From glaciers to the desert: Assessing hydrologic change and social vulnerability across a tropical Andean waterscape

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ABSTRACT

Widespread glacier retreat has heightened concerns about water resources, especially in regions where glacier-fed runoff flows to arid regions. The Pacific-draining Andean watersheds of Peru epitomize this condition and provide a rich case study context; here Earth’s largest concentration of tropical glaciers in the Cordillera Blanca, Peru, have been receding for half a century and buffering the Santa River discharge that terminates in a desert. Our transdisciplinary collaboration has been researching the changing hydrology below the rapidly retreating glaciers in this watershed, as well as the societal context in which water resources are distributed and utilized. We have coupled multiscalar observations of changes in glacier volume, hydrology, water quality, and land usage with social and economic data about perceptions of and responses to environmental change. We also examine various water withdrawal mechanisms and institutions transecting the entire watershed: agriculture, land use, irrigation, hydroelectricity generation, and mining. We find that the historic allocations of water use do not track biophysical realities. We advocate a holistic hydro-social framework that explicitly accounts for five major human variables critical to hydrological modeling future scenarios.

Keywords: Andes, tropical glaciers, water resources, vulnerability, climate change.

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INTRODUCTION

The majority of Earth’s tropical glaciers are found in the Andes, and of those a full 70% are located in Peru (Kaser and Osmaston, 2002). The orientation and tectonic setting of the South American continent form the basic conditions permitting glaciers to exist along the narrow Andean escarpment that forms a topographic barrier to the moisture-bearing easterly trade winds. The western coast in the lee side of the Andes is hyper-arid as a result of the rainshadow effect, and cold upwelling Pacific currents. The tropical climate sustains perennial ice only at sufficiently high elevation, where snow accumulates in a highly seasonal precipitation regime. The glaciers are highly sensitive to changes in climate, and modeling of future climate has shown that enhanced warming at elevation puts these glaciers at risk of accelerating rates of mass loss (Bradley et al., 2006; Vuille, 2013). Furthermore, since the majority of Peru’s human population resides in urban areas along this desert coast, they rely heavily on water generated in the Andes for municipal supplies. Peru as a nation has lots of water, but because only 2% of all national water resources are available along the most populated coast, there is an hydraulic interdependence across the Andean escarpment (Bury et al., 2013). By extension, rivers delivering water to the arid coastal regions is seasonally variable given precipitation runoff, and thus the contribution of seasonally delayed glacier input is pronounced (Kaser et al., 2010).

Project scope

In this presentation I discuss work conducted by a multidisciplinary and internationally collaborative team of researchers, and I gratefully acknowledge funding by the National Science Foundation (NSF). Our project (NSF# DEB-1010384) has been supported under the NSF cross-cutting program, Dynamics of Coupled Human and Natural Systems, and is entitled: “Collaborative Research: Hydrologic Transformation and Human Resilience to Climate Change in the Peruvian Andes.” The Co-PIs include: Jeffrey Bury, University of California, Santa Cruz; Kenneth Young, University of Texas, Austin; and Mark Carey, University of Oregon.

During the four-year course of our investigation (2010-14), we initiated a collaborative research confederation we have named the Transdisciplinary Andean Research Network (TARN). The motivating context for our TARN research is climate change and impacts to society in the tropical Andes. Three basic questions have emerged from observations gathered over a decade quantifying climatic variations based on glacier changes in the Peru, Ecuador and Bolivia:

1. How much mass are the glaciers losing?
2. How is downstream hydrology changing in the watershed?
3. What impact does this have on people?

Our TARN approach attempts to focus research not on only the quantifying the scale and cause of glacier retreat, but also on tracing the hydrological impacts to society. Furthermore, since the social forces that constrain water use are not contained within the topographic limits of a “watershed,” we refer to our study as an evaluation of the Peruvian ‘waterscape’ to recognize that social forces influencing water allocation and usage exist beyond the catchment. As featured recently in Nature News (Fraser, 2012), our approach involves multiple disciples, and researchers combining field efforts to share and synergize.
SETTING

The Santa River watershed covers 12,000 km², spanning a vertical range from the high summits of the glacierized Cordillera Blanca (>6500 m) to the Pacific Ocean pour point just north of the coastal city of Chimbote (Fig. 1). The upper watershed is known as the Callejón de Huaylas, where the Santa River captures drainage from glacierized tributaries of the Cordillera Blanca on the west and non-glacierized Cordillera Negra on the west. Demand for water is shared by different end users within the Callejón de Huaylas, characterized by culturally distinct mountain market cites along the Santa River like Huaraz (capital of the Ancash Department), Caraz and Yungay. Most of the population participates in agro pastoralism, while over half of the watershed is currently under mining claims. The Santa River begins at Conococha lake (~4050 m a.s.l.) and flows to the North through the steep Cañon del Pato canyon where a hydroelectric power plant named after the canyon is located. At the lower reaches of the Santa, most of the dry season discharge is withdrawn from the river course to irrigate large-scale industrial agriculture in two
collective corporations, Chinecas the South and Chavimochic to the north, transecting four watersheds to Trujillo (Fig. 2).

