Climate Change and Water Resources in the Tropical Andes

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Acronyms

ACCION	Andean Climate Change Interamerican Observatory Network
ENSO	El Niño-Southern Oscillation
GCM	General Circulation Model
IPCC	Intergovernmental Panel on Climate Change

Abstract

Climate change will without a doubt affect future access to clean drinking water as well as to water for sanitation, irrigation and agriculture, mining operations, and hydropower production in the tropical Andes. Some of these changes will be felt directly through altered precipitation regimes and changes in total rain or snowfall amount or changes in the length of the wet seasons. Other changes may be modulated by adjustments in ecosystem services, such as retreating glaciers or degrading wetlands (*paramos*) leading to altered water quality or seasonality of streamflow in rivers. Social, economic, and environmental conflicts surrounding the struggle for control over water will be exacerbated in areas where water scarcity is juxtaposed with rapidly growing water demand due to population pressure and expanding economic activities, thereby threatening traditional irrigation and water use practices.

This paper describes the challenges surrounding current and future water use in the tropical Andes by first reviewing the modern and future projected hydrological cycle and anticipated impacts on environmental services provided by glaciers and wetland vegetation. The discussion then elaborates on the current tensions and conflicts surrounding water use from a social and economic perspective, and ends by focusing on the challenges ahead and looking at possible solutions for more-sustainable and equitable future water use in the region.

1. Observed and Projected Changes in Andean Climate and Its Hydrologic Cycle

The tropical Andes effectively separate the low-level atmospheric circulation, thereby leading to one of the strongest east-west climatic gradients observed worldwide.[1] On the western side of the Andes, south of the equator, cold and dry conditions are maintained by a cold ocean and large-scale sinking of air masses. These two features, in combination, effectively prevent moisture from penetrating inland and upslope toward the Andes. To the east, on the other hand, abundant moisture transport from the tropical Atlantic leads to very humid conditions and high precipitation rates over the Amazon basin. Over the Andes itself, easterly winds promote moisture influx toward the mountains during the summer months, which leads to a very distinct rainy season between November and April in much of Peru, while further south in Bolivia and northernmost Chile, the wet season lasts only from December through March.[2] In the Andes of Ecuador, the seasonality of precipitation is bimodal, with two main wet seasons from March to May and September until November.[3] The Andes of Colombia, located in the northern hemisphere, are quite humid, with precipitation seasonality being modulated by topography, but the main wet season extends from June to August.[4]

Year-to-year variations in precipitation can be substantial and are caused primarily by the El Niño-Southern Oscillation (ENSO) phenomenon. During El Niño events the warm surface waters off the coast of Ecuador and Peru often cause torrential downpours over the coastal deserts.[5] This precipitation, however, does not reach above ~2000 meters and hence does not affect the Andes beyond the lower western slopes. In fact, El Niño leads to strong westerly flow over much of the tropical Andes, which inhibits significant moisture transport from the Amazon basin and causes drought conditions over the tropical Andes, in particular over the Altiplano region of Bolivia and southern Peru.[6] Drought during El Niño is also often observed in the Andes of Colombia and northern Ecuador.[7] El Niño events also lead to a large-scale warming over the

[1] Garreaud et al. 2009.
[2] Garreaud et al. 2003.
[3] Vuille et al. 2000a.
[4] Poveda et al. 2001.
[5] Garreaud et al. 2009.
[6] Garreaud and Aceituno 2001; Vuille 1999; Vuille et al. 2000b; Vuille and Keimig 2004; Lavado Casimiro et al. 2012.
[7] Poveda et al. 2001; Vuille et al. 2000a.

tropical Andes, hence these episodes can generally be characterized as being warm and dry, while La Niña events tend to lead to cold and wet conditions in much of the tropical Andes.[8]

The mean climatic conditions in the tropical Andes underwent significant changes during the twentieth century. The temperature increased by about 0.7°Celsius between 1939 and 2006,[9] although the increase varies, depending on elevation and slope.[10] Several studies have documented similar warming trends on a more regional level.[11] This temperature increase is relevant for understanding current and future rates of glacier retreat, as the freezing level determines not only the extent to which a glacier is exposed to surface melt but also the ratio of rain versus snow falling on a glacier.[12]

Precipitation trends are weaker and much less coherent, owing to the strong modulation of precipitation characteristics by the Andean topography. There are also far fewer high-quality stations with long precipitation series in existence, which makes an assessment of long-term changes in precipitation very challenging. Based on an analysis of 42 stations in the Andes of Ecuador, Peru, and Bolivia between 1950 and 1994, Vuille et al. in 2003 found a trend toward increased precipitation north of ~11°S, while most stations located further south showed a precipitation decrease.[13] While this large-scale precipitation signal showed some spatial coherence, most of the individual station trends were not significant. Haylock et al., however, in 2006 confirmed these results, also reporting a change toward wetter conditions in Ecuador and northern Peru, with opposite trends in southern Peru.[14] Finally, Thibeault et al. in 2010 identified a tendency toward a later onset of the wet season in the Bolivian Altiplano, with less frequent but more-intense rainfall.[15]

