quicker warming in comparison to the tropics and land warming faster than the oceans (Collins et al., 2013). Urrutia and Vuille developed a more focused model, a regional climate model (RCM), for analyzing the tropical Andes to conduct climate change projections in this highly vulnerable region (2008).

2.1 Warming of the Andes

The RCM that Urrutia and Vuille developed considered two future scenarios, RCM-A2 which is based on medium-high emissions and high population growth, and RCM-B2 that considers a lower emission future and reduced population growth into 2100 (2008). These projections consider a population of 15 billion people with an 850 ppm CO2 concentration and 11 billion people with a CO2 concentration of 550 ppm by 2100 respectively (Urrutia & Vuille, 2008). Both regional climate models were compared to a 20th century control model and predicted large temperature changes in the tropical Andes by the end of the 21st century. The large glacierized catchment of the Rio Santa Basin is fed by the mountains in the Cordillera Blanca, which is projected to see some of the largest high elevation warming in the tropical Andes (Urrutia & Vuille, 2008). Urrutia and Vuille modelled warming patterns throughout South America in reference to the 20th century baseline. Both RCM-A2 and RCM-B2 produced similar warming patterns, but with RCM-A2 predicting temperature increases 3 degrees Celsius greater than RCM-B2 in most locations, as figure 2 visually depicts (Urrutia & Vuille, 2008).

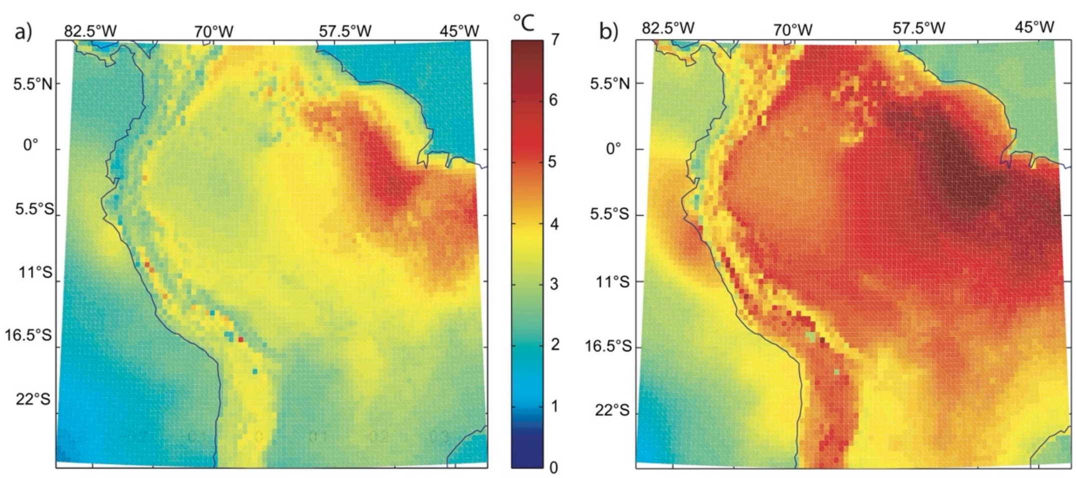

Figure 2: The difference between mean annual surface temperature of scenario RCM-B2 (a) and RCM-A2 (b) in reference to the 20th century control model (Urrutia & Vuille, 2008).

In each scenario the Tropical Andes are projected to see significant warming, with the coldest years near the end of the 21st century (2071-2100) being warmer than the hottest years in the past (Vuille, 2013). The mean annual temperatures for the base 20th century scenario and both RCM-A2 and RCM-B2 are represented by the probability density functions (PDF) in figure 3 (Urrutia & Vuille, 2008). The PDF for RCM-A2 shows that extremely warm years would be more probable in its high emission scenario as seen by the lower amplitude of the function. The estimated temperature increases or mean annual temperature in the Andes, more particularly in the Cordillera Blanca, will be different in the high mountains where the glaciers are located.

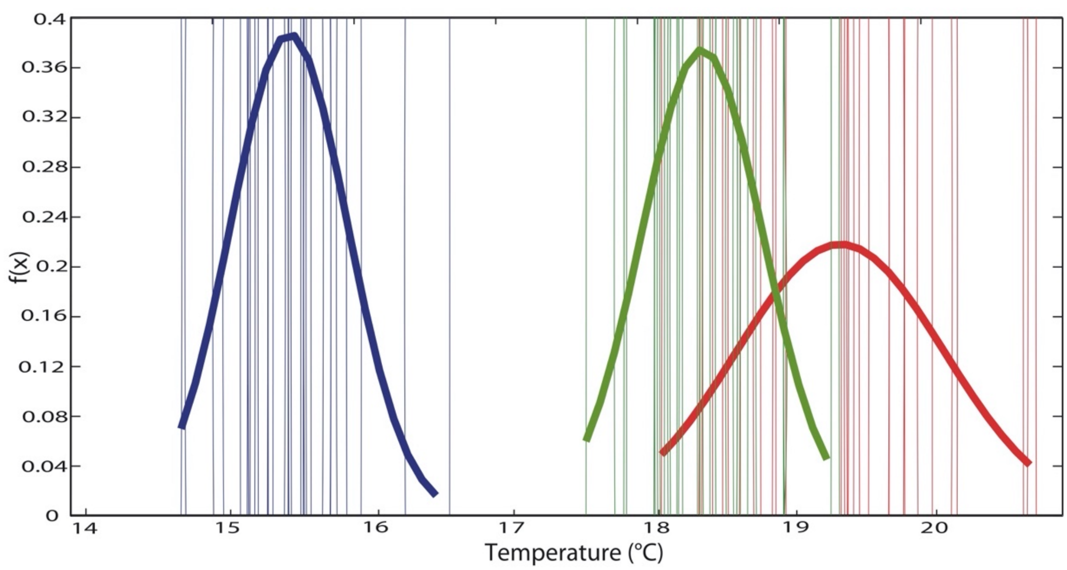

Figure 3: Probability density functions (PDF) for 20th century control (blue), RCM-B2 (green) and RCM-A2 (red) (Urrutia & Vuille, 2008).

2.2 High Mountain Warming

Near the western coast of Peru along the Andes, figure 2 illustrates warming in the high mountains is expected to be larger with respect to the rest of the region confirming what Bradley et al. determined in 2006 (Urrutia & Vuille, 2008; Bradley et al., 2006). This was estimated by Urritia and Vuille in 2008 as figure 4 shows the change in temperature with respect to increasing altitude, wherein higher peaks are expected to see greater warming than mid altitudes where population centers are located (2008).