Figure 2: Map of Pacific coastal end of Santa River watershed, locating the areas irrigated by the redirected discharge of Santa River: Chavimochic (brown, to north); Chinecas (yellow, to south).

Glacier recession has been progressive over the past five decades, and has been documented in a combination of ground surveys, aerial photogrammetry, and satellite remote sensing (Burns and Nolin, 2014). An example is seen in repeat photographs of the Yanamarey Glacier (Fig. 3).

Figure 3: Photos taken of the Yanamarey glacier terminus in 1998 (left) and 2010 (right).

METHODOLOGY

We have documented glacier retreat in the Cordillera Blanca by repeat observations using multiple methods. As a case study, we have made a detailed survey of surface area and volume change at the Yanamarey glacier. We covered it with an airborne light distance and range (LIDAR) survey taken in 2008 to document extent of glacier change from a previous epoch of control when surface elevation was surveyed by aerial photography in 1962.
How do glaciers impact the downstream water users is a question we have addressed across scales using a creative assortment of methods (Mark and Seltzer, 2003; Mark et al., 2005). At the glacier lake, effluent waters are separated with water balance and hydrograph separation, and at the confluence downstream with non-glacierized streams end-member mixing methods evaluate the relative contribution of glacier melt. At the scale of the full glacierized tributary, we have further refined the hydrochemical mixing model approach (Baraer et al., 2009) and made a diagnostic review of how discharges in the Santa tributaries and the Callejon de Huaylas are being transformed over time with respect to progressive glacier melt using an innovative combination of in situ stage recording, discharge measurement with acoustic doppler current profiling (ADCP) and glacier-hydrologic modeling (Baraer et al., 2012). We also conducted a reach survey along the entire course of the Santa River from Conococha to the Pacific Ocean during the dry seasons of 2011 and 2012 to measure discharge with the ADCP and sample hydrochemistry. Our final discharge measurement defining the Pacific terminating pour point of the watershed was at Pte Careterra, where the Panamerican Highway crosses the Santa River (Fig. 1).

Understanding the broader implications of this hydrological transformation has involved a multidisciplinary team of geographers studying ecological and social dimensions. We have utilized trace metals to track water quality changes (Fortner et al., 2011), as well as satellite remote sensing, household livelihood surveys, archival work, and institutional key interviews to assess coupled dynamics in the watershed (Bury et al., 2013). We have been specifically interested in how water has been utilized historically along the river, vis-à-vis the volumetric change in glaciers.

RESULTS

Updated surveys of the Yanamarey Glacier show that a surface area loss of about 85% from 1962 (1.155 km$^2$) to 2008 (0.165 km$^2$). The average surface lowering of the glacier is 144 m during this period (Huh et al., 2012).

![Figure 4: Maps of changes in extent of Yanamarey glacier between 1962, based on aerial photography, and 2008, based on airborne LIDAR. Base map is hill-shaded view of LIDAR-based DEM (<1 m resolution). Left: Surface area changes. Right: gridded surface elevation changes.](image)

Our work has allowed us to document that the majority of tributary valleys and the entire Callejon de Huaylas likely passed “peak water” decades ago (Fig. 5), and are now experiencing a persistent decline in dry season flow (Baraer et al., 2012). This is in contrast to previous estimates
that presumed sustained near future high flows as glacier recession released meltwater from frozen storage (Pouyaud et al., 2005).

![Figure 5: Hydrograph showing relative position of tributary valleys (locations in Fig. 1) and Santa River based on last year of historical discharge measurements (in parenthesis). The hydrographs depict relative curves of total annual discharge (Q), dry season discharge (Qd), and coefficient of variability (Cv). The numbers depict relative stages (after Baraer et al., 2012).](image)

Natural water-rock interactions in the presence of rapid glacier recession have resulted in certain naturally acidic conditions with high concentrations of dissolved metals, some in excess of WHO standards (Fig. 6) (Fortner et al., 2011).

