# Climate Change and Tropical Andean Glacier Recession: Evaluating Hydrologic Changes and Livelihood Vulnerability in the Cordillera Blanca, Peru

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Climate change is forcing dramatic glacier mass loss in the Cordillera Blanca, Peru, resulting in hydrologic transformations across the Rio Santa watershed and increasing human vulnerability. This article presents results from two years of transdisciplinary collaborative research evaluating the complex relationships between coupled environmental and social change in the region. First, hydrologic results suggest there has been an average increase of 1.6 (± 1.1) percent in the specific discharge of the more glacier-covered catchments (>20 percent glacier area) as a function of changes in stable isotopes of water ($\delta^{18}O$ and $\delta^{2}H$) from 2004 to 2006. Second, there is a large (mean 60 percent) component of groundwater in dry season discharge based on results from the hydrochemical basin characterization method. Third, findings from extensive key interviews and seventy-two randomly sampled household interviews within communities located in two case study watersheds demonstrate that a large majority of households perceive that glacier recession is proceeding very rapidly and that climate change–related impacts are affecting human vulnerability across multiple shifting vectors including access to water resources, agro-pastoral production, and weather variability. *Key Words: climate change, glacier recession, hydrology, livelihoods, vulnerability.*

在秘鲁的科迪勒拉布兰卡地区，气候变化正在导致急剧的冰川物质损失，造成了里约圣塔流域的水文变化，并增加了人类的脆弱性。本文介绍了在该地区进行了两年之久的跨学科的合作研究成果，以评价环境和社会变革的之间的复杂关系。首先，水文结果表明，从 2004 到 2006 年，根据水的稳定同位素（δ18O 和 δ2H）的变化结果，该地区具有较高冰川覆盖的蓄水流域区（大于百分之二十的冰川面积）产生了平均增长百分之 1.6（± 1.1）的单位流量增长。第二，基于水化学盆地分析方法的结果，存在一个较大的（平均百分之六十）旱季流量的地下水体。第三，本文对位于上述两个个案流域内的社区进行了广泛的重点访谈和随机的 72 户抽样访问，研究结果表明：大部分的家庭感觉到冰川衰退地非常迅速，与气候变化有关的影响非常广泛，影响到人类的脆弱性，包括水资源的利用，农牧业生产和天气变化。*关键词：气候变化，冰川衰退，水文，生计，脆弱性。*

El cambio climático está causando una dramática pérdida de masa en los glaciares de la Cordillera Blanca, Perú, generando transformaciones hidrológicas en toda la cuenca del Río Santa e incrementando la vulnerabilidad humana. Este artículo presenta los resultados de dos años de investigación colaborativa transdisciplinaria para evaluar las complejas relaciones entre los cambios ambientales y sociales en la región. Primero, los resultados hidrológicos sugieren que ha habido un incremento promedio del 1.6 (±1.1) por ciento en la descarga específica de los desagües con mayor cobertura de glaciares (>20 por ciento de área glaciada), como una función del cambio en isótopos estables del agua ($\delta$18O and $\delta$2H) entre 2004 y 2006. Segundo, hay un gran componente (media de 60 por ciento) de agua subterránea en el descargue de la estación seca basado en resultados del método de caracterización de la cuenca hidroquímica. Tercero, los descubrimientos derivados de detalladas entrevistas a informantes claves y setenta y dos entrevistas de muestra aleatoria administradas a hogares de comunidades pertenecientes a dos estudios de caso de cuencas, demuestran que la gran mayoría de la gente intuye que la recesión de los glaciares está avanzando rápidamente y que los impactos relacionados con cambio climático afectan la vulnerabilidad humana por medio de muchos vectores cambiantes, incluyendo el acceso a los recursos hídricos, producción agro-pastoral y variación meteorológica. *Palabras clave: cambio climático, recesión de glaciares, hidrología, medios de vida, vulnerabilidad.*

*Annals of the Association of American Geographers*, 100(4) 2010, pp. 794–805 
Initial submission, July 2009; revised submission, November 2009; final acceptance, January 2010
Published by Taylor & Francis, LLC.

Rapid glacier recession in the tropical Peruvian Andes due to recent climate change exemplifies environmental changes in mountain regions that have critical water supply implications for millions of people globally (Intergovernmental Panel on Climate Change 2007; Viviroli et al. 2007). Modern glacier recession is strongly correlated with a significant rising trend in atmospheric temperatures, and climate models predict enhanced future rates of glacier loss with increased warming at higher tropical altitudes (Barry and Seimon 2000; Bradley et al. 2009). This recession will significantly affect the future availability and use of water resources because human populations are highly dependent on glacial melt water to buffer the seasonally arid climate of the central Andes (Vuille et al. 2008). Although progress has been made in tracing glacier changes over time and space, new and more integrated research is needed to evaluate these ongoing social and hydrological transformations (Mark 2008).

The Cordillera Blanca, Peru, is a unique location to study these issues as more than 25 percent of the world's tropical glaciers are located in the range. There is also a long history of environment–society dynamics in this region that has been densely settled for many centuries and the spatial extent of human activities is often conditioned by water availability. The range has also been the epicenter of some of the most disastrous hazards in recorded history (Carey 2010). Finally, the differential glacial coverage of watersheds in the Cordillera Blanca region provides a natural continuum to compare hydrologic and human responses to climate change across subcatchments simultaneously as a proxy for sequential changes in time. This article presents results from our ongoing collaborative research project in the region. Working as a transdisciplinary team, we are evaluating the regional impact of glacier melt on seasonal and interannual water availability and assessing human vulnerability and governance shifts related to the political economy of climate change.