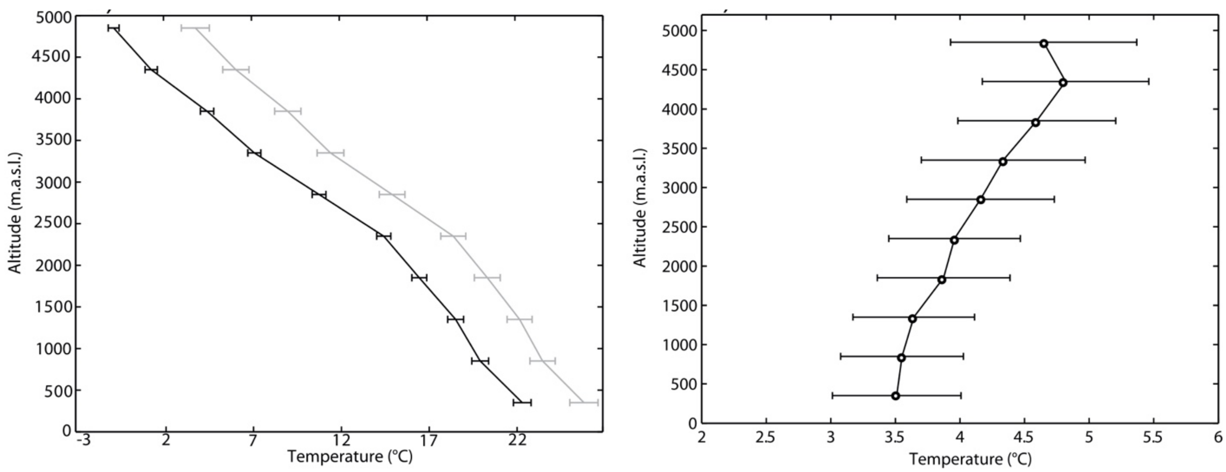

Figure 4: Left: Projected temperatures at increasing elevations in the Cordillera Blanca with 20th century control in black and RCM-A2 in grey. Right: Estimated temperature increases in the Cordillera Blanca with respect to elevation (Urrutia & Vuille, 2008).

This will have major implications on the snow line and therefore the amount of precipitation falling as snow annually. The alteration of precipitation from the movement of the snowline to higher altitude will further increase the vulnerability of glaciers to additional recession. Current extents of recession and predictions to the end of the 21st century are expanded upon in the following section.

3.0 GLACIER RECESSION IN THE CORDILLERA BLANCA

The Cordillera Blanca mountain range contains the largest concentration of tropical glaciers in the world and contains 35% of Peru's glacierized area (Bury et al., 2011; Mark et al., 2010). There has been a major reduction in glacier area over the last few decades due to accelerated effects of climate change. This has led to a more negative annual mass balance in recent decades for the glaciers in the Peruvian Andes. The estimated glacierized area in the Cordillera Blanca in 1960 was 728 km^2 and the most recent glacier estimate from Burns and Nolin in 2010 was 482 km^2 (Condom et al., 2012; 2014). Figure 5 portrays glacier recession trends for 6 glaciers in the Cordillera Blanca Range from 1968 to 2006.

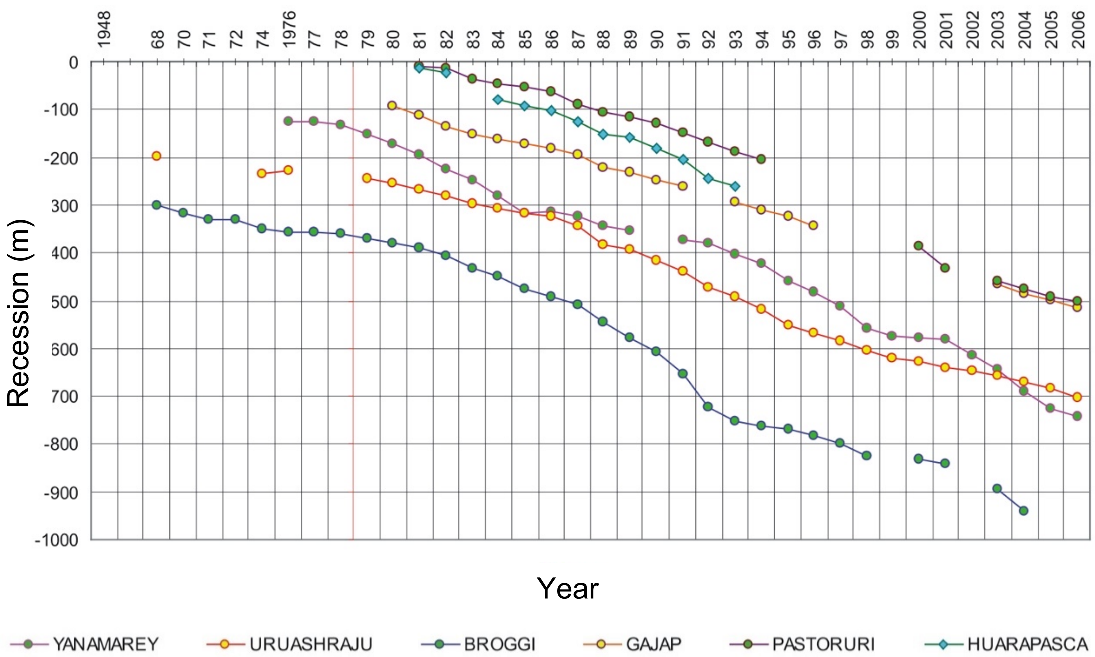

*Figure 5: Cumulative glacier recession for 6 glaciers in the Cordillera Blanca mountain range (*Portocarrero & Gómez*, 2008).*

More recently, the rate of recession has increased to 87 km^2 from 2004 to 2010 in comparison to 14.6 km^2 from 1996 to 2004 (Burns & Nolin, 2014). This equates to 2.5% and 0.3% of glacial area per year respectively. Minimal recession seen in the period from 1996 to 2004 can be attributed to the end of an El Nino cycle in 1997 to 1998 in which some glacier advancement began afterwards (Burns & Nolin, 2014). During the 1987 to 1996 monitoring period the glacier recession was approximated at 1% per year which is a more accurate representation of past trends (Burns & Nolin, 2014). When considering climate projections through the 21st century and the acceleration in recent decades, it would be expected to see higher annual loss percentages in the future.

3.1 Causes of Further Recession

Climate change effects are leading to the increased rates of recession in the Cordillera Blanca. This recession is in turn reducing the albedo, therefore further accelerating glacial melt in the region. The positive feedback loop of the ice-albedo relationship will only further increase future glacier recession rates as more solar radiation will be absorbed as more ice melts from glaciers. Furthermore, with the projected warming in the high mountains of the Cordillera Blanca as glaciers retreat, the snow and freezing line will increase in altitude as well. Therefore, the amount of precipitation falling as snow will decrease along with the movement of the snow line.

3.2 Freeze Level Heights

Based on the IPCC's greenhouse gas concentration pathways, RCP2.6 and RCP8.5, the freezing level height (FLH) will increase in both scenarios (Schauwecker et al., 2017). RCP2.6 is a low emissions (renewable energy) pathway and RCP8.5 is a high emission ("business as usual") pathway, both are used in most climate change related estimates. Schauwecker et al.'s freeze level height model predicts an average increase of 230m for RCP2.6 and 850m for RCP8.5 by 2100, but these values may range from 40m at minimum to 1240m increase at the maximum (2017). Movement of the FLH to higher elevations due to climate change with lead to changes in water supply for the Rio Santa Watershed as well as the sub basins within.

3.3 Water Storage

With glacier and snow accumulation expected to happen at higher elevations into the 21st century, water storage in the form of glacial snow and ice will be altered. This storage buffers the water supply during the dry season (June to August (JJA)) as significantly minimal precipitation falls during this time. With less mountainous area accumulating snow and ice during the wet season (December to February (DJF)) less meltwater will be present during austral winter to buffer the supply capacity (JJA). The extent of the reductions and annual variation estimates will be outlined to understand the adaptations required in the Rio Santa Watershed.