Studies on future climate change are fairly limited and focus primarily on changes in temperature and precipitation by the end of the twenty-first century based on different Intergovernmental Panel on Climate Change scenarios. Bradley et al., for example, in 2004 analyzed temperature changes in the Andes under scenarios of doubled carbon dioxide concentrations.[16] Temperature changes in the simulations show a strong elevation-dependency,

[8] Vuille et al. 2000a,b; Vuille et al. 2008b.
[9] Vuille et al. 2008a.
[10] Vuille and Bradley 2000; Vuille et al. 2003.
[11] Mark 2002; Mark and Seltzer 2005; Racoviteanu et al. 2008; Poveda and Pineda 2009.
[12] Favier et al. 2004; Bradley et al. 2009.
[13] Vuille et al. 2003.
[14] Haylock et al. 2006.
[15] Thibeault et al. 2010.
[16] Bradley et al. 2004

with the largest warming at high elevations where glaciers are located. In 2006, Bradley et al. used the high emission A2 scenario to document that the tropical Andes might experience a warming on the order of 4.5–5°Celsius by the end of this century—again with largest temperature increases at higher elevations.[17]

In a follow-up study, Urrutia and Vuille conducted the first high-resolution, regional climate model simulation for this region.[18] Figure 1 shows the projected surface warming by the end of the twenty-first century based on a high (A2) and a low (B2) emission scenario. The results suggest a substantial warming of 5–6 °Celsius in many parts of the Andes under an A2 scenario by the end of the century. The largest warming is projected for the highest elevations in the Cordillera Blanca region, Peru. In the lower emission B2 scenario, the surface warming is about half the amplitude of the A2 projection.

Maybe even more disconcerting are projections of future interannual variability and the likelihood of extremely hot years. Figure 2 shows the Andean temperature distribution by 2071–2100 in A2 and B2 scenarios compared with a control run for the years 1961–90. The results clearly document that the future climate will not only be significantly warmer, it will also feature a much higher likelihood of extremely hot years. Most important, Figure 2 shows that even the coldest years in a future world under an A2 or B2 scenario will be much warmer than the warmest years observed in today's climate. We are essentially entering a "no-analog" situation, which will pose a severe threat to the adaptive capacity of Andean ecosystems who have adjusted to current conditions over several millennia.

Future changes in precipitation amount or seasonality are much more difficult to simulate. This is partly due to model uncertainties and their limited ability to accurately simulate the global hydrological cycle, but the problems are exacerbated when considering changes on a regional scale in a region where precipitation is so strongly modulated by Andean topography. Urrutia and Vuille examined changes in precipitation by the end of the twenty-first century under the A2 scenario with the same regional model used in their temperature analysis.[19] According to their results, precipitation might increase along the coastal regions of Colombia and Ecuador and in some places along the eastern Andes south of the equator, while the southern tropical Andes, including the Altiplano region, might see a decrease in precipitation. These results, however,

[17] Bradley et al. 2006.
[18] Urrutia and Vuille 2009.
[19] Ibid.

should be interpreted with caution, given that they are based on only one regional circulation model and only one driving global model (HadCM3).

More recently, Minvielle and Garreaud took a different approach, called statistical downscaling, where they exploited the observed very close empirical relationship between upper-level circulation and precipitation over the Altiplano region to infer changes in rainfall for the end of this century based on simulated future circulation changes.[20] Their results, based on 11 different general circulation models (GCMs) following the A2 scenario, indicate an almost year-round future decrease in easterly flow over the Altiplano. Since strong easterlies are required to sustain significant moisture flux toward the Altiplano under current climatic conditions, this result can be interpreted as a high likelihood of a future reduction in precipitation, which was quantified by Minvielle and Garreaud to be on the order of 10–30 percent below today's amounts.[21]

2. Impacts of Climate Change on Natural Systems and Their Environmental Services

The observed changes in temperature have led to a rapid and accelerated retreat of tropical glaciers throughout the tropical Andes. While a decline in precipitation may have contributed to that retreat on a regional scale, the lack of a coherent negative precipitation trend across the entire range of the tropical Andes suggests that precipitation changes were not the main driver of the observed change.[22]

In Venezuela, the five remaining cirque glaciers (out of 10 that still existed in 1952) are no longer in equilibrium with modern climate and only cover a combined 1.2 km^2.[23] They all retreated rapidly over the course of the twentieth century, losing more than 95 percent of their surface area since 1850.[24] (See Figure 3).