## Setting

The Cordillera Blanca contains the world's largest concentration of tropical glaciers, most of which flow westward toward the Santa River (Figure 1 and Table 1). According to glacial inventories conducted in the 1970s, 35 percent of Peru's glacierized area and 40 percent of its glacial reserves (by volume) are stored in the more than 700 glaciers located in the range (Ames et al. 1989). The Santa River flows northwest over 300 km, draining a total watershed of 12,200 km$^2$ to become the second largest and most regular flowing Peruvian river to reach the Pacific Ocean (Mark and Seltzer 2003). The upper Santa River watershed, or Callejón de Huaylas, has an area of 4,900 km$^2$ defined by the outflow at the La Balsa station (Figure 1). Within the Callejón de Huaylas, tributary streams to the Santa River from the Cordillera Blanca define subcatchments with different percentages of glacial coverage. For some of these tributaries historical discharge records are available for forty years. Monthly average discharge from these gauged tributary streams is higher during the months of October through April, closely reflecting the seasonality of precipitation where greater than 80 percent of precipitation falls between October and May, and the austral winter months of June to September are known as the dry season.

**Table 1.** Characteristics of the Cordillera Blanca watersheds that have available historical discharge data

| Stream | Period of record | Watershed area (km$^2$) | Percentage glaciated area |
|---|---|---|---|
| **Llanganuco** | 1953–1997 | 85 | 36 |
| Chancos | 1953–1997 | 221 | 22 |
| **Quilcay** | 1953–1983 | 243 | 17 |
| Olleros | 1970–1997 | 175 | 10 |
| ***La Balsa*** | 1954–1997 | 4,768 | 8 |
| Pachacoto | 1953–1983 | 194 | 8 |
| Quitaracsa | 1953–1997 | 383 | 7 |
| **Querococha** | 1956–1996 | 62 | 3 |

*Note:* The case study watersheds are in bold type, and the La Balsa discharge station is italicized to indicate that it is located on the Rio Santa.

According to our subdistrict spatial analysis of the 2007 Peruvian Census data, the population of the Callejón de Huaylas is approximately 267,000 inhabitants. Major urban and periurban clusters along the valley include the cities of Huaraz (96,000), Caraz (13,000), Yungay (8,000), Carhuaz (7,200), Recuay (2,700), and Catac (2,400), and approximately 1,500 small rural settlements (INEI 2007). Our population estimate is roughly 25 percent higher than previous estimates, which significantly heightens the potential social risks of recent climatic change in the region (Byers 2000; Young and Lipton 2006). The watershed is also a critical source of water for urban centers, agricultural activities, and several hydroelectric power plants that account for approximately 10 percent of the

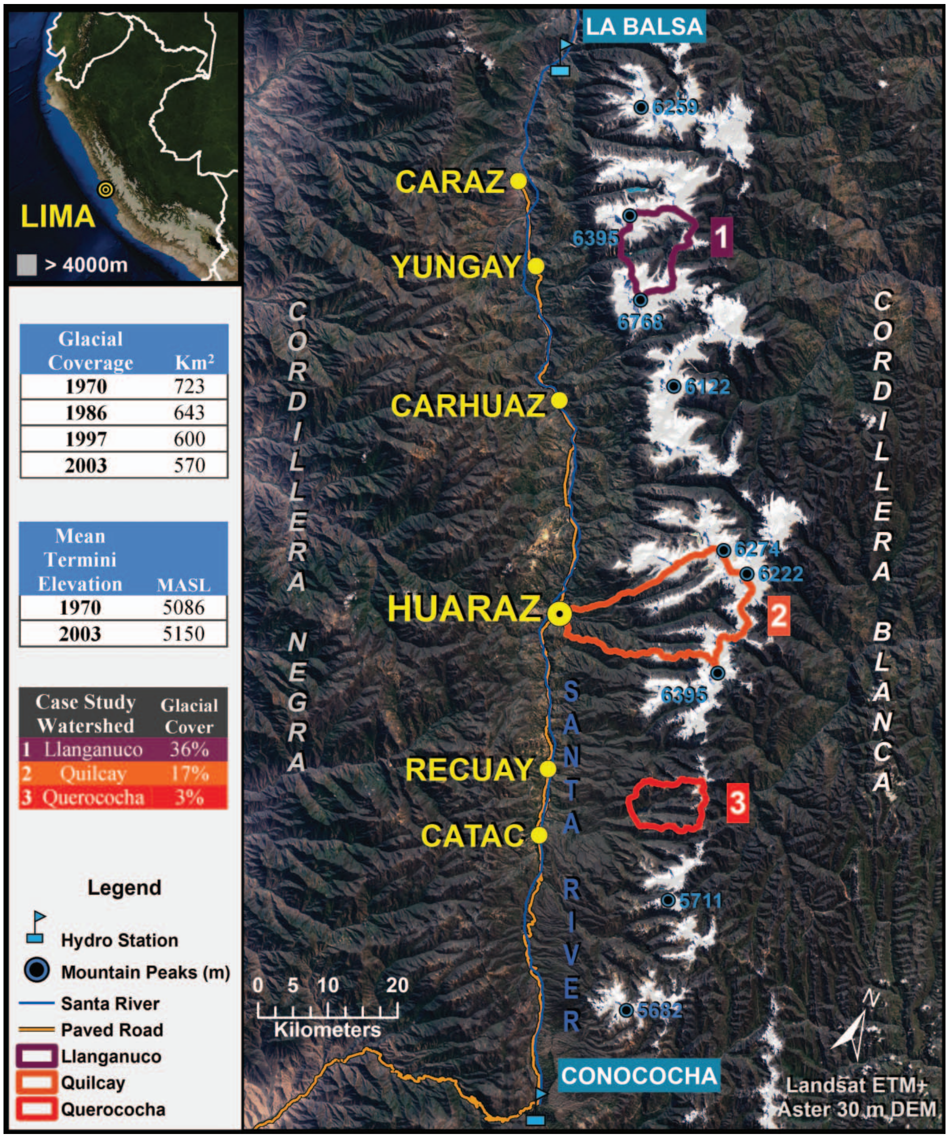


**Figure 1.** Map of the Cordillera Blanca, with study sites indicated. Inset tables include data on glacier coverage (Ames et al. 1989; Racoviteanu, Arnaud, and Williams 2008).



country's hydroelectric capacity (Ministry of Energy and Mines 2008).