4.0 IMPACT ON WATER SUPPLY

The water supply in the Rio Santa Basin has large annual fluctuations due to a significant difference between the wet (DJF) and dry season (JJA) precipitation patterns. In figure 6 from Bury et al. the seasonality of the water supply or discharge is adamant (2010). This data was from an assessment on the glacier recession in the Yanamarey watershed, which is a sub basin in the greater Rio Santa. Figure 6 also shows that storage always has a negative mass balance even in peak wet season (DJF) (Bury et al., 2010). It is expected that as glaciers in the basin continue to retreat, the seasonality will become more drastic with the dry season (JJA) seeing the largest reduction in flow.

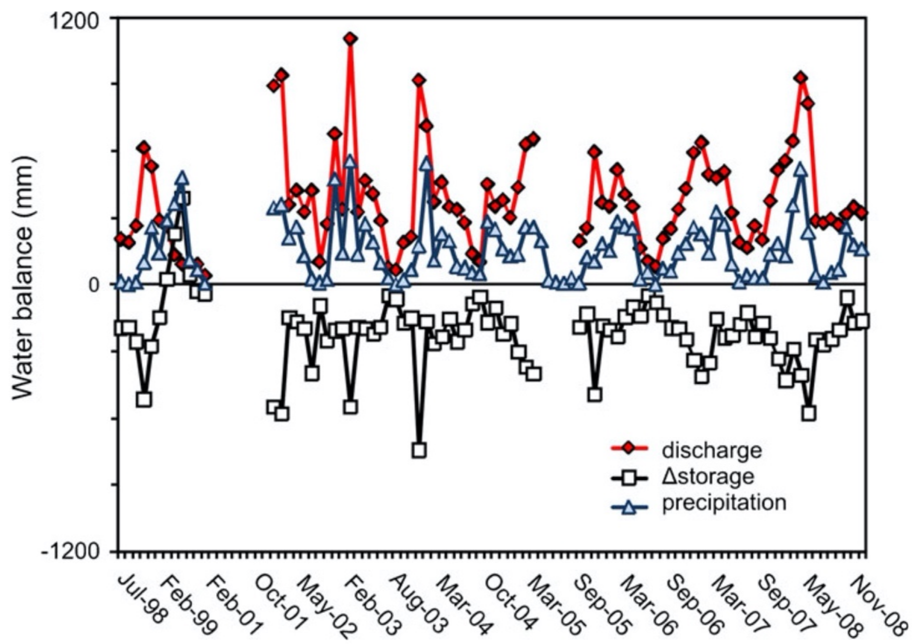

Figure 6: Discharge, storage, and precipitation values for the Yanamarey watershed from July 1998 to November 2008 (Bury et al., 2010).

4.1 Changes to Glacier Contributions

There is a key point in time where meltwater contributions from glaciers reach their peak discharge volume, after that peak meltwater stage the annual discharge values will continue to decline until a new glacial balance is met. Therefore, for water users there is an illusion that annual discharge, or more importantly dry season discharge, is gradually increasing due to rapid glacier melt, but this a short-term increase and proves that the water source is vulnerable (Vuille, 2013). It has been determined that most glaciers in the Cordillera Blanca have passed their peak meltwater stage and will see a continual decrease in meltwater through the 21st century, figure 7 (Vuille, 2013). Dry season discharge has already begun to see a large reduction in flow. From 1954 to 1997 the Callejon de Huaylas watershed, figure 8, saw a 17% reduction in discharge, yet this estimate did not consider human extraction or use changes (Mark et al., 2010).

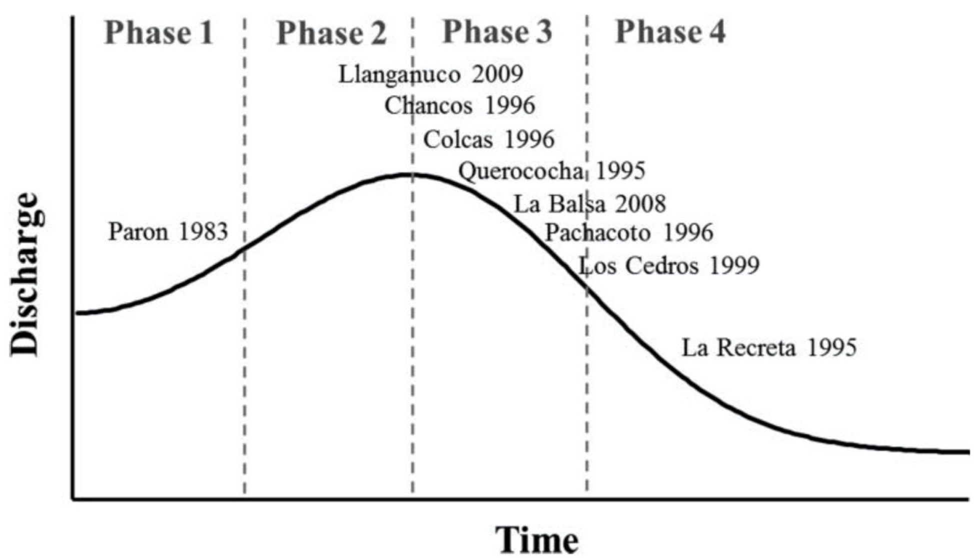

Figure 7: Conceptual hydrograph that shows the meltwater contribution stages of sub-basins within the greater Rio Santa Basin with phase 1 being increase in meltwater, phase 2 being a noticeable slowdown, phase 3 being a pronounced decease in meltwater (past peak meltwater) and phase 4 being a lower and new equilibrium (Bury et al., 2013).

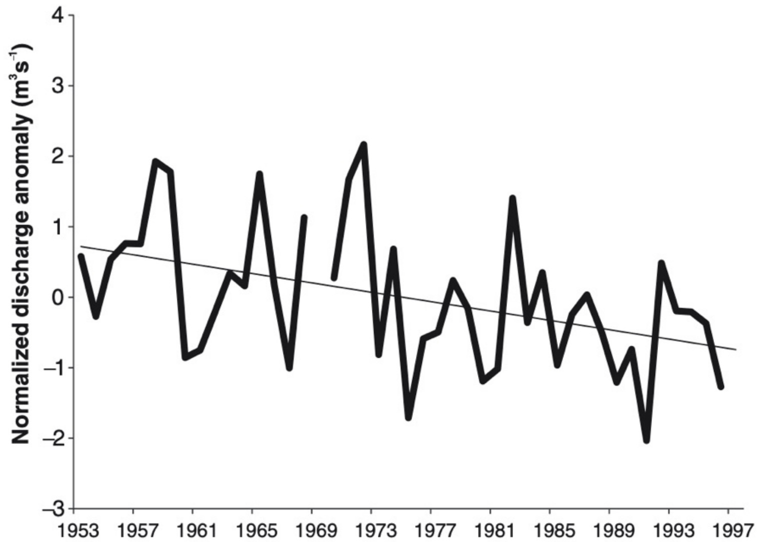

Figure 8: Normalized annual discharge in the Santa River at La Balsa station from 1953 to 1997 (Mark et al., 2010).

These measurements are taken at the La Balsa gauging station, which is located on the Santa River just downstream of all the glacier catchments in the Cordillera Blanca. Glacier meltwater can be attributed to 38% of the annual discharge at La Balsa gauging station, but the value is much higher during the dry season at approximately 67% (Condom et al., 2012). This can be seen in the La Balsa outflow chart below, figure 9, for the 3 decades between 1969 and 1998. Considering the estimated glacier retreat in the upper Rio Santa Basin, dry season discharge (baseflow) could be reduced by 50 – 84%, but more accurate groundwater contributions are required (Glas et al., 2018). At the exit of the entire Rio Santa Basin dry season discharge could be expected to reduce by 30% as glaciers retreat (Baraer et al., 2012). This will have major long-term impacts on the watershed since it is already water stressed and is expecting population and economic growth in the future.