In Colombia, six glacierized mountain ranges remain today, while eight glaciers disappeared entirely during the last century.[25] According to Poveda and Pineda, Colombia's total

[20] Minvielle and Garreaud 2011.
[21] Ibid.
[22] Rabatel et al. In press.
[23] Carillo 2011.
[24] Schubert 1992, 1998.
[25] Ceballos et al. 2006.

remaining glacierized area was 45 km^2 in 2007, with an average glacier area loss rate estimated at 3.0 km^2 yr^{-1}.[26]

In Ecuador, the glaciers on the volcanoes Antizana, Cotopaxi, and Chimborazo have been studied in most detail. A glacier on Antizana, named glacier 15, has been in a state of retreat for the past 50 years, but the rate of retreat was seven to eight times faster between 1995 and 2000 than during 1956–1993.[27] Superimposed on the long-term trend are periods of faster or slower retreat, which have been linked to the phase of ENSO, due to the highly negative mass balance on Antizana during El Niño, while the mass balance is almost in equilibrium during La Niña events.[28] Glacier extent has also been reconstructed on the Cotopaxi volcano using aerial photography. Results show that Cotopaxi lost approximately 42 percent of its ice cover between 1976 and 2006.[29] The total mass (thickness) loss on selected Cotopaxi glaciers equaled 78 meters between 1976 and 1997, consistent with similar values obtained from Antizana. On Chimborazo volcano, recent glacier retreat was also quite large, with glaciers losing 59.3 percent of their surface area between 1962 and 1997.[30]

The largest fraction of tropical glaciers is located in the Peruvian Andes and in particular in the world's most densely glacier-covered tropical mountain range, the Cordillera Blanca. In 1970 the 722 glaciers in the Cordillera Blanca still covered an area of 723.4 km^2,[31] but by the end of the twentieth century this figure had dropped to less than 600 km^2.[32] Racoviteanu et al. estimated that the total glacier area had decreased by 22.4 percent between 1970 and 2003.[33] Large retreat rates were also found on individual Cordillera Blanca glaciers that were studied in more detail,[34] but also in the more arid Cordillera Ampato in southwestern Peru[35] and in the Cordillera Vilcanota in southern Peru.[36]

Rapid glacier retreat has also been observed in the Cordillera Real of Bolivia.[37] Glaciers on Charquini, for example, have lost between 65 and 78 percent of their Little Ice Age size and

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[26] Poveda and Pineda 2009.
[27] Francou et al. 2000.
[28] Francou et al. 2004.
[29] Jordan et al. 2005; Caceres 2011.
[30] Caceres 2011.
[31] Ames et al. 1989.
[32] Georges 2004.
[33] Racoviteanu et al. 2008.
[34] Hastenrath and Ames 1995; Kaser et al. 1996; Ames 1998; Mark et al. 2005; Raup et al. 2006; Bury et al. 2011.
[35] Racoviteanu et al. 2007; Silverio and Jaquet 2012.
[36] Brecher and Thompson 1993; Thompson et al. 2006.
[37] Jomelli et al. 2009, 2011; Soruco et al. 2009a.

recession rates have increased by a factor of four over the last decades.[38] Chacaltaya glacier, formerly also located in the Cordillera Real[39] and used as a small ski resort (the world's highest at 5400 meters), completely disappeared in 2009. Its disappearance is representative of many small glaciers in the region, where retreat rates have increased once the glacier reaches a critical size and warm air advection from the surrounding ice-free rocks becomes critically important.[40] Soruco et al. recently estimated that the 376 glaciers in the Cordillera Real on average had been subject to an estimated 43 percent (0.9 km^3) volume loss between 1963 and 2006 and a 48 percent decline in surface area between 1975 and 2006.[41]

These changes in glacier volume will eventually lead to significant changes in the seasonal glacier hydrology downstream, with the most significant changes in streamflow expected during the dry season, when glacier melt water, initially retained as snow and ice, accounts for a significant amount of total river flow.[42] Snow falling in the Andes is initially stored as ice in mountain glaciers, before being released with a delay, thereby adding to the dry-season base flow. Hence glaciers play a vital role as critical buffers against seasonal precipitation and provide water during the dry season for a multitude of domestic, agricultural, or industrial uses.[43] This environmental service provided by glaciers was documented, for example, by Kaser et al., who showed that the percentage of glaciated area in tropical Andean catchments is highly correlated with their capacity to store precipitation.[44]