Livelihoods in the region are generally dependent on access to water and other natural resources for agricultural and livestock production, as more than 80 percent of the population of the region is engaged in smallholder production (INEI 2007). Since the late 1990s, agricultural production along the Santa River has been shifting toward water-intensive crops for consumption outside the region and, similar to trends across the country, several new transnational polymetallic mining facilities have recently begun operating along the Cordillera Negra (Bury 2005; Bebbington and Bury 2009). However, more than 50 percent of the population still lives in conditions of poverty (defined as lacking more than one basic necessity) and 33 percent of the rural population is illiterate (INEI 2007).

## Background and Rationale

Observations of continued glacier recession exist throughout the Andes, but the Cordillera Blanca is one of only a few locations in the tropics where research has quantified changes in the hydrologic regime due to glacier volume loss on a scale relevant to human impact. The range has lost one third (>30%) of its glacierized area since maximum extensions of the nineteenth century, with clear evidence of significant climate change over the twentieth century (Vuille et al. 2008). Multiscale studies have traced climate forcing and the hydrologic impacts of glacier volume changes over time (Mark 2008). Mark and Seltzer (2003) estimated that 35 to 40 percent of the mean annual discharge in the Querococha watershed during 1998 and 1999 was supplied by nonrenewed melt from the Yanamarey glacier. This increased to 58 percent over the observation period from 2001 to 2004 (Mark, McKenzie, and Gómez 2005). The Yanamarey glacier is projected to disappear within a decade and our recent research has been directed toward understanding the implications of this late-stage glacial retreat for hydrologic processes and downstream communities (Bury et al. forthcoming).

Changes in the stable isotopes of water observed over recent years in glacier-fed streams demonstrate relative increases in glacier melt water (Mark and McKenzie 2007). However, this enhanced melt contribution will diminish as glacier mass disappears, causing the streams to have smaller dry season flow and increased variability (Kaser et al. 2003; Mark and Seltzer 2003; Juen, Kaser, and Georges 2007). Glacier recession also modifies watersheds by forming wetlands, lakes, and groundwater reservoirs that alter the surface drainage. There is an outstanding need to understand and quantify hydrologic processes in these dynamic and transforming landscapes, particularly in view of the potentially severe water stress impacts of glacier loss highlighted in future climate change scenarios for Peru.

Complementing research on glacier recession and hydrologic change, our research also builds on recent environment–society research examining the adaptive behavior of human communities to environmental change in the Peruvian Andes (Young and Lipton 2006; Postigo, Young, and Crews 2008). Geographic research in the Andes has long focused on human responses and adaptation to diverse processes of environmental and socioeconomic change (Sauer 1941; Knapp 1991; Zimmerer 1991; Denevan 1992; Bebbington 2000; Bury 2004). As Sauer (1941) noted, the complex shifts that climatic change induces across landscapes have been an enduring theme in geography.

This research also has theoretical links to research on human vulnerability and adaptation to global change. In geographic studies, vulnerability research has evolved significantly from its foundations in early risk-hazard studies (White 1942; Burton, White, and Kates 1978) and subsequent critiques of this work for a lack of attention to political economy and structural conditions (Hewitt 1983; Watts and Bohle 1993). More recent vulnerability studies have developed integrative approaches that examine how biophysical, social, economic, and political factors interact with and feed back on one another across scales of analysis (Liverman 1990; Cutter 2003; Turner et al. 2003; Polsky 2004; Eakin 2006; Leichenko and O'Brien 2008). Much of this work makes a case for the transdisciplinary collaborations, place-based analyses, and mixed methodological approaches that we are currently utilizing in our research.

## Methodology

The linked foci of this research are on shifts in regional water resources and the impacts of such changes on household livelihood strategies and vulnerability in the Cordillera Blanca. To examine these questions we have integrated in situ observations with geospatial analyses, hydrochemical mixing models, semistructured household surveys, and key interviews. Our methodology also identifies and analyzes patterns across nested spatial and temporal scales. The uneven distribution of modern glaciers in the tributary watersheds of the Santa River provides a natural continuum over which to evaluate changes in hydrologic processes related to different amounts of glacier coverage. Furthermore, the research is focused on the dry season when water resources are more stressed and glacier melt production is relatively more important.

Using geographic information systems, remote sensing techniques, and site visits we selected three representative tributary watersheds to the Santa River with different glacial coverage, variable hydrological characteristics and diverse livelihood pursuits to understand and measure hydrologic processes, calibrate hydrochemical mixing models, and evaluate the spatial distribution of household resource use patterns. These case study watersheds are Llanganuco, Querococha, and Quilcay (Figure 1). Specific digital products utilized to identify glacierized areas, generate digital elevation models, delimit watershed areas, and evaluate human activities include satellite imagery from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Landsat, and Quickbird platforms.

Historic discharge records in the Callejón de Huaylas are available for the Santa River at La Balsa and for eleven tributaries of the Santa River, dating from the 1950s through the end of the twentieth century when observations were largely disbanded due to the privatization of the state-run water resources office (Mark and Seltzer 2003). To compare trends over time, normalized anomalies of annual discharge were generated for La Balsa and seven glacierized, noncontrolled (i.e., no dams) tributary watersheds with the longest records (Table 1). Discharges were normalized by subtracting the series mean from the annual value, then dividing that difference by the series standard deviation. We computed anomalies for both the total annual discharge and the dry half of the year (May–October).

To characterize the temporal and spatial variability of glacier melt water discharge in the case study watersheds, we measured dissolved ion concentrations and isotopic signatures ($\delta^{18}O$ and $\delta D$) of water samples collected between 1998 and 1999 and 2004 and 2009 (after Mark and Seltzer 2003; Mark and McKenzie 2007). We used the hydrochemical basin characterization method (HBCM), based on a multicomponent mass balance approach to identify hydrologic end member's relative or absolute contributions at a sample point (Baraer et al. 2009). Dry season discharge measurements and hydrochemistry results from 1998 and 1999 and 2004 to 2008 at the Querococha watershed were used to calibrate the HBCM and examine interannual variations of the melt water contribution from a single glacier (Mark and Seltzer 2003; Baraer et al. 2009). Spatial variability of glacier melt water was evaluated based on samples collected in the case study watersheds, spread along the Cordillera Blanca, during the 2008 dry season. A simplified two-component hydrograph separation using hydrochemical and isotopic signatures was used to deconvolve watershed discharge into melt water and groundwater. The interannual changes in water isotopes from tributary streams to the Rio Santa were also analyzed to trace the relative changes in glacier melt contribution to the larger Callejón de Huaylas watershed (after Mark and McKenzie 2007).

We formulated a mixed set of social science methods directed toward maximizing levels of objective confidence and minimizing potential biases in our findings. We purposively selected case study communities in each watershed to generate the largest set of observable livelihood activities and possible impacts of recent glacier recession. We developed a stratified random sampling frame for individual household selection based on preliminary participatory community mapping activities. Individual case study households were then selected in the field based on their proximity to randomly generated coordinates using portable Global Positioning System field units and 1 m resolution satellite imagery (Figure 2). We conducted intensive semistructured household surveys and a diverse array of unstructured key interviews in each community. Overall, the findings reported in this article are based on seventy-two semistructured household surveys, twenty-one unstructured household surveys, and thirty-seven formal key interviews in the Querococha (QUER) and Quilcay (QUIL) case study watersheds (Table 2).

**Table 2.** Demographic variables listed for both the Querococha (QUER) and Quilcay (QUIL) case study watersheds

| Case study sample demographic summary | QUER | QUIL |
|---|---|---|
| Total case study area population | 3,249 | 1,200 |
| Total households in sample population | 40 | 32 |
| Total sample population | 181 | 124 |
| Household sample percentage of total community population | 5.5 | 10.3 |
| Average age of respondents | 47 | 51 |
| Gender percentage of respondents | | |
| Male | 35 | 53 |
| Female | 65 | 47 |

## Results

### Shifts in Regional Water Resources

Glacier-fed stream discharge from the Cordillera Blanca correlates strongly with climate changes, but the magnitude of glacier melt influence is scale dependent. Streams draining the two watersheds with greatest amounts of glacier coverage (glacial > 20% of watershed by area, $n = 2$) experienced a significant increase ($p = 0.023$) in average annual discharge over the forty-three-year period of historical records (Figure 3). However, there is no significant trend in annual discharge averaged for all tributaries with glaciers ($n = 7$), implying that glacier melt enhancement is not discernable on an annual basis below a threshold amount of glacier coverage. A significant ($p = 0.004$) correlation between annual discharge and regional mean air temperature over the same time suggests that streamflow responds rapidly to regional-scale climatic forcing.

In the same glaciated watersheds, dry season (May–October) stream discharge increased significantly until the early 1980s but since 1983 has declined considerably (Figure 4). This change in trend indicates that glacier melt water buffers discharge only temporarily in local watersheds, and future dry season streamflow is likely to decline further. On the Santa River scale, discharge draining the entire Callejón de Huaylas watershed (< 10 percent glacier coverage) at La Balsa has declined

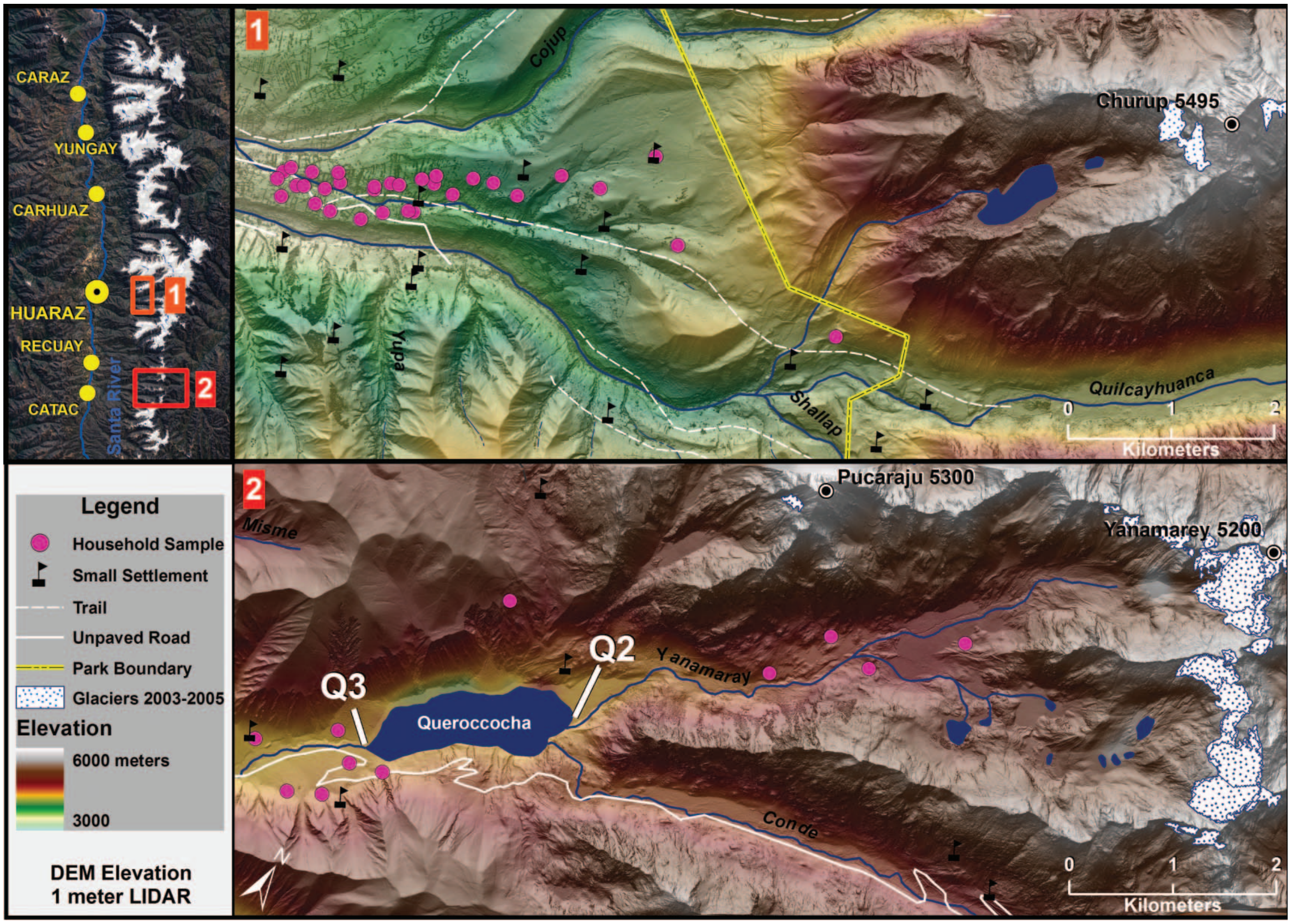


**Figure 2.** Shaded relief maps of portions of the populated sections of the Quilcay (1) and Querococha (2) case study watersheds, illustrating the location and distribution of case study locations and glaciers. Digital elevation data obtained by airborne light distance and ranging (LIDAR) survey flown in 2008 (by Horizons South America, S.A.C.).

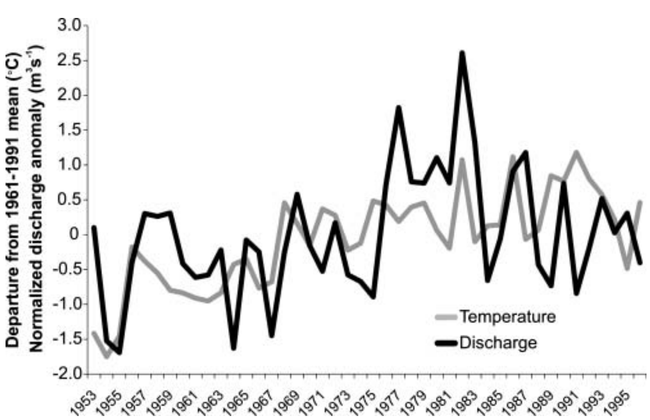


**Figure 3.** Average normalized anomalies of annual discharge for those tributary watersheds of the Santa River with > 20 percent glacier coverage ($n = 2$; see Table 1) and annual deviation of temperature from the 1961–1991 average from twenty-nine Peruvian meteorological stations between 9–11°S (from Mark and Seltzer 2005).

very significantly ($p = 0.004$), equaling a 17 percent decline from 1954 to 1997 (Figure 5).

Our analysis of stable isotope values from Callejón de Huaylas subcatchments with and without glaciers confirms a relative increase in dry season discharge due to recent glacier melt (Figure 6). Annual dry season samples (2004–2008) from Cordillera Blanca tributaries with glaciers describe a progressive depletion trend in $\delta^{18}O$ (i.e., more negative), whereas nonglacierized Cordillera Negra waters show no systematic change. The total isotopic change correlates to watershed glacier coverage (area percentage), translating to an increase in area-averaged discharge of 1.6 ($\pm$ 1.1) percent (Mark and McKenzie 2007).

Relative groundwater contributions during the dry season were first evaluated using HBCM at Q2, the inflow to Querococha Lake (Figure 2), to explore interannual variability. This location drains a 28 km$^2$

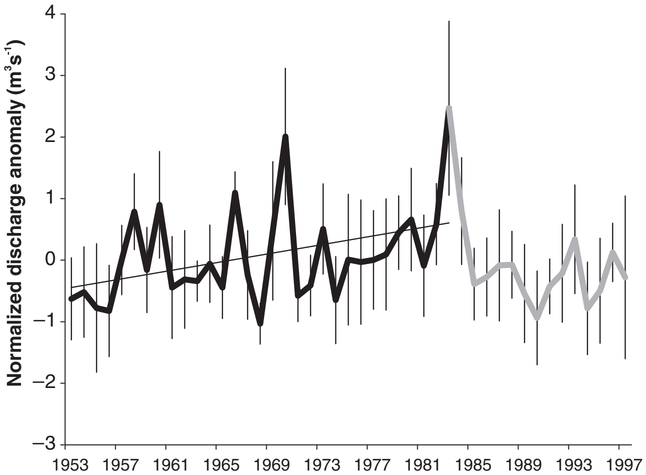


**Figure 4.** Normalized discharge anomalies for glacierized tributaries ($n = 7$) of the Santa River from 1953 to 1997. Prior to 1983, there is a significant ($p = 0.025$) positive trend shown with dark line; after 1983 there is a downward trend that is not quite significant ($p = 0.057$) shown in lighter gray. Vertical bars show range of variability at $2\sigma$ level ($\pm$ 1 *SD*).