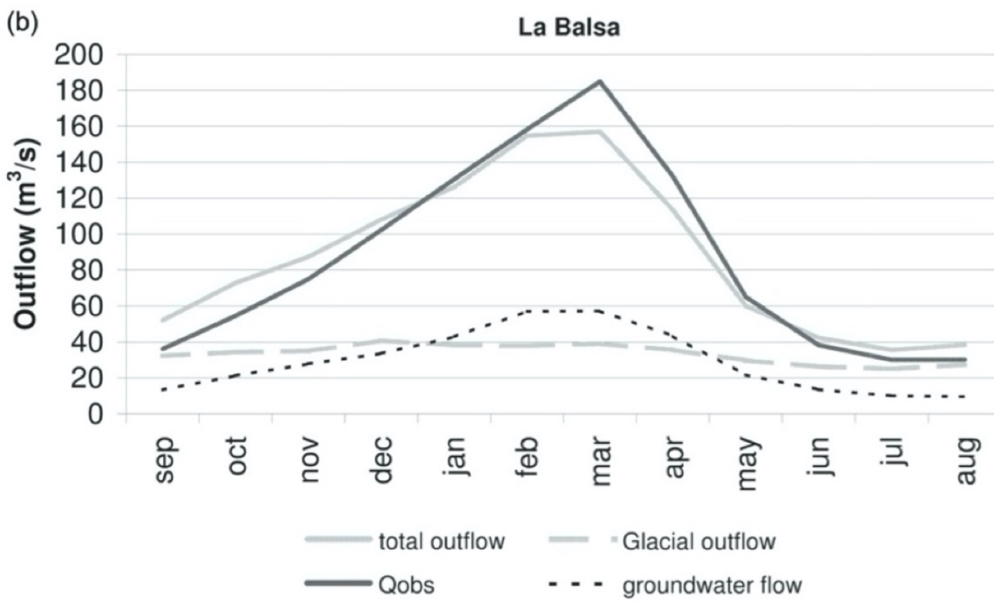

Figure 9: Calculated and simulated streamflow at La Balsa gauge station (Condom et al., 2012)

4.2 Water Supply Seasonality

Glacier retreat or complete loss would lead to a lower dry season discharge, but wet season flow would be relatively unchanged. As previously mentioned, large declines in dry season flows are expected as glaciers recede, but the wet season will continue to provide similar flows to previous decades. The difference between dry and wet season flow is drastic in the upper Rio Santa with outflows approximately 30 – 40m^3/s and 110 – 190m^3/s respectively. Dry season flow is crucial for agricultural production as it is the largest water use sector in the Rio Santa Basin at 80% of the consumption and could continue to grow as export agriculture grows (Condom et al., 2012). Therefore, agricultural practices may have to be altered or improved to account for future water supply issues.

5.0 WATER ASSOCIATED CONFLICTS

Aside from the changing climate and water supply in the Rio Santa Watershed another cause for concern are the water conflicts that are ongoing and Peru's issues with water governance. Furthermore, most of the economic activities occur on the Pacific side of the Andes where approximately 2% of Peru's water drains (Salem et al., 2018). The Pacific region contains 94% of the country's resource extraction industry and around 67% of agricultural productivity (Salem et al., 2018). Two of the largest industries in Peru are competing for water use rights in the arid west of the country, with competing use requirements.

5.1 Competing Interests

According to the National Society of Mining, Oil and Energy 60% of socio-environmental conflicts in Peru are due to water with more than half of these caused by water contamination and discharge (Salem et al., 2018). In addition, what is meant by effective land use differs between farmers, government, and mining operations. This is because farmers rely on their land and water for their livelihood while the government and mining companies see large scale resource extraction operations as profitable, thus neglecting water resource impacts from activities (Tanaka et al., 2011). Due to the large economic benefits of mining in Peru, increased resource extraction usually is considered before the interests of the locals in the Santa River headwaters (Vuille, 2013).

5.2 Agricultural Water Allocation

Agriculture is the largest water consumer in Peru and most of the large-scale production occurs on the pacific coast to support the export economy (Vuille, 2013). Consequently, water regulations differ between the upstream and downstream irrigators to ensure that industrial agriculture is guaranteed enough water (Lynch, 2012). The upper Rio Santa is composed of small-scale farmers who have approximately 40% of the available irrigated land while the industrial irrigators on the coast make up the rest (Lynch, 2012). Both groups of irrigators are allotted water based on different allocation rules, the large irrigators on the coasts are guaranteed a fixed annual volume of 10,000 m3/ha while upstream users are given a share of available water (Lynch, 2012). This means that as climate change alters the flow regime of the Santa River the upstream users will be allotted less water yearly as base flows decline while downstream users will be relatively unaffected in terms of water allowances. In times of droughts the highland communities will become more vulnerable to food production and urban water usage crises.

Considering the different preferences and rules for certain water users it shows that locals and small-scale users are not being considered or brought into the planning process when new developments are being created. There is a gap in the understanding of water management practices and interdisciplinary approaches to effectively managing water for all users. With climate change expected to increase water stress and scarcity during the dry season, better water governance or practices must be considered.

6.0 FUTURE WATER ISSUES

Industries including tourism, agriculture, and mineral extraction are expected to grow in the Rio Santa Basin; therefore, water consumption will increase along with conflicts between the water users. This subsequent increase in population, agriculture, and tourism numbers will put extreme stress on the future water availability regardless of the long-term decrease in water supply.

6.1 Population Projection

Water conflicts will only continue to grow due to the estimated climate change effects along with projected increases in population and economic activities. Based on the 2007 Peruvian Census, Mark et al. approximated that 267,000 people live in the Callejon de Huaylas (upper Rio Santa) (2010). Further, the estimated population for the entire Rio Santa Basin based on the 2005 census was 1.7 million (USAID, 2011). Approximately 50% reside in the Ancash province and 50% in the La Libertad province. Most of the population within the La Libertad region does not reside within the Rio Santa Basin, but is relevant when discussing water usage due to canals that feed water from the Santa River to the urban centers and agriculture in the province (USAID, 2011). This population projected to 2021 based on yearly population growth numbers estimates that 2 million people currently reside in the basin and canal fed regions (The

World Bank, 2021). The average growth rate in Peru over the last decade has been 1.23% per year, therefore using this to estimate future population in the region would lead to a population around 2.8 million by 2050 and 5.2 million by 2100 assuming a constant growth rate (The World Bank, 2021). Condom et al., determined an estimate for daily water consumption in the Rio Santa Basin to be 300 L/day which combines both urban and agricultural uses (2012). Based on this value, and assuming water consumption remains the same, by 2050 the increase in water demand based only on an increase in population would be approximately 240,000 m3 per day.

6.2 Tourism

The Rio Santa watershed is fed by the meltwater of the Cordillera Blanca range and is therefore a major tourist destination in Peru. Large peaks of the Cordillera Blanca make it a premier destination for mountaineers around the world. Tourist visits to the region have a large impact on an already stressed water supply as foreign visitors use more water than the domestic population as seen in figure 10 (Schreier, personal communication, July 2021).