In a future scenario where glaciers continue to retreat and eventually disappear entirely, at least from lower-elevation catchments, it is logical to assume that the runoff behavior will gradually transition from a situation with continuous water supply to one with most of the runoff concentrated in the wet season and with little to no base flow during the dry season. This problem is of special concern in the tropical Andes, where the strong solar radiation precludes the development of a seasonal snow cover. Unlike the situation in the Alps or the Rocky Mountains, snow melt therefore does not provide an additional, seasonally changing water reservoir.[45]

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[38] Rabatel et al. 2006.
[39] Ramirez et al. 2001; Francou et al. 2003.
[40] Francou et al. 2003.
[41] Soruco et al. 2009b.
[42] Viviroli et al. 2011.
[43] Vuille et al. 2008a.
[44] Kaser et al. 2003.
[45] Kaser et al. 2003, 2010.

The hypothetical scenario just described can already be observed in some regions of the tropical Andes. Mark et al., for example, reported that 30–45 percent of the streamflow out of the Cordillera Blanca into the Rio Santa valley during the dry season can be attributed to non-renewed glacier melt.[46] And Mark and McKenzie showed that the relative glacial discharge to the upper Rio Santa watershed is increasing.[47] Similarly, on Zongo glacier in the Cordillera Real, measurements indicate that more water leaves the catchment in the form of runoff than is supplied by precipitation, with the difference being provided by glacier melt.[48]

This situation raises sustainability concerns, especially in the light of the rapidly increasing population and industry in valleys downstream.[49] Users quickly adapt to enhanced short-term water availability, even though such a runoff increase is not sustainable in the long run. There are indications, however, that we may have already passed this threshold in some watersheds. Baraer et al., for example, found that seven out of nine studied watersheds in the Cordillera Blanca have already crossed a critical threshold where glaciers have become so small that dry-season discharge is already reduced.[50] According to their results, dry-season discharge will be reduced by up to 30 percent once glaciers disappear completely from these catchments. Indeed, discharge of the entire Santa River watershed draining the Cordillera Blanca has declined by 17 percent from 1954 to 1997, although the contribution of human extraction upstream is unknown.[51]

How exactly these changes will play out in the future is still anybody's guess, as very few hydrologic modeling studies on this topic exist, and uncertainties in hydrologic modeling are very large.[52] Juen et al. simulated how monthly runoff might change in the Cordillera Blanca based on simulations of streamflow out to the years 2050 and 2080, using a glacier-runoff model forced with output from several GCMs.[53] According to their results, dry-season runoff will be significantly reduced, particularly in a high emission A2 scenario, while wet-season discharge is higher due to enhanced direct runoff. The overall discharge does not change very much in their results, but the seasonality intensifies significantly. It is also noteworthy that changes in

[46] Mark et al. 2005.
[47] Mark and McKenzie 2007.
[48] Ribstein et al. 1995.
[49] Kaser et al. 2003; Young and Lipton 2006; Buytaert and DeBievre 2012.
[50] Baraer et al. 2012.
[51] Mark et al. 2010.
[52] Buytaert et al. 2010.
[53] Juen et al. 2007.

streamflow are far greater in 2050 in the A2 scenario than in 2080 under the more moderate B1 scenario, illustrating a strong dependency on the emission path followed.[54]

The amplitude of the simulated streamflow change depends highly on the current degree of glaciation within the catchment. A currently heavily glaciated catchment will undergo a large change in its seasonal runoff behavior as glaciers become smaller and smaller. A catchment where the glacier is already small today, on the other hand, and therefore incapable of buffering runoff, will not see a large change even if the glacier disappears entirely in the future.[55] These results clearly highlight the importance of considering future changes and hence any adaptation measures on a case-by-case basis rather than implementing broad-brush measures that may not be adequate for many watersheds.

It is important to emphasize, however, that this process is highly scale-dependent, as the influence of glacier melt to total streamflow decreases with increasing distance from the glacier itself. Hence while the glacial melt contribution is highly relevant to Andean populations living near the glaciated mountain range, it is far less important for population centers located far away. In addition, the impact of glacier retreat on streamflow hydrology downstream depends on the precipitation seasonality of the surrounding lowlands. As a general rule, the glacier contribution to seasonally delayed runoff is most relevant in regions such as Bolivia or Peru, where rivers enter seasonally arid regions.[56] In countries such as Ecuador or Colombia, on the other hand—where glaciers are very small, the climate is much more humid, and precipitation is more equally distributed throughout the year—these changes in glacier hydrology are likely not very relevant on a larger scale. In addition these countries benefit from an important buffering capacity of tropical wetlands.[57]