subwatershed with 7.2 percent glacier coverage. Results indicate a median 59 percent dry season groundwater contribution to the Q2 discharge (Figure 7). The largest calculated contribution was 74 percent in 2007 and the minimum contribution was 18 percent in 1998. With such high variability and dominant overall contribution, groundwater is likely as essential as melt water in Q2 discharge. Second, HBCM applied to different tributary watersheds simultaneously indicates that groundwater aquifers having significant yield likely exist in each case study watershed. A simplified two-component model of the 2008 dry season estimates

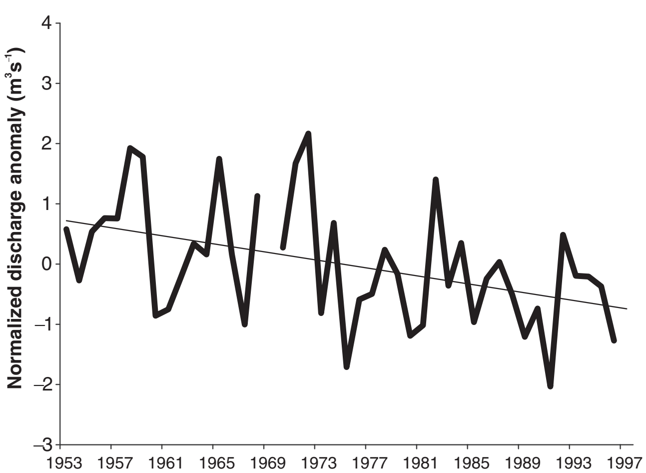


**Figure 5.** Normalized anomaly of annual discharge for La Balsa station on the Santa River (1953–1997).

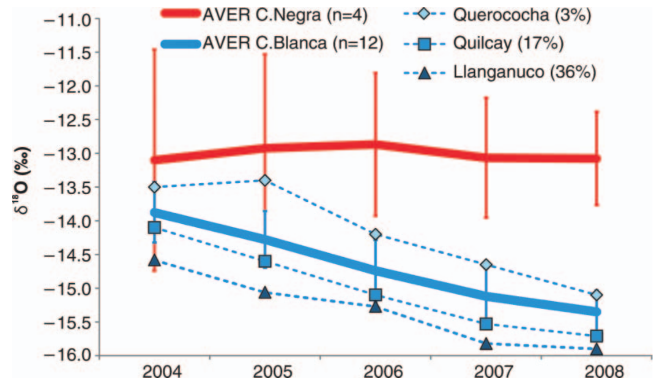


**Figure 6.** Oxygen isotope values of annual dry season water sampled from three watersheds with varying amounts of glacier coverage (dotted lines with symbols) plotted with average isotopic values for the Cordillera Blanca (with glaciers) and the Cordillera Negra (no glaciers) from 2004 to 2008, shown in thick lines with $2\sigma$ variability in vertical lines ($\pm$ 1 *SD*).

groundwater contributes 0.19 $m^3s^{-1}$ (77 percent) of discharge at Q2 and 0.15 $m^3s^{-1}$ (26 percent) of Quilcay discharge. The difference between these estimated groundwater contributions is partly explained by the relative amount of glacier coverage, equal to 3 and 17 percent in the Querococha and Quilcay watersheds, respectively.

## Livelihoods and Emerging Vectors of Vulnerability

Communities in the Querococha and Quilcay watersheds are embedded within diverse communal, private, and public governance institutions that affect household access to key livelihood resources such as land and water. Land tenure and land use vary across watersheds and among a variety of institutions beginning with privately titled land parcels at the bottoms of the watersheds, ranging upward across communally managed lands and terminating at high lakes and the glaciers that remain the sole property of the state and are within Huascaran National Park. Access to the upper watersheds is thus governed by a complex and often conflictual nexus of state–community regimes (see Figure 2). For example, grazing access to the upper Querococha watershed is controlled by the 2,200 members of the Campesino Community of Catac and access to the upper Quilcay watershed is controlled by the 240 associates of the Quilcayhuanca Users Group. In addition, a number of land management practices across both watersheds are officially proscribed by National Park authorities.

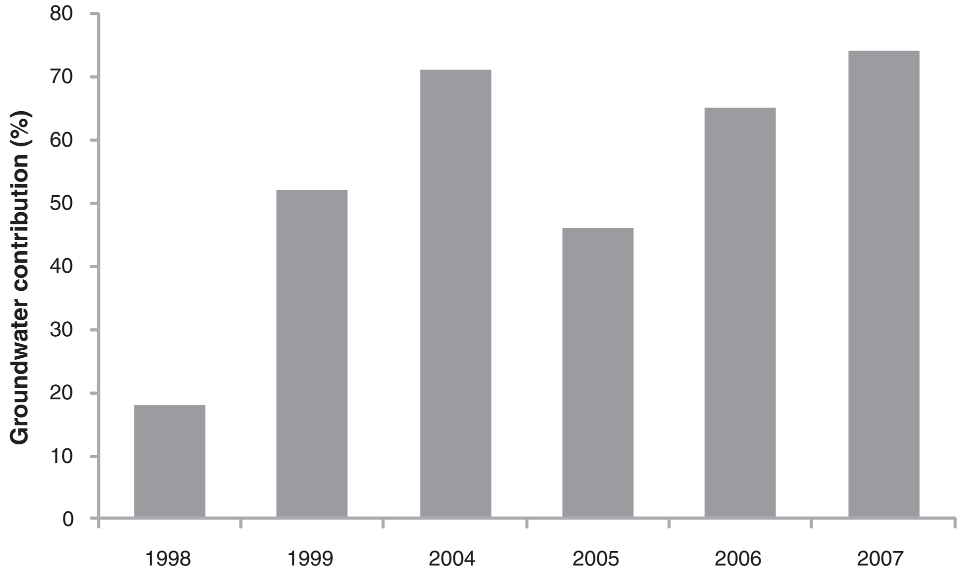


**Figure 7.** Interannual variation of the groundwater relative contribution modeled by hydrochemical basin characterization method at the inflow to Querococha Lake, Q2, in the Querococha watershed.

Households engage in a variety of livelihood activities across both watersheds, but the principal sources of household subsistence are agriculture and livestock. Table 3 presents a comparative summary of household livelihoods across both case study communities. Households in Catac are more dependent on livestock production largely due to the fact that they have access to much more communal land (~66,000 ha) and that the lowest vertical range of the community (3,500 m above sea level) limits the production of key staple crops such as corn. Conversely, households in the Quilcay watershed engage in more agricultural, commercial, and manual labor activities because part of the community is located at a lower elevation (3,300 m above sea level) and due to the proximity of Huaraz, where many household members travel on a frequent basis to generate income.

**Table 3.** Major livelihood activities in the Querococha (QUER) and Quilcay (QUIL) case study watersheds

| | | Percentage of households | |
|---|---|---|---|
| Type of activity | Description and variety | QUER | QUIL |
| Livestock | Cattle, sheep, pigs, horses, guinea pigs, burros | 85 | 78 |
| Agriculture | Potatoes, olluco, oca, mashua, corn, wheat, barley, oats, quinua, beans, herbs | 68 | 100 |
| Agroforestry | Eucalyptus, pine, quenual (*Polylepis*), capuli (*Prunus serotina*), colle (*Buddleja coriacea*) | 68 | 72 |
| Commercial | Livestock, agricultural products, market, prepared food | 45 | 78 |
| Manual labor | Temporary agricultural labor, carpentry, manufacturing | 38 | 40 |
| Tourism | Guiding, animal caretaker, burro rental, cook, boat rental | 25 | 27 |
| Dairy products | Milk, cheese, eggs | 15 | 9 |
| Artisanal | Hand-spun fabrics, clothing, ceramics | 15 | 3 |

Our evaluation of the ways in which household livelihood vulnerability is being affected by climate change and glacier recession demonstrates the combined ways in which new vectors of environmental and social change have begun to affect household activities and access to resources. Table 4 presents a summary of findings on household perceptions of these changes. Nearly all of the households in the case study communities are acutely aware of the pace of glacier recession that is taking place in nearby watersheds and frequently noted in great detail the accelerating rate and magnitude of recession that has been taking place over the past several decades. In addition, older respondents often presented detailed accounts of the extent of glacial coverage in the upper watersheds long before instrumental records were begun. Overall, households noted uniformly that recent climate change is already negatively affecting their lives. The key factors identified by respondents that are currently affecting household livelihood activities and pose significant challenges to their future trajectory are shifting water availability, increasing weather extremes, and threats to tourism.

**Table 4.** Climate change perception and new vectors of household vulnerability (95 percent confidence interval) in the Querococha (QUER) and Quilcay (QUIL) case study watersheds

| | Percentage | |
|---|---|---|
| Perceptions and vectors | QUER | QUIL |
| Household perceptions of recent climate change | | |
| Households reporting significant recession of nearby glaciers | 100 | 94 ± 3.96 |
| Households responding that they are very preoccupied by recent climate change taking place in the region | 91 ± 4.3 | 84 ± 6.11 |
| Households reporting that they have noted negative changes in their lives due to recent climate change | 94 ± 3.66 | 88 ± 5.42 |
| New vectors of vulnerability affecting households | | |
| Households reporting that water supplies during the dry season have been decreasing | 93 ± 3.61 | 81 ± 6.54 |
| Households reporting significant changes in recent weather patterns that negatively affected crops or livestock | 95 ± 3.61 | 100 |
| Households reporting recent freezing or extreme precipitation events that negatively affected human health, crops, or livestock | 91 ± 3.61 | 100 |
| Respondents reporting that glacier recession already is or will negatively significantly affect tourism | 100 ($n = 27$) | 100 ($n = 26$) |

Water constitutes one of the most important resources for households in the region for human consumption as well as agro-pastoral activities. Regular glacial discharge has historically provided perennial supplies of water to households with access to land resources in the case study communities, but according to case study respondents this temporal regularity is shifting due to increasing local and regional demands on water supplies and because the magnitude of water resources during the dry season is declining. Across both case study communities, more than 90 percent of respondents (QUER, 93 percent; QUIL, 94 percent) indicated that water supplies in the watersheds have been decreasing during the dry season. Although less than 5 percent of households in both communities argued that they did not have enough water for human consumption, roughly one quarter of households (QUER, 26 percent; QUIL, 22 percent) indicated that they did not have enough water for irrigation. Households reported that these changes have had significant impacts on agricultural and livestock productivity. Respondents in both communities also noted that many of the perennial and intermittent springs in the watersheds have begun to disappear. Households noted that diminishing spring flows in the upper reaches of the Querococha watershed are negatively affecting livestock productivity in terms of health and growth rates, and that the decline or disappearance of springs in the lower reaches of the Quilcay watershed would have grave consequences, as 90 percent of case study households noted that they depend on fewer than five springs across the entire area for all of their potable water resources. Interviewees also uniformly indicated that one major spring above the community (located at ~4,000 m) disappeared in the past several years and that this has already affected dry season water availability.