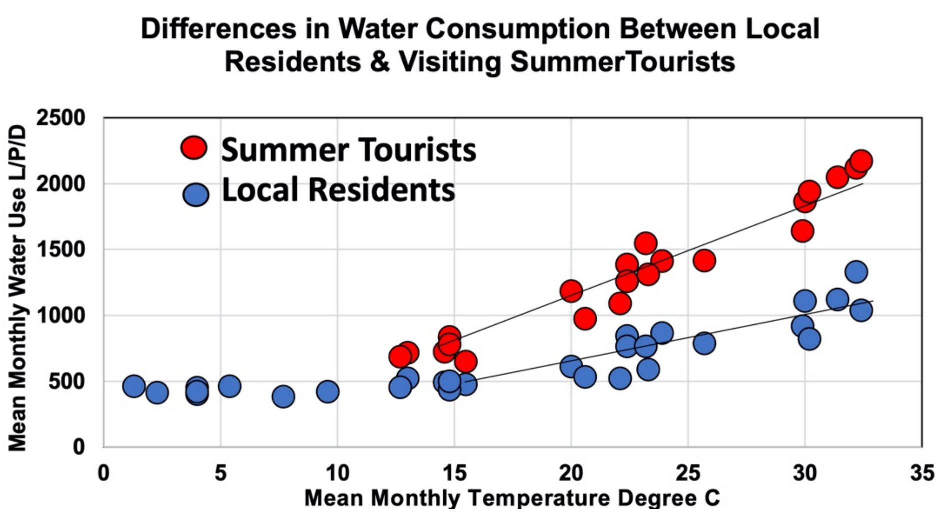

Figure 10: Difference between tourist and domestic water consumption in relation to increasing temperatures (Schreier, personal communication, July 2021)

Inbound tourists have increased at an average rate of 14.6% per year from 1992 to 2015 in the Ancash province of Peru (Observatorio Turistico Del Peru, 2018a). Over this period the number of tourists in the province increased from approximately 2,600 to 61,300 people annually (Observatorio Turistico Del Peru, 2018a). This has further impacted rural and urban populations pushing more rural residents towards larger population centers for careers and involvement in the tourism industry. Additionally, domestic tourism makes up the larger share of tourism in Ancash with growth from 185,000 in 1992 to 461,000 in 2018 (Observatorio Turistico Del Peru, 2018b). In the last decade of available data from Observatorio Turistico Del Peru, 2015 for inbound and 2018 for domestic, tourism numbers increased by 23,000 and 91,000 people respectively, therefore showing that considerable growth is still taking place in the region (2018a; 2018b). This leads to inbound tourism growth at approximately 5.99% and domestic tourism growth estimated at 2.44% annually. These growth rates will lead to an increase in inbound and domestic tourism of 470,000 and 1,000,000 visitors respectfully by 2050. If these trends accurately predict the future of Ancash's tourisms industry there will be major impacts on water supply, specifically during peak tourist season, April to October, which coincides with Rio Santa's dry season. From figure 9, the difference in water consumption between locals and tourists becomes more apparent at high temperatures. Considering the average temperature in the Rio Santa Basin ranges between 8 and 19 degrees Celsius, a reasonable estimate suggests that tourists consume 50-100 L/capita/day more than local residents.

6.3 Agriculture Industry

The inequities in water allocation between large industrial export driven agriculture and smaller scale farmers located in the Callejon de Huaylas (Upper Rio Santa Basin) are already apparent, but future growth of the industry will further exacerbate these issues. There has been a shift toward producing more crop for export, which in most cases are water-intensive (Mark et al., 2010). There are two large irrigation projects, the Chavimochic and the Chinecas, along the Pacific Coast of Peru that are fed by the Santa River and produce crops such as white asparagus, red peppers, avocados, artichokes, onions, pineapples, mangos, blueberries, beans, and sugar cane (IPTRID, 2006; Portugal, 2020). The water requirements for these crops can be seen in table 1 below. The two industrial agricultural areas and the canals that feed them are seen in figure 11, which clearly shows the extent of land outside the basin that the Rio Santa Watershed is responsible for irrigating.

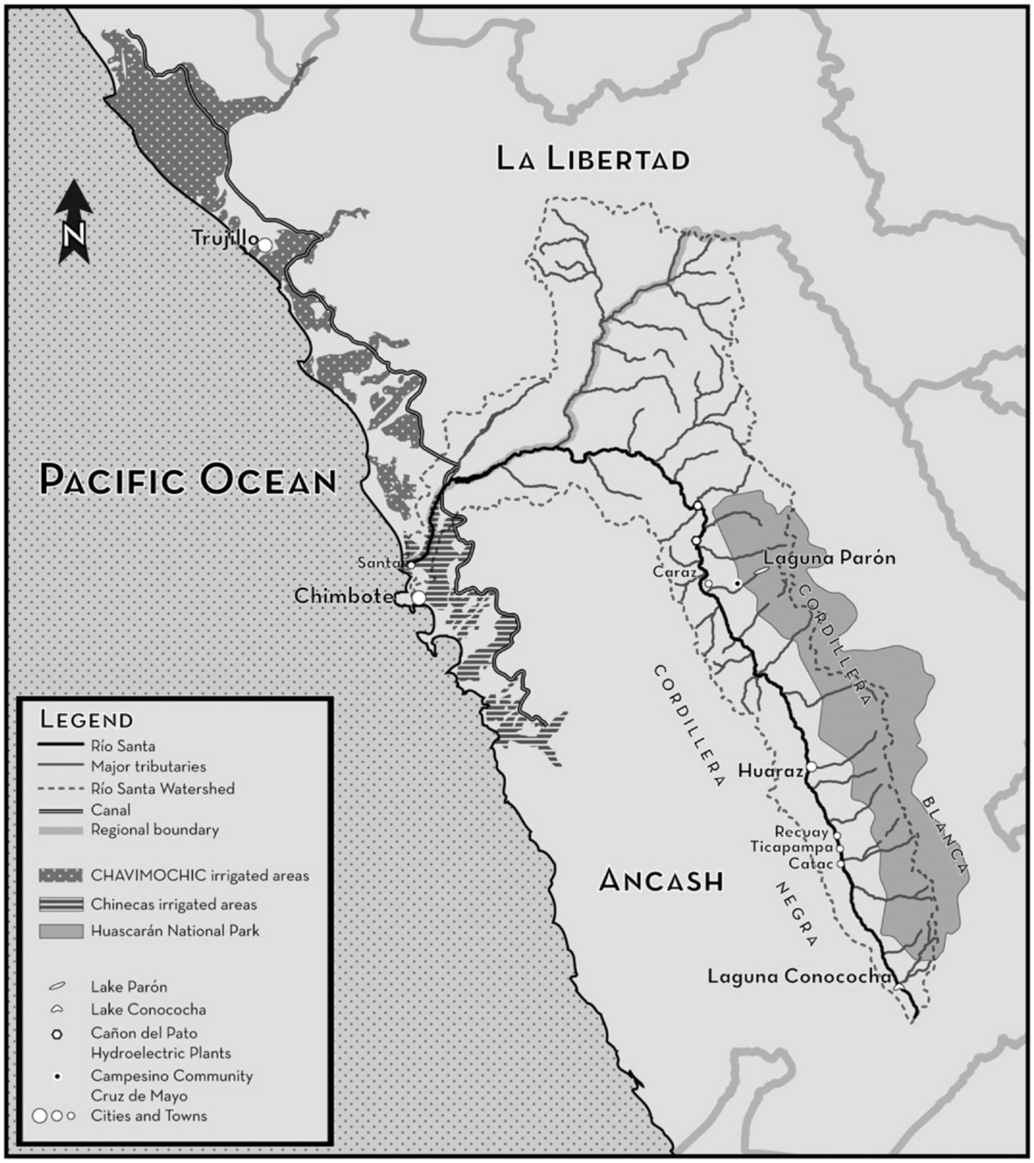

Figure 11: The Rio Santa Basin with the canal fed industrial agricultural areas of Chavmochic and Chinecas detailed (Lynch, 2012).