These wetlands, known as *paramos*, are Neotropical alpine ecosystems, covering the northern tropical Andes between Venezuela and northern Peru from the upper tree line at ~3500 meters to the permanent snowline at ~5000 meters.[58] *Paramos* are considered a major water source for Andean highlands and provide water for a vast area of the much drier lowlands on the Pacific coast of Ecuador and northern Peru.[59] Many of the largest cities, such as Bogota in Colombia and Quito in Ecuador, also receive much of their water supply from *paramos*. Similar

[54] Vuille et al. 2008a.
[55] Ibid.
[56] Kaser et al. 2010.
[57] Buytaert et al. 2006.
[58] Josse et al. 2011; Young et al. 2011.
[59] Harden 2006.

to glaciated catchments, rivers sourced by *paramos* are also characterized by a high and sustained base flow as a result of the high water retention capacity of the soils.[60]

Paramos are also increasingly threatened by climate change, as higher temperatures will displace ecosystems upslope, coupled with biodiversity loss and increasing spatial isolation.[61] Higher temperatures will also lead to increased evapotranspiration and result in lowered water production from *paramos*. Future changes in precipitation amount and seasonality will also affect *paramo* ecosystems through increased soil dryness, altering organic matter decomposition and reducing the soil water retention capacity, which might lead to increased flow variability.[62] More important in the short term, however, are population pressure and human-induced land use changes and the expansion and intensification of agriculture and livestock, causing enhanced soil erosion and increased river sediment loads, thereby affecting both water quality and quantity for urban consumption and hydropower production.[63]

Upslope movement of ecosystems and associated biodiversity loss is expected due to the projected 3–5°Celsius warming in the twenty-first century.[64] *Paramos* are a biodiversity hotspot with several thousand different plant species, of which many are endemic and adapted to the specific climatic conditions. Given that climate at the end of this century will essentially resemble a "no-analog" situation (see Figure 2), the adaptive capacity of Andean ecosystems will be severely tested and the extinction of many species that are unable to migrate upslope at a sufficient pace is a strong possibility.[65] At the same time, some vegetation zones may be able to expand their habitat, as indicated, for example, by the upslope migration of Andean tree species.[66] Higher temperatures may also lead to a spread of new invasive species and disease into hitherto unoccupied new territories.[67]

Finally, glacier retreat can also directly affect the species composition of ecosystems through changes in downstream water supply. This is the case, for example, for wetlands that are directly fed by and dependent on glacier melt water (e.g., *bofedales*). Aquatic species may also be strongly affected, as proglacial zones with their characteristic temperature and flow regime will be lost once glaciers disappear completely from a region. Aquatic species adapted to these

60 Buytaert et al. 2006.
61 Buytaert et al. 2011.
62 Buytaert and Beven 2011.
63 Buytaert et al. 2006.
64 Urrutia and Vuille 2009.
65 See, e.g., Anderson et al. 2011.
66 Feeley and Silman 2010.
67 See, e.g., Seimon et al. 2007.

conditions are extremely vulnerable to extinction as, unlike terrestrial species, they cannot simply displace their altitudinal distribution to higher altitudes in search of a no longer existing glacial stream habitat.[68] In the Andes of Ecuador, for example, Jacobsen et al. estimated that 11–38 percent of the regional species, including endemics, may disappear following the complete disappearance of glaciers.[69] Of course, many aquatic species, especially fishes, are also vulnerable to other impacts of climate change and human disturbance, such as deforestation, water withdrawals or pollution, hydropower development, or increasing water temperature due to climate change.[70] It is estimated that 400–600 different freshwater fish species exist in the Andes, of which nearly 40 percent are endemic.[71]

3. Social and Economic Tensions due to Water Stress

The change in seasonality of streamflow and in particular the reduction of river runoff during the dry season will have implications for water use in all its aspects, ranging from access to drinking water to water availability for sanitation, irrigation and agriculture, mining operations, and hydropower production.[72]

Indeed the observed and projected future decreases in streamflow have already led to increased tensions, in particular between local peasants and mining companies. These tensions are aggravated because mines are usually located in the headwater areas where glacier contribution is most relevant and where changes in streamflow are projected to be most apparent. In addition, mining is a heavily polluting and dirty industry and can negatively affect water quality for downstream users.[73] Mining is of course a key economic sector in many Andean countries and is unlikely to take a back seat to water interests of indigenous populations. Large-scale industrial agriculture along coastal areas, mainly in Peru, is also water-intensive and favored by institutional arrangements that are primarily concerned with states' economic interests toward export-oriented products.[74]

[68] Jacobsen et al. 2010.
[69] Jacobsen et al. 2012.
[70] See, e.g., Anderson and Maldonado-Ocampo 2010.
[71] Ibid.
[72] Vergara et al. 2007.
[73] Bebbington and Williams 2008.
[74] Lynch 2012.

Similarly, hydropower production is the main energy sector in several Andean countries; it is efficient and economic, given the topographic setting, and has a low carbon footprint.[75] Hydropower production is projected to increase on a very large scale to the east of the Andes, where 151 new dams greater than 2 MW are planned over the next 20 years, constituting more than a 300 percent increase in production.[76] These dams would include five of the six major Andean tributaries of the Amazon and have potentially significant ecologic impacts along the Andes-Amazon nexus.

There are however, also significant social and economic impacts related to hydropower production in the high Andes themselves. Carey et al., for example, vividly document the case of Lake Parón, in the Cordillera Blanca, where rural farmers clashed with a hydroelectric energy corporation in 2008 over water management from a local reservoir.[77] This lake was equipped with a tunnel and floodgates in the 1980s to regulate lake level and thereby prevent a climate-related outburst flood that could have threatened lower-lying villages and infrastructure. This construction was a successful adaptation to climate change, but the potential to regulate the natural flow of water out of the reservoir led to very different desires and priorities for water management by stakeholders such as rural farmers, urban residents, tourism promoters, National Park officials, and the hydroelectric company. The decades' long tensions ultimately led to a coalition of local community groups seizing control over the reservoir from a large multinational energy corporation. At the end of 2011 the conflict was still unresolved, with Peru's National Water Authority conducting studies as to who should be involved in managing the lake and regulating its outflow in the future.[78]

Such cases add to the growing concern that future water scarcity may lead to increasing struggles for power to regulate and gain access to water and that displacement of local populations and centuries-old water use practices may be the end result.[79] It is therefore of fundamental importance to document such cases and address them at the level of regional and national governments when the uses and allocation of water and access and control issues are being discussed and regulated. Historically unequal power relationships (e.g., mining or hydropower companies versus local peasants) have helped shape government policies

[75] Vergara et al. 2007.
[76] Finer and Jenkins 2012.
[77] Carey et al. 2012.
[78] Ibid.
[79] Carey 2010.

determining who has control over and access to water.[80] Significant political power has been exerted in that way, for example in Ecuador or Peru, leading to renegotiation of water management rules, effectively replacing widespread informal practices and customary uses that have been in place for centuries.[81] Protection of vulnerable water users for these reasons has historically not been a priority of Andean nations.[82]

One aspect that could potentially alleviate some of the pressure is the ability of the Andean population to adapt to water stress. Resilience to environmental change is closely coupled with human perceptions of the change but also with societal activities, adaptive capacity, and existing strategies of response to current and future climate change scenarios. The current understanding about the resilience of local households and their capacity to adapt to such shifts in water availability is insufficient, but there is evidence from several studies that local communities in the Andes are indeed adapting in a number of ways.

As discussed in Bury et al., farmers from the town of Catac, located in Cordillera Blanca, have noticed decreased water supplies during the dry season negatively affecting their crops and agricultural productivity.[83] This reduction in water supply has also affected their livestock through reduced pasture and grass productivity and forced them into larger daily vertical movements in search of riverbeds that carry sufficient water. As indicated by local interviewees, this has led to reduced growth rates of livestock and negatively affected fish stocks. Fully 91 percent of the respondents interviewed by Bury et al. indicated that they were very concerned about the recent changes in climate in the region.[84]

Livelihoods may also be affected by climate change in regions where the hydrologic cycle may remain stationary. For example, it has been shown that in some areas the warmer temperatures have lead to an upward expansion of the upper limit of potentially cultivable land, leading to the ironic situation that more land can now be cultivated, hence requiring even more water.[85] Projections also suggest that, as a result of higher temperatures, planting and harvesting dates may be earlier and crop cycles may be shorter, but overall yields will be lower—in particular, for certain potato crops.[86]

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[80] See, e.g., Carey et al. 2012.
[81] Crabtree 2002; Carey 2010.
[82] Lynch 2012.
[83] Bury et al. 2011.
[84] Ibid.
[85] Hole et al. 2011.
[86] Sanabria and Lhomme 2012.

These struggles over access to sufficient water need to be discussed in the context of a growing Andean population, which will put additional pressure on resources. Indeed, the problems associated with climate change and impacts on water resources are of concern primarily in regions where large population pressure and significant economic activity are juxtaposed with large projected changes in water availability, thereby leading to increased competition for water rights. Buytaert and DeBievre, for example, recently argued that demographic changes in major Andean cities may be more relevant in this context than changes in climate, simply due to the rapid population growth, which may be outpacing the impact of climate change on water resources.[87] Given the large uncertainties in any projections of future climate change, however, these results will have to be re-evaluated once better estimates of future climate change scenarios in this region become available. The study also does not consider impacts on rural populations living close to glaciated watersheds, which will likely be the most strongly affected. There is, however, some concern that future water scarcity in some areas may lower the carrying capacity of the land and induce migration of large segments of the rural population to urban centers, thereby further enhancing water pressure in Andean cities.

4. Challenges Ahead

The current problems surrounding water availability in the tropical Andes coupled with future projections of glacier retreat, potential reductions in precipitation, and continued population growth, require swift development and implementation of adaptation and mitigation strategies, which could help alleviate, both in the short and the medium term, the conflicts surrounding access to clean water. The main goal of such adaptation efforts should be to increase the resilience and reduce the vulnerability of local indigenous populations who will likely be most heavily affected by future climate change impacts on the hydrologic cycle.

Unfortunately, there has historically been a general disconnect between the various groups involved in these discussions, and this has proved to be a major challenge and impediment for moving forward with such an agenda. Scientific studies, for example, have so far contributed little to improving our predictive understanding of future Andean water supply and demand and therefore have had virtually no impact on improving the livelihood of affected populations. We still do not fully understand the spatially varying importance of glaciers in

[87] Buytaert and DeBievre 2012.

different parts of the Andes, for instance. The same is true for ecosystems downstream of glaciers and their potential relevance for regulating water supply. Scientific studies have hitherto also failed to provide useful metrics for planning purposes that could serve as a guideline for water managers and other decision makers. Much of this lack of progress is related to limitations imposed by an often inadequate environmental monitoring network in the region.[88] Modeling studies also suffer from large uncertainties as far as changes in the hydrologic cycle are concerned,[89] but there has been a general reluctance of many funding agencies to invest in impacts-related research, even though it is the only way to design and develop better downscaling techniques and scenarios.

Adaptation projects therefore often move forward without having received proper guidance from the scientific community. To some extent this is triggered by the reluctance of scientists to translate their scientific results into a language that is understandable by the various stakeholders and to make them accessible to everyone involved in the adaptation process.[90] As a result, some plans—such as painting mountain tops white to lower the albedo and thereby artificially induce glacier growth—go forward without adequate scientific evaluation. Similarly, adaptation projects often fail to acknowledge existing local adaptation strategies and therefore do not take advantage of traditional local knowledge to the extent that they could. A better support framework for local and regional mechanisms, initiatives, and traditions would allow for a better integration of various actors affected not just by climate change but also by the planned adaptation projects. Up until now adequate participation of the most vulnerable groups, the rural indigenous communities, has often been neglected.

This lack of discourse between different stakeholders has been a major impediment for real progress toward applied solutions in the region. One recent initiative, ACCION (Andean Climate Change Interamerican Observatory Network, funded by the US State Department),[91] is working toward improved coordination and data sharing between actors and across disciplines, with the hope that it could help promote synergies, dialogue, and collaboration but also maximize the effectiveness of often rather limited financial resources. A key aspect of this project is the recognition that real progress in the region requires better education and capacity building at all levels, promoting exchange of scientific expertise. This will be achieved through

[88] Coudrain et al. 2005; Casassa et al. 2007.
[89] Buytaert et al. 2010.
[90] Viviroli et al. 2011.
[91] See www.ecpamericas.org/Initiatives/default.aspx?id=74.

fellowships and through training and education of South American students at partner institutions in the United States and Europe.

Several workshops on glacier hydrology and climate change are being held in Andean countries to train young scientists, managers, and educators. Distributing teaching toolkits and materials on water resources for schoolchildren will allow dissemination of environmental information into the classroom, and policy briefs and glossy brochures will help inform policy makers and decision makers. Ultimately, however, these activities need to be put on a more sustainable footing with guaranteed continued funding; otherwise there is a danger that such initiatives come and go without having the desired multiplier effect of prolonged and sustained impact.

In some instances, technical solutions may be able to alleviate some of the water stress, be it through building small reservoirs, reducing the fraction of polluted water that goes unused through construction of water treatment plants, tapping into new groundwater resources, or simply installing private water storage systems.[92] Implementation of such measures, however, is often hampered by gaps in understanding of water availability, quality, and dynamics. Fundamental physical processes of water flow, storage, and quality are poorly understood in many catchments. Groundwater contribution, for example, has historically been considered negligible in glacierized valleys, given the high relief and steep slopes, but the real role of aquifers and their recharge rates are virtually unknown. In addition, new constructions, such as water reservoirs, would have to consider the negative impacts such as loss of land, water loss due to evaporation, the potential for displacement of local populations, and the shortened lifetime of reservoirs in glacial watersheds due to high sedimentation rates. Water conservation, new irrigation methods, and sanitation projects may also provide some relief in certain regions. New drip-water irrigation projects along coastal areas of Peru, for example, use only a small fraction of the water consumed in traditional irrigation projects.