Another key vector of vulnerability affecting livelihood activities in the case study communities is increasing short-term weather variability. As Table 4 illustrates, households across both communities report that intense precipitation events, freezing events, strong winds, shifting rainfall patterns, and intense heat spells have all negatively affected household health, agricultural productivity, and livestock health. Households also noted increasing interannual or seasonal variability in weather events and temperatures such as longer freezing periods, more damaging freezing events, and shifts in crop planting or harvest periods. Respondents indicated that the cumulative effects of these increasing climatic extremes pose new risks for basic household food security, are the source of greater uncertainty about agricultural cycles, and are often responsible for substantial declines in crop productivity.

Finally, another important set of vectors affecting household livelihoods are the effects of new climate-induced shocks on tourism activities in the region. More than one quarter of households in both case study communities engage in the provision of tourism services. Because the high glaciated peaks are one of the primary reasons tourists visit the region, glacier recession constitutes a significant threat to tourism-related income for households. In fact, glacier recession has already had significant consequences for households in the vicinity of the Querococha watershed as the Pastoruri glacier, which was visited by more than 40,000 people in 2006, became the first glacier in the Cordillera

Blanca to be closed due to "adverse climatic conditions" and is likely to completely disappear by 2015 (INEI 2007).

## Discussion

Glaciers are an integral component of the coupled natural–human systems of the tropical Central Andes and their rapid recession is transforming downstream hydrology. Our integrated research has innovatively quantified these changes and initiated new understanding of groundwater processes. Our isotope analyses show that the relative amount of glacier melt water is increasing in glacierized tributaries of the Santa River, reflecting an increased rate of glacier recession in all the case study watersheds. Historically, a significant increase in discharge was observed until 1983, after which time the trend is weakly negative. This inflection point in the discharge trend is suggestive of a systemic threshold in glacier response to climate forcing, whereby glacierized watersheds initially provide more discharge but then diminish in influence over time. In addition, temperature is closely correlated to discharge, reflecting a regional climate control. It is important to note that 1983 was a major El Niño year, and the role of El Niño southern oscillation has been identified as controlling discharge and glacier mass balance on multiyear intervals (Francou et al. 1995; Vuille, Kaser, and Juen 2008). Nevertheless, the overall decrease in discharge at La Balsa is not altered by these episodic influences. Our results demonstrate that groundwater is proportionately at least as important as glacier melt with respect to total current dry season streamflows, and as glaciers recede, the influence of groundwater, and its role as a seasonal buffer, will become increasingly important.

Livelihood vulnerability in our case study watersheds is also being significantly affected by recent glacier recession. Our results clearly show that households are acutely aware of these changes and that new vectors of vulnerability, including shifting water availability, increasing weather extremes, and threats to tourism, are affecting household access to resources. Respondents across both watersheds uniformly indicated that these factors are significantly affecting their current livelihood activities. Because our methodology was designed to limit biases through the use of a random sampling frame, and our total household sample constitutes a statistically significant representative population for both watersheds, our findings are highly suggestive that livelihood vulnerability has already increased significantly and that there is a compelling need to address these concerns.

Our transdisciplinary findings suggest that there is an intriguing scale-dependent discontinuity between household perceptions, on one hand, and what our physical measurements and models demonstrate on the other. Ongoing glacier melt in the Cordillera Blanca tributaries is accompanied by increasing discharge and relatively more glacier melt water contribution in streamflows from highly glacierized watersheds. However, households from communities situated in both of our glacierized case study watersheds indicate very strongly that water supplies are declining, a trend that is only clearly measured in the Santa River discharge from the entire Callejón de Huaylas. Although we are considering a number of possible alternative explanations, given the minimal hydrologic influence of glaciers on the entire Santa River basin (i.e., < 10 percent glacier cover), we hypothesize that increasing basin-wide water withdrawals from human activities might be an important explanatory factor.

With this report we present an initial synthesis of results from two of three case study watersheds and establish the context for our ongoing research project. Exploring the way in which these observed patterns and hydrologic processes are currently interacting provides an important rationale for continued observations, model development, and testing and more intensive social research so that we might better integrate our transdisciplinary research with the project's social and scientific components and provide useful analyses to broader scientific and policy audiences. Finally, although this research focuses rather exclusively on human vulnerability, our larger research goals are intended to address household resilience and adaptive capacity as well as larger governance questions affecting the management of water resources throughout the Santa River watershed.

## Acknowledgments

This research was funded by the National Science Foundation (NSF No. 0752175, BCS—Geography and Regional Science) and included a Research Experience for Undergraduates (REU) Supplement. Additional funding for the LIDAR flight came from the National Aeronautics and Space Administration (NASA No. NNX06AF11G), The National Geographic Society Committee for Research and Exploration, and the Ohio State University Climate, Water & Carbon

Program, and the Faculty Senate of the University of California, Santa Cruz. We acknowledge the cooperative assistance of Peruvian colleagues Ing. Ricardo J. Gomez, Ing. Marco Zapata, and others at the Unidad de Glaciología y Recursos Hídricos in Huaraz, Peru, and the following interview research assistants: Carlos Torres Beraun, Oscar Lazo Ita, Erlinda Marilu Pacpac, Jesus Yovana Castillo, and Gladys Jimenez. We recognize REU undergraduates Laurel Hunt, Sarah Knox, Galen Licht, Sara Reid, Michael Shoenfelt, Patrick Burns, Alyssa Singer, and Shawn Stone for fieldwork assistance. We also thank Kyung In Huh for assisting with LIDAR data display. This is Byrd Polar Research Center contribution number 1396.



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