Table 1: Water requirements for export and domestic crops in Peru based on millimeters of water per growing season (Chapagain & Hoekstra, 2004).

Crop	Water Requirement (mm/growing season)	Crop	Water Requirement (mm/growing season)
Asparagus	751	Wheat	278
Artichokes	1032	Oats	275
Avocados	827	Barley	275
Beans	251	Corn	319
Blueberries	300	Quinoa	228
Mangos	1086	Potatoes	374
Onions	613	Olluco	174
Pineapples	393	Oca	204
Peppers	386	Mashua	204
Sugar Cane	1008	Beans	210

These agricultural lands have been developed to increase crop exports throughout Peru. Fruit exports in Peru have grown by approximately $3 billion USD since 2010, figure 12, with a consistent growth pattern annually (USDA, 2021). Some fruit crops such as mangos have seen steady production since 2010; but the number of mangos exported has increased drastically, leading to a decrease in local consumption (USDA, 2021). Peru has now grown to be one of the top 10 fruit exporting countries since 2017 and is in line with major exporters in the Southern Hemisphere such as South Africa and Ecuador. Increasing crop production for exports throughout both the Ancash and La Libertad provinces will put more stress on the water supply system because they are both irrigated by canals connected to the Santa River.

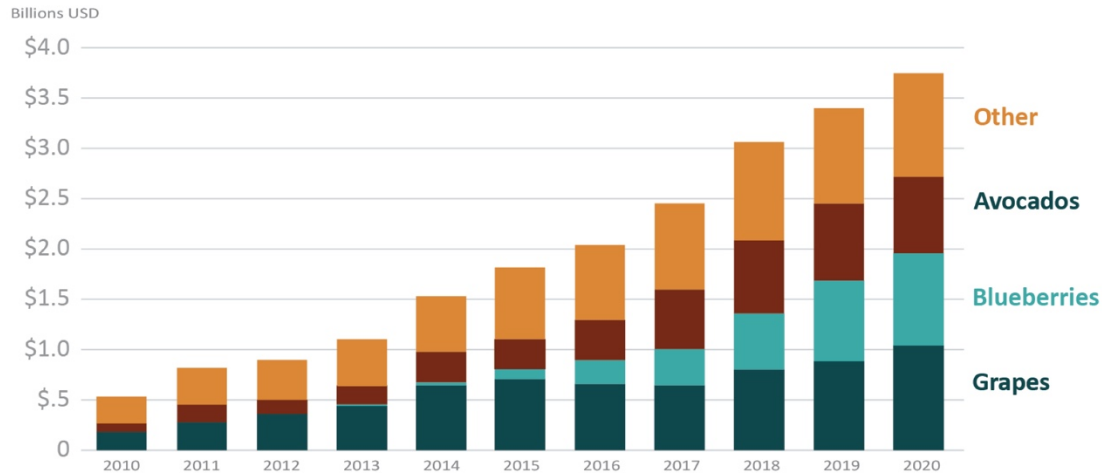

Figure 12: Fruit export value in billions of USD for Peru from 2010 to 2020 (USDA, 2021).

The upper portion of the watershed, the Callejon de Huaylas, has different agricultural activities due to their focus on production for consumption and local market sale (Mark et al., 2010). This region grows potatoes, corn, barley, oats, quinoa, wheat, olluco, oca, mashua, beans and herbs and the water requirements can be seen in table 1 as well (Mark et al., 2010; Chapagain & Hoekstra, 2004). Even the upper reaches of the Rio Santa Basin may see increases in water use due to an increase in arable land (Vuille et al., 2018). Larger temperature increases at higher altitudes may suggest the rural farmers are able to expand their farms upland and therefore will require more water for irrigation (Hole et al., 2011). This has occurred in the Cordillera Vilcanota since the recent rise in temperatures has made crop production possible at higher elevations (Hole et al., 2011).

6.4 Resource Extraction Industry

Peru also has a large mineral extraction industry making up most of the economic activity in the Upper Rio Santa Basin. Exporting minerals occupies more than half of Peru's annual export earnings, ranging from 54 – 62% over the last decade (Statista, 2021). Providing a large share of the country's annual earnings makes it improbable that the country would adjust mining rights to protect local water interests, as has already been noted with the industrial agricultural water allocation numbers (Vuille, 2013). In 2010 Bury et al. stated that there were three mining operations in the watershed, but at least six were in the planning process (Bury et al., 2013). These operations resulted in water contamination from inadequate legislation and procedures with respect to environmental protection (Salem et al., 2018). In 1981, 1999 and 2000 water quality testing took place throughout the watershed to test the water for human, animal, or agricultural use (Bury et al., 2013). In many cases the water quality standards were exceeded with arsenic, lead, iron, manganese, and zinc showing up in 89%, 78%, 48%, 53%, and 24% percent of measurements respectively (Bury et al., 2013).

The issues caused by mining have led to intense conflicts with local Peruvians, with 60% of these conflicts being related to contamination and competition (Salem et al., 2018). Socio-environmental issues with mining companies caused vast discontent from locals, which must be addressed if Peru wants to move forward with expanding their mineral extraction sector (Salem et al., 2018). Salem et al. further details that once a conflict surfaces with the government and mining companies, it is difficult to regain the communities trust (Salem et al., 2018). Therefore, communication and planning should be at the forefront of new mining operation with water regulations and rights at the center.

7.0 ADAPTATION OPTIONS

Based on past conflicts within the basin a general approach to improving water allocation and consumption may be to develop better relationships between the government, industry, and the local indigenous people. Many conflicts arose due to lack of consultation with local communities and farmers when building new mining operations or implementing water regulations, as seen by disproportionate water rights and export prioritization. Developing solutions with productive stakeholder engagement may aid in creating holistic approaches to ongoing economic development in the region. Past conflicts in Peru have led to local protests against dam or mine construction in favour of protecting their land, many are successful, but there is a mistrust of government and industries that needs to be addressed for the sake of the region (Vuille et al., 2018). Many locals are now taking adaption into their own hands and developing strategies to deal with climate and water related issues based on local knowledge of vulnerabilities and the environment (Vuille, et al., 2018); many of these locals been successful therefore showing that locals need to be a part of the conversation regarding environmental and community protection.

Agriculture is growing rapidly in the region with exports increasing yearly, and with approximately 80% of water consumption in the Rio Santa Basin used for agriculture the largest reductions could be seen in this industry (Condom et al., 2012). The large irrigation projects on the Pacific coast of the Ancash and La Libertad provinces are mainly export focussed, with many crops requiring large quantities of water during the growing season. Crops such as artichokes, asparagus, avocados, and mangos are water intensive, therefore their importance to Peru's economy could be re-evaluated and less intensive crops could be grown in place, which also have high export value. Furthermore, developing more efficient irrigation methods for small and medium scale farmers could aid in reducing consumption in the basin. The irrigation projects of Chavimochic and Chinecas mostly use modern drip irrigation methods to produce crops in the sandy coastal soils, which is approximately 88-90% efficient. (Vos & Marshall, 2017; Schreier, 2021). Smaller scale farms cannot afford modern irrigation infrastructure therefore they are waterlogging their soils due to a lack of knowledge on appropriate techniques and monitoring (Vos & Marshall, 2017). Government programs do exist to support the transfer to drip or sprinkler irrigation but could be improved to increase funding opportunities and educate farmers about irrigation methods and monitoring (Vos & Marshall, 2017).