Finally, it is important that the institutional standing of authorities involved in glacier research and water management be strengthened. In some instances environmental governance institutions may have to be modified or new entities may have to be created to better address changing water management requirements. Institutional arrangements, however, will have to

[92] See, e.g., Jeschke et al. 2012.

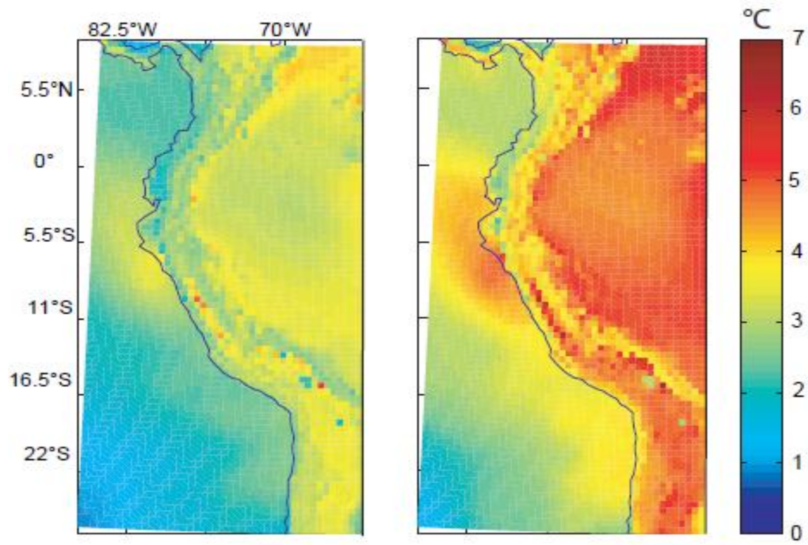
include meaningful participation of local affected populations in watershed governance in order to avoid conflicts and water competition among economic sectors.[93]

In the end, only the combination of various approaches will lead to reduced vulnerability and increased resilience of water users affected by climate change. Given the scale and complexity of the problem, collaboration and partnership between all the actors and stakeholders involved is critically important. It is the only way forward toward a more sustainable future in the tropical Andes, a future where sufficient access to clean water is guaranteed and water allocation addresses the concerns of all water users.

[93] Lynch 2012.

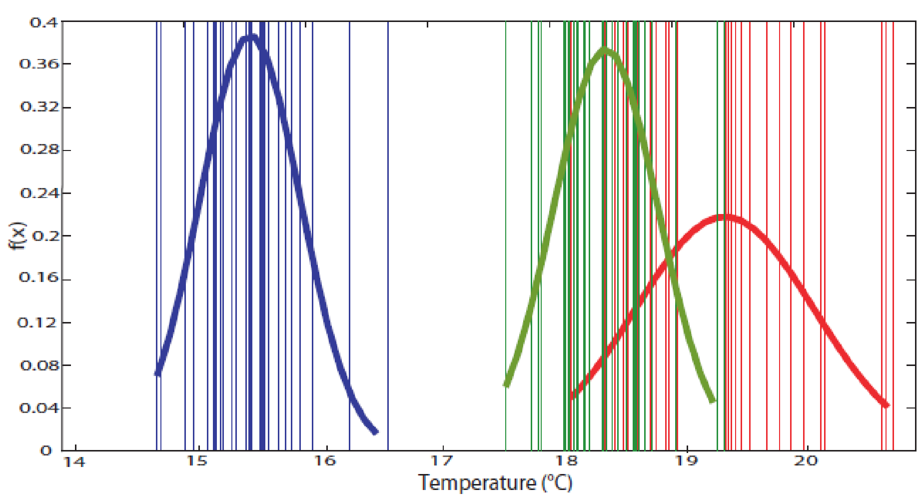
Figures

Figure 1. Increase in mean annual surface temperature along the tropical Andes by 2071–2100 compared with 1961–1990 in a regional climate model simulation based on (left) an IPCC low emission (B2) and (right) a high emission (A2) scenario. Degree of warming (in °C) is indicated by vertical bar on the right.



Source: Modified from Urrutia and Vuille 2009.

Figure 2. Probability density function for mean annual temperature for 1961–1990 (blue) and 2071–2100 in B2 scenario (green) and A2 scenario (red) along the western slope of the tropical Andes. Thin vertical lines represent the mean annual temperature in the 30 individual years for each simulation.



Source: modified from Urrutia and Vuille (2009).

Figure 3. Disappearance of glacier Espejo on Pico Bolivar in Venezuela as documented in photos from 1910 (left), 1988 (middle), and 2008 (right).

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Source: Photos courtesy of Eduardo Carillo

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