![Figure 6: Comparative histogram showing measured dissolved concentrations of select ions and trace metals (DOC = dissolved organic carbon). Values from Quilcay and tributaries are in the Cordillera Blanca based on Fortner et al. (2011), and are compared to other published data: ¹(Cameron et al., 1995); ²(Schuster, 2005).](image)

However, obvious human pollution sources such as mine tailings in the Santa River flood plain comprise other potential threats to water quality. Ongoing analyses have documented elevated metals with some health concerns (i.e. elevated As and Pb levels) along the Santa.
Insights from our mixed physical-social science methodology reveal new vectors of vulnerability related to spatial rescaling of water access, governance struggles and even scarcity struggles (Mark et al., 2010; Bury et al., 2011). Proglacial wetland areas in the Quilcayhuanca valley have declined in extent over the past decade, as documented in satellite image analyses (Bury et al., 2013) (Fig. 7).

Figure 7: Wetland change in glaciated Quilcayhuanca valley from 2000 to 2011 based on TM satellite imagery (Bury et al., 2013).

Mining claims in the Santa watershed have increased exponentially since neo-liberal reforms initiated in the 1990s that relinquished state control and permitted private claims (Fig. 8).

Figure 8: Mining claims filed within the Santa River watershed, Ancash Department, Peru, dating back to beginning of 20th century up to 2009, plotted by number of claims (red) and area in hectares (blue).

Increased demand for municipal waters is demonstrated by urban potable water consumption reported for cities in the Callejon de Huaylas between 1999 and 2010: Huaraz has expanded from 3.2 million m$^3$ to 4.8 million m$^3$; Caraz from 502,000 m$^3$ to 896,000 m$^3$. Along the coast, Trujillo now receives 70% of its potable water from the Santa River, where it had none before the
Chavimochic canal was completed in 1990. Hydroelectric generation capacity at the Cañon del Pato station has increased from 50 MW in 1958 to 263 MW in 2001, effectively increasing the Santa River water usage from 45 m$^3$s$^{-1}$ to 79 m$^3$s$^{-1}$. Concurrent with this expansion, 12 additional hydroelectric stations within the Santa watershed have been constructed since the 1950s. Along the coast, the extent of irrigation expansion afforded by re-routing the Santa drainage is astounding; in 1958, 7500 hectares were irrigated, but by 2004 this was 144,000 hectares by Chavimochic and 30,000 by Chinecas. We measured the discharge along the Santa River from Conococha to the outflow from the Santa at Pte Careterra (where the Panamerican Highway crosses river just before Pacific Ocean) with an ADCP in 2011 and 2012, and found that the outflow is 82% and 90% reduced from 30-year historic average (1969-99) (Fig. 9). During this time, Peru has outpaced the US in asparagus production, and become the leading exporter (Mapstone, 2012).

**SUMMARY DISCUSSION**

Our work documents multiple aspects of a coupled human and natural system in the wake of ongoing cryospheric changes induced by climate change in the Peruvian Andes. It is a waterscape case study example of how global forcing has local ramifications that need to be placed in a context described social as well as physical science.

Physical evidence of accelerating glacier retreat is strong, with new technology (LIDAR) allowing measurement of total volume change rather than simply surface area. This is important in constraining the energy exchange involved in this phase change as well as the volume of meltwater released from storage that becomes mobilized in the surface runoff to stream flow. Moreover, careful assessments of how this glacier change is impacting stream flow over time have shown that this storage release has already passed its maximum “peak water,” and that future flows will likely continue to decline. Nevertheless, when measures of water resource usage are accounted for over time, it is apparent that political and economic factors are more determinative in defining water allocations (Carey et al., 2013). Availability is not synonymous with supply, as competing demands arise from different use sectors. Moreover, as flows are decreasing, variability is increasing. Metal concentrations already threaten water quality in glacial melt streams, resulting from natural water-rock interaction (i.e. sulfate oxidation). As flows are decreased, then other sources of pollutants will become more significant. Emergent vulnerabilities are scale dependent, and are not contained only within the watershed boundaries. Global economic forces have already...
impacted the allocation of water within this waterscape, and will continue to impose challenges to resource management.

Adaptation to changing hydrologic scenarios of the future will depend as much on social values and perceptions, economic development and governance as it will upon the physical supply of glacier runoff to stream flow. A systematic understanding of this coupled system thus requires an integration of sustainable embedded observations, modeling and social science, with an open policy of data sharing between different researchers, corporations, and government agencies.

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