Aside from the agriculture industry and due to the large growth estimated for both population and tourism, implementing measures to reduce daily consumption may be highly effective. Even though residential and visitor consumption makes up a smaller portion of the overall water use in the basin, having appropriate measures in place to reduce their consumption would be beneficial long term. These measures may be in the form of water tariffs for residents or water pricing structures in hotels and other accommodations to reduce water use of high consumers (Barde & Lehmann, 2014; Deta-Tortella et al., 2016). Success in this area would also require educational tools to be in place in order to promote water wise behaviours in the watershed.

Reducing water consumption is a more obvious option when faced with water supply issues, but in this basin are there opportunities to develop additional water sources? Investing in new infrastructure, for example, reservoirs may help with glacial lake outburst floods and supplying additional water (Vuille, 2013). The issues surrounding this approach includes further environmental impacts through loss of land and an increase in frequency of sedimentation issues in glacial reservoirs (Vuille, 2013). Additionally, local populations may have to relocate making this approach a more in-depth process requiring assessments, consultations, and major construction before any actual benefits are noticed (Vuille, 2013). An alternative supply option entails constructing desalination plants on the pacific coast. These do come with high costs and high energy requirements, but after water reductions are seen in agricultural and domestic use, these policies may be some of the few options left to meet the demands of a growing population.

Investments will be required to see reductions in demand and smarter, more efficient water use by industries. This amount varies drastically between the previously mentioned policy suggestions, but the appropriate methods moving forward will depend on government plans and policies, local consultations, growth, required reductions and urgency to see results. Recommendations for the Rio Santa Basin are detailed in Section 9.0.

8.0 CONCLUSION

The information discussed in this report has been presented in order to describe water supply issues in the Rio Santa Basin. With glacier meltwater from the Cordillera Blanca Mountain Range being the main source of water to this basin, it is more vulnerable to the effects of climate change. This paper demonstrated the need to address water supply and consumption issues in this region through estimating glacier recession, discharge reductions, population increases, and agricultural activities to give a better sense of what issues this basin may face in the 21st century.

It was found that extreme warming will take place throughout the tropical Andes by 2100. Average annual temperatures are expected to increase between 3 – 4 degrees Celsius depending on the emissions and population scenarios. This showed that even cold years in the future will still be hotter than the warmest of years from the 20th century. Further, the emission scenario followed has a large impact on variability of annual average temperatures with more extreme temperatures having a higher probability than lower emission estimates. The high mountains of the Andes are even more vulnerable because as glaciers recede due to warming the albedo will be reduced causing the ice-albedo positive feedback loop to persist.

The glaciers in the Cordillera Blanca have seen a massive recession in the past decades receding from 728 km^2 in 1960 to 482 km^2 in 2010. This rate of recession is expected to increase throughout the 21st century when considering temperature trends and the increased high mountain warming. With glaciers receding passed their “peak meltwater” stage, the variability in water supply is projected to increase with dry season (JJA) discharge reducing between 50 – 84% and annual flows down 30%.

Furthermore, population growth and tourist visits are expected to continue growing based on 21st century trends, therefore putting increased stress on the water supply system. In conjunction with these trends, exports, both agricultural and mineral, are becoming the focus for revenue in the region subsequently putting the future of domestic water supply quantity and quality in jeopardy. Considering all these factors there is room for efficiency improvements, better environmental regulations, and a holistic watershed approach. These recommendations will ideally aid in the future of water governance and allocation in water stressed regions, especially the Rio Santa Basin.

9.0 RECOMMENDATIONS

Based on the expected decline in water supply due to glacier recession and changing climatic conditions, concerns regarding water consumption must be addressed. The conflicts developing in the Rio Santa Basin surround availability and allocation of water, with Peruvian communities and small-scale farmers being the most vulnerable. The priority would be to reduce agricultural consumption by changing export crops for other high value less water intensive options. Table 2 provides alternative export crops that could replace current water intensive options. The crops selected in table 2 as replacements require much less water than their counterparts and are either produced in Peru already as export crops or have the potential to be.

Table 2: Water intensive crops in Peru and potential replacement crops to reduce water consumption (Chapagain & Hoekstra, 2004)

Current Crop	Water Requirements (mm/growing season)	Replacement Crop	Water Requirements (mm/growing season)	Water Savings (mm/growing season)
Artichokes	1032	Other Vegetables	380	652
Asparagus	751	Green Beans	210	541
Avocado	827	Pineapples	393	434
Mangos	1086	Tangerines	725	361

Another key area for improvement would be switching small and medium scale irrigators to drip irrigation techniques. As the initial step educational programs could be put in place to help these farmers irrigate their land more efficiently and reduce waterlogging in the basin. During this time government funding could be allocated to support the switch to drip irrigation infrastructure. Furthermore, additional money for government subsidies could be recovered from large export companies on the coast by increasing the cost of water.

The other key priority in the basin is reducing residential and tourist water consumption. With population, inbound tourism and domestic tourism projected to increase by 800,000, 470,000 and 1,000,000 people respectively by 2050 large reductions in water consumption can be seen here. For residential or local water use a means-tested tariff system could be implemented to price water according to use, income level, size of property and housing location. This system will better tackle the problem of traditional water tariffs which end up targeting poor communities, since in many cases poorer households consume greater amounts of water (Barde & Lehmann, 2014). For the tourist industry water pricing structures could be applied to hotels and other accommodation in which visitors pay additional dollar amounts according to their water usage during their stay (Deya-Tortella et al., 2016). Ideally this will reduce tourist's water use, but money received from high consumers may also be reinvested back into the basin's water infrastructure to see additional reductions.

Overall, better water governance needs to be at the forefront of all future decision that surround water supply and consumption. Inequalities need to be sorted out in a manner that ensures local communities have access to enough water year-round to maintain their livelihoods. This means looking into allocation contracts for industrial irrigators and revaluating the availability of water year-round in order to make appropriate adjustments in times of critically low supply without harming the local communities. Incorporating the beliefs and values of these communities will be key moving forward to ensure long-term sustainable success with respect to new infrastructure or industry developments.

Alongside these changes, ongoing research of glacier recession and water supply in the region must take place considering the complexities of a watershed of this magnitude. More data will allow for accurate trends to be established and more sustainable solutions to be implemented, regarding increasing potential supply (desalination or reservoirs) or minimizing consumption.

REFERENCES

Baraer, M., Mark, B. G., McKenzie, J. M., Condom, T., Bury, J., Huh, K. I., Portocarrero, C., Gómez, J., & Rathay, S. (2012). Glacier recession and water resources in Peru's Cordillera Blanca. *Journal of Glaciology*, *58*(207), 134–150. https://doi.org/10.3189/2012jog11j186

Barde, J. A., & Lehmann, P. (2014). Distributional effects of water tariff reforms – An empirical study for Lima, Peru. *Water Resources and Economics*, *6*, 30–57. https://doi.org/10.1016/j.wre.2014.05.003

Berkeley Earth, B. (2021, January 20). *Global Temperature Report for 2019*. Berkeley Earth. http://berkeleyearth.org/2019-temperatures/

Burns, P., & Nolin, A. (2014). Using atmospherically-corrected Landsat imagery to measure glacier area change in the Cordillera Blanca, Peru from 1987 to 2010. *Remote Sensing of Environment*, *140*, 165–178. https://doi.org/10.1016/j.rse.2013.08.026

Bury, J. T., Mark, B. G., McKenzie, J. M., French, A., Baraer, M., Huh, K. I., Zapata Luyo, M. A., & Gómez López, R. J. (2010). Glacier recession and human vulnerability in the Yanamarey watershed of the Cordillera Blanca, Peru. *Climatic Change*, *105*(1–2), 179–206. https://doi.org/10.1007/s10584-010-9870-1

Bury, J., Mark, B. G., Carey, M., Young, K. R., McKenzie, J. M., Baraer, M., French, A., & Polk, M. H. (2013). New Geographies of Water and Climate Change in Peru: Coupled Natural and Social Transformations in the Santa River Watershed. *Annals of the Association of American Geographers*, *103*(2), 363–374. https://doi.org/10.1080/00045608.2013.754665

Chapagain. A. K., & Hoekstra, A.Y. (2004). Water Footprint of Nations Research Report No. 16, Volume 2: Appendices. UNESCO-IHE. https://www.waterfootprint.org/media/downloads/Report16Vol2.pdf

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner. (2013). Long-term Climate Change: Projections, Commitments and Irreversibility. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the

Fifth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter12_FINAL.pdf

Condom, T., Escobar, M., Purkey, D., Pouget, J. C., Suarez, W., Ramos, C., Apaestegui, J., Tacsi, A., & Gomez, J. (2012). Simulating the implications of glaciers' retreat for water management: a case study in the Rio Santa basin, Peru. *Water International*, *37*(4), 442–459. https://doi.org/10.1080/02508060.2012.706773

Deyà-Tortella, B., Garcia, C., Nilsson, W., & Tirado, D. (2016). The effect of the water tariff structures on the water consumption in Mallorcan hotels. *Water Resources Research*, *52*(8), 6386–6403. https://doi.org/10.1002/2016wr018621

Glas, R., Lautz, L., McKenzie, J., Mark, B., Baraer, M., Chavez, D., & Maharaj, L. (2018). A review of the current state of knowledge of proglacial hydrogeology in the Cordillera Blanca, Peru. *WIREs Water*, *5*(5). https://doi.org/10.1002/wat2.1299

Hole, D. G., Young, K. R., Seimon, A., Gomez, C., Wichtendahl, D. H., Paez, K. S., ... & Ramirez, E. (2011). Adaptive management for biodiversity conservation under climate change–a tropical Andean perspective. *Climate change and biodiversity in the tropical Andes, Inter-American Institute for Global Change Research*, 19-46.

IPTRID. (2006, February). Changing deserts into agricultural lands. *Grid*, *24*. http://www.fao.org/3/a0409e/A0409E00.htm#TOC

Lynch, B. D. (2012). Vulnerabilities, competition and rights in a context of climate change toward equitable water governance in Peru's Rio Santa Valley. *Global Environmental Change*, *22*(2), 364–373. https://doi.org/10.1016/j.gloenvcha.2012.02.002

Mark, B. G., Bury, J., McKenzie, J. M., French, A., & Baraer, M. (2010). Climate Change and Tropical Andean Glacier Recession: Evaluating Hydrologic Changes and Livelihood Vulnerability in the Cordillera Blanca, Peru. *Annals of the Association of American Geographers*, *100*(4), 794–805. https://doi.org/10.1080/00045608.2010.497369

Observatorio Turistico Del Peru. (2018a). Ancash – Receiving Tourism. http://www.observatorioturisticodelperu.com/mapas/ancatrec.pdf

Observatorio Turistico Del Peru. (2018b). Ancash – Internal Tourism. http://www.observatorioturisticodelperu.com/mapas/ancatint.pdf

Portocarrero, C., & Gómez, A. (2008). Water management to face climate change. In *Water management to face climate change*. Practical Solutions (ITDG).

Portugal, I. M. (2020). Collective action and water management in the Moche and Virú valleys of the peruvian coast. *Problemas Del Desarrollo. Revista Latinoamericana de Economía*, *51*(200). https://doi.org/10.22201/iiec.20078951e.2020.200.68186

Salem, J., Amonkar, Y., Maennling, N., Lall, U., Bonnafous, L., & Thakkar, K. (2018). An analysis of Peru: Is water driving mining conflicts? *Resources Policy*, 101270. https://doi.org/10.1016/j.resourpol.2018.09.010

Schauwecker, S., Rohrer, M., Huggel, C., Endries, J., Montoya, N., Neukom, R., Perry, B., Salzmann, N., Schwarb, M., & Suarez, W. (2017). The freezing level in the tropical Andes, Peru: An indicator for present and future glacier extents. *Journal of Geophysical Research: Atmospheres*, *122*(10), 5172–5189. https://doi.org/10.1002/2016jd025943

Statista. (2021, July 2). *Peru: mining industry as share of exports 2010–2019*. https://www.statista.com/statistics/1030692/peru-mining-sector-share-total-exports/

Tanaka, M., Z arate, P., & Huber, L. (2011). Mapa de la conflictividad social en el Perú. http://repositorio.iep.org.pe/bitstream/handle/IEP/701/tanaka_mapa-conflictividad.pdf?sequence=2&isAllowed=y

The World Bank. (2021). *Population growth (annual %) - Peru | Data*. The World Bank. https://data.worldbank.org/indicator/SP.POP.GROW?end=2020&locations=PE&start=2010&view=chart

Urrutia, R., and M. Vuille (2009), Climate change projections for the tropical Andes using a regional climate model: Temperature and precipitation simulations for the end of the 21st century, J. Geophys. Res., 114, D02108, doi:10.1029/ 2008JD011021.

USAID. (2011). Adaptation to Climate Change: Case Study – Glaciial Retreat and Adaptation Options in Peru’s Rio Santa Basin (Draft Final). https://www.caee.utexas.edu/prof/mckinney/Peru/Peru%20Case%20Study%20Jul2011_v6_Draft_Final.pdf

USDA. (2021). Spotlight: Peru's Fruit Sector Races to New Heights. *International Agricultural Trade Report. https://www.fas.usda.gov/sites/default/files/2021-06/PeruIATR-Final_0.pdf*

Vos, J. & Marshall, A. (2017). Conquering the desert: drip irrigation in the Chavimochic System in Peru. In J-P. Venot, M. Kuper & M. Zwarteveen (eds.), *Drip irrigation for agriculture. Untold stories of efficiency, innovation and development* (pp. 134-150). Routledge. https://doi.org/10.4324/9781315537146

Vuille, M., Kaser, G., & Juen, I. (2008). Glacier mass balance variability in the Cordillera Blanca, Peru and its relationship with climate and the large-scale circulation. *Global and Planetary Change*, *62*(1–2), 14–28. https://doi.org/10.1016/j.gloplacha.2007.11.003

Vuille, M. (2013). Climate Change and Water Resources in the Tropical Andes. 10.13140/2.1.3846.9124.

Vuille, M., Carey, M., Huggel, C., Buytaert, W., Rabatel, A., Jacobsen, D., Soruco, A., Villacis, M., Yarleque, C., Elison Timm, O., Condom, T., Salzmann, N., & Sicart, J. E. (2018). Rapid decline of snow and ice in the tropical Andes – Impacts, uncertainties and challenges ahead. *Earth-Science Reviews*, *176*, 195–213. https://doi.org/10.1016/j.earscirev.2017.09.019