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# Glacier loss and hydro-social risks in the Peruvian Andes

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## ABSTRACT

Accelerating glacier recession in tropical highlands and in the Peruvian Andes specifically is a manifestation of global climate change that is influencing the hydrologic cycle and impacting water resources across a range of socio-environmental systems. Despite predictions regarding the negative effects of long-term glacier decline on water availability, many uncertainties remain regarding the timing and variability of hydrologic changes and their impacts. To improve context-specific understandings of the effects of climate change and glacial melt on water resources in the tropical Andes, this article synthesizes results from long-term transdisciplinary research with new findings from two glacierized Peruvian watersheds to develop and apply a multi-level conceptual framework focused on the coupled biophysical and social determinants of water access and hydro-social risks in these settings. The framework identifies several interacting variables—hydrologic transformation, land cover change, perceptions of water availability, water use and infrastructure in local and regional economies, and water rights and governance—to broadly assess how glacier change is embedded with social risks and vulnerability across diverse water uses and sectors. The primary focus is on the Santa River watershed draining the Cordillera Blanca to the Pacific. Additional analysis of hydrologic change and water access in the geographically distinct Shullcas River watershed draining the Huaytapallana massif towards the city of Huancayo further illuminates the heterogeneous character of hydrologic risk and vulnerability in the Andes.

## 1. Introduction

As in mountains worldwide, tropical Andean glaciers are undergoing a loss of mass that demonstrates categorical evidence of global climate change (Roe et al., 2016) and raises concern for sustainable water supplies (Bradley et al., 2006). Analyses show that climate forcing is complex and can vary by scale in these low latitude settings (Vuille et al., 2008; Schauwecker et al., 2014), but a warming troposphere is strongly implicated by increased freezing levels (Bradley et al., 2009) and the rapid recession of glaciers with low headwall elevations (Rabatel et al., 2013). In the highly seasonal tropical Andean precipitation regime, this net glacier-mass loss represents a release of water from storage that otherwise would buffer streams, initiating a downstream transformation of hydrology that impacts both human and natural processes and their coupled dynamics. After initial augmentation of discharge from this storage loss, streams are thought to pass "peak water" and are characterized by diminished discharge and increasing variability, which has important implications for water availability in relation to a wide array of ecosystem processes and human uses (Hock, 2005; Stahl et al., 2008; Baraer et al., 2012).

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Assessing the social risks related to glacier loss and hydrologic shifts requires deciphering the magnitude and diversity of these changes over space and time, and exploring how such changes interact with dynamic social relations and processes. Future scenarios based on model outputs have attempted to quantify the relative impact of climate change on water availability for glacier-fed catchments globally (Kaser et al., 2010) and for Andean urban centers (Buytaert and De Bievre, 2012). These analyses suggest that while seasonal dependence on glacier storage is high in the semi-arid Andes, there is limited impact to future water supplies. Such approaches assume population density in relative proximity to glaciers is the best metric for water use; thus while they may provide insights into general trends linked to large populations, they may overlook a range of impacts on less-densely populated regions as well as pathways of risk and vulnerability impacting supra-local processes and end-users tied to local water supplies through multi-level dynamics (e.g. through regional and global-scale economic linkages).

We argue that such complexity must be studied from a systemic perspective that couples biophysical and social processes, while it acknowledges the heterogeneous and multi-dimensional character of exposure, risk, vulnerability, and resilience to hydrologic change. We draw specifically upon conceptualizations of hydro-social systems that treat water as a substance connecting ecosystems and biophysical phenomena, water users and institutions, and water-use practices and technologies across scales that extend beyond the physical boundaries of the watershed (Swyngedouw, 2009; Sivapalan et al., 2012; Carey et al., 2014). In this paper, we develop and apply a conceptual framework focusing on these multiple dimensions of water access through the integration and synthesis of results from a long-term transdisciplinary research collaboration with new findings from two glacierized watersheds in the Peruvian Andes. Our framework (Fig. 1) encompasses interacting determinants of water access and related hydro-social risks including the physical availability and quality of water; links among hydrology, ecosystems, land use and land-cover change; water use in rural livelihoods and regional economies; technologies and infrastructure that deliver water supplies; and the diverse social institutions and governance processes that legally and culturally shape water access and use.

We open the paper with a review of the geographic setting and of the development of our integrated methodological approach for analyzing the coupled dynamics of hydro-social systems. We then present key results related to each of the dimensions included in our conceptual framework. In the Discussion and Conclusion, we address the interactions and feedbacks between the diverse processes shaping complex and differential risks and vulnerabilities to altered hydrologic regimes and suggest that our framework can be usefully extended to sites beyond the Peruvian Andes.

## 2. Setting

The Peruvian Andes comprise the most glacierized tropical landscape on Earth. Given the vertical range of biomes in a low-latitude context, this region is characterized by especially biodiverse ecosystems in which water interconnects biotic and abiotic elements downstream of glaciers. This verticality and diversity contribute to the region's rich natural resource endowments and long history of complex coupled human-environment dynamics (Young, 2009). In this context, we have focused research on two transforming hydro-social systems: the Santa River watershed draining the western side of the Cordillera Blanca to the Pacific Ocean, and the Shullcas River watershed draining the Huaytapallana massif to the intermontane valley confluence with the Mantaro River at the city of Huancayo (Fig. 2). Glaciers are rapidly losing mass at the headwaters of both watersheds, but the scale, physical characteristics, and social interface with water downstream of the glaciers varies in each, thus providing contrasting but complementary case-study locations to examine the multiple dimensions of hydrologic change, water resource access, and linked hydro-social risks.

The Santa River watershed contains the largest and highest mountain range in Peru, the Cordillera Blanca, and comprises almost 7 km of vertical relief within a 12,000 $km^2$ catchment area draining to the Pacific Ocean. Most of the Cordillera Blanca is contained within the 3400 $km^2$ Huascarán National Park, established in 1975, and recognized as a UNESCO World Heritage Site and Biosphere Reserve (Lipton, 2014). Huascarán (6768 masl) is the tallest mountain in Peru, and the summit lies west of the drainage divide so that the adjoining tributaries drain all runoff to the Pacific coast. Glaciers are distributed over the > 120 km span of the NW-SE trending Cordillera Blanca, though considerable variability in glacier coverage exists at the sub-watershed scale. Glacier melt-fed tributary streams drain to the SW and

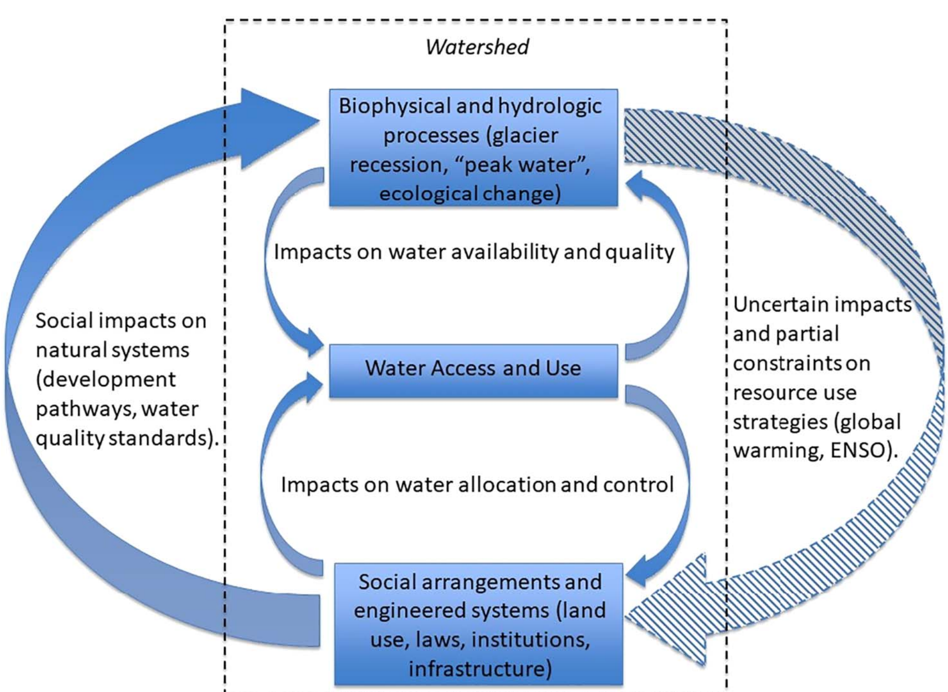


**Fig. 1.** Conceptual diagram illustrating the dynamic interplay between select biophysical and social components impacting water access and use in multi-scale, Andean hydro-social systems. A framework encompassing these coupled dynamics must account for interacting flows and feedbacks across the vertical dimension within the watershed, as well as influences and feedbacks that transcend the watershed's hydrographic boundary (dashed border).

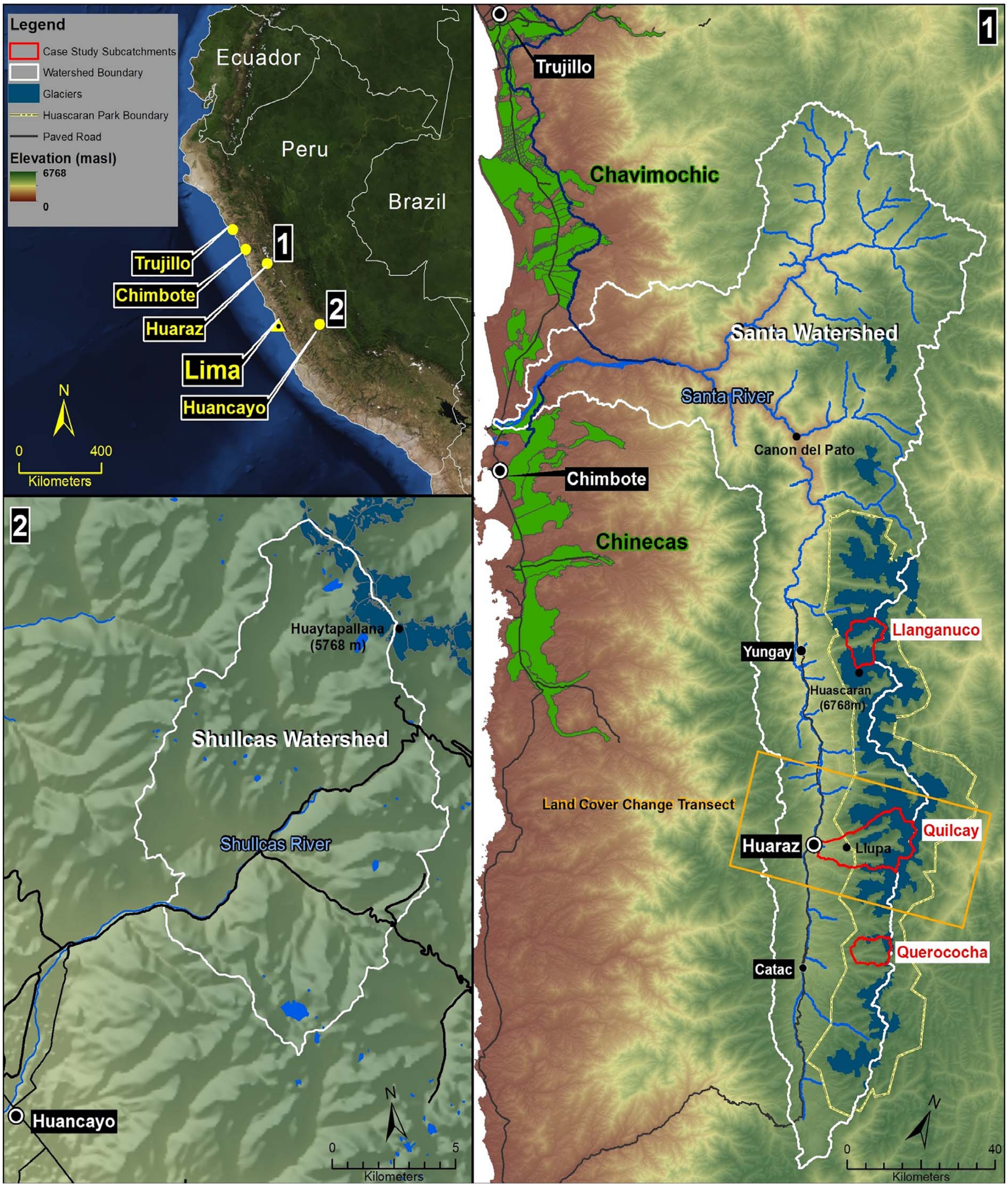


**Fig. 2.** Map of Peru (upper left) depicting the two principal watershed study sites along with additional locations mentioned in the text. The numbers corresponding to additional map panels with different scales/orientation, illustrating outlines and localities for: (1) The Santa River watershed, including the Cordillera Blanca mountain range, that drains to the Pacific coast. Tributary watersheds flowing to the Santa River that are featured in the text are outlined in red and labelled. The orange rectangle outlines the area covered by land cover change analysis depicted in Fig. 6. (2) The Shullcas watershed drains from the southwestern side of the glacierized Huaytapallana massif towards the city of Huancayo. The watershed maps show glacier area in blue, and are hillshaded and colored according to elevation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

collectively buffer base flow, comprising two-thirds of the NW flowing Santa River discharge during the dry season (Mark et al., 2005). The region's semi-arid highland climate with a highly seasonal precipitation regime underscores the importance of glacier-buffered base flow, with 80% of total annual precipitation (800 to 1200 mm $yr^{-1}$) falling between October and May during the austral summer (Kaser et al., 2003). The region's glaciers are also accelerating in recession: in the 1970s, 723 $km^2$ of glacier area in the range accounted for 40% of Peru's total glacial volume (Ames et al., 1989), but by 2010 only 482 $km^2$ of glacial cover remained (Burns and Nolin, 2014).

Over its 300 km course to the ocean, the Santa River transects varied landscapes and political boundaries as it supplies water to a diversity of end users. The upper Santa River valley that captures drainage from the sub-catchments of the Cordillera Blanca is known as the Callejón de Huaylas, with an area of 4900 km$^2$ and a population of > 250,000 (Mark et al., 2010). This region includes Huaraz, the largest city in the upper watershed and the capital of the Ancash Department, as well as a number of smaller cities located along the main Santa River course. Before runoff from the Santa's tributaries reaches the main river channel, rural inhabitants of the region utilize and depend on glacial and seasonal water resources for a host of economic and subsistence activities. Water from all but the highest of the Cordillera Blanca tributaries support small to medium-scale agriculture, which varies in character from rain-fed subsistence production on marginally arable lands at elevations between 3000 and 4000 masl to irrigated commercial production of specialty crops (e.g. ornamental flowers and fruits) between 2000 and 2500 masl (French et al., 2016). Agricultural production is often coupled with other livelihood activities including pastoralism, agroforestry, tourism services, dairy production, artisanal crafts, and contract labor (Young and Lipton, 2006; Mark et al., 2010).

Water from the Santa River and its highland tributaries has long been seen as an important dry-season resource for downstream development (Antunez de Mayolo, 1957; Landeras, 2004; Carey, 2010), especially for hydropower and commercial agriculture. Hydroelectricity production in the upper and middle reaches of the watershed and its tributaries benefits from the basin's high flows and elevation gradients. The largest facility is a run-of-course station in the Cañon del Pato gorge. Energy produced at the Cañon del Pato plant supplies the national grid and provides electricity to cities, villages, polymetallic mining operations, and heavy industry in the watershed and beyond, amounting to 10% of the national hydropower-generation capacity (Mark et al., 2010). Since the 1990′s, agricultural production in the watershed has been shifting towards irrigated, high-value export- crop production, especially along the arid coastal shelf, where the large-scale, state-subsidized projects of Chavimochic and Chinecas collect Santa river flows for irrigation, energy production, and potable water provision (Carey et al., 2014).

Rapid growth over recent decades in economic activities linked to globalization, including mining, ecotourism, and the production of non-traditional export crops, have created localized booms in the watershed that have contributed to the diversification of livelihoods, urban migration, and declining poverty rates (Painter, 2007). The effects of these changes remain highly uneven, however (Mendoza Nava, 2015; Wrathall et al., 2014), and related impacts are placing heightened pressures on hydrologic resources through growing demand and contamination (Bury et al., 2013; Drenkhan et al., 2015). Rapid urbanization in both the Callejón de Huaylas and in the large coastal cities of Chimbote and Trujillo, for example, has driven increased potable water provision, but without concomitant development of wastewater treatment facilities (INADE, 2001). Growth in both Peruvian and transnational-led mining has also led to increased water demand in the basin and a proliferation of impacted sites and associated conflicts (Himley, 2012; Peru, 2015). In 2009, an estimated 41% of the surface area of the Santa watershed was covered by mining concessions, and mining revenue accounted for 40% of all economic production in the region (Bebbington and Bury, 2009).

The Shullcas River watershed drains to the SW from the glacierized Nevado Huaytapallana (5768 masl), capturing runoff from a catchment area of 155 km$^2$ as defined by a pour point at 3580 masl where water is diverted for municipal supply to the city of Huancayo and for agricultural irrigation canals (Crumley, 2015). The Huaytapallana massif has eight summits and is one of several ranges that provide glacier melt to streamflow in the Mantaro valley. It is located within 30 km of Huancayo, with road access making it a popular destination for tourists and local residents who venerate the mountain. The headwaters contain multiple lakes, and many have dammed outlets with flow regimes that can be managed. Economic activities in the headwaters region include pastoralism, fish farming, small-scale agriculture, and mining. The glacierized area of the Huaytapallana massif has reduced in recent decades as documented by different studies of satellite imagery: one study showed a coverage in 1976 of 35.6 km$^2$ and in 2006 of 14.5 km$^2$ (Zubieta and Lagos, 2010), while another analysis documented 55% reduction in area between 1984 and 2011 (López-Moreno et al., 2014).

Huancayo, an expanding urbanized area located in the Mantaro Valley, has a population of ~470,000 and is the capital city of the Junin Department. Approximately 70 km long and 2 to 8 km wide, with an area of 582 km$^2$, the Mantaro Valley ranges between 3150 and 3400 masl elevation and experiences an average annual precipitation of 650–700 mm and mean annual temperatures between 4 and 18 °C. This intermontane region plays an important role in the national economy. Agricultural production in the valley provides significant food for Lima's domestic market. The larger Mantaro River basin is also a critical source of hydroelectric generation, supplying ~35% of the nation's capacity (Silva et al., 2008). The Mantaro Valley features active mining operations and dozens of abandoned mines, and the larger Mantaro watershed is the basin with the highest concentration of mine-contaminated sites (1466) in the country (MINEM, 2016).

## 3. Methods

### 3.1. Pro-glacial hydrologic transformation

We have incorporated field observations with modeling to understand how the water cycle is being transformed, from melting glaciers to access points downstream throughout the watershed. We have focused our case-studies in locations representing the diversity of proglacial valley systems within the Cordillera Blanca. They include wet meadows, which are dominated by puna plant species including tussock grasses, and wetland systems referred to as ‘bofedales’ (Squeo et al., 2006; Cooper et al., 2010). Our study sites contain different levels of glacier cover and experience varying levels of human use and grazing intensity. Our approach to data collection involves locating, planning and installing equipment in situ using local materials and expertise. We take care to install discretely to minimize obstruction and theft. Instruments are maintained in partnership with both the Glaciology and Hydrology division of the National Water Authority based in Huaraz and the Geophysical Institute of Peru, and have been installed with permission from the Huascarán National Park and with agreement from local communities. Sharing mission objectives with other scientists and resource managers has improved sustainability of data recovery. Where possible, we duplicate and distribute multiple sensors to avert loss or malfunction. Our investigation follows a vertical cascade from the glacier snout, through the proglacial valleys, and on to the tributary pour points of successively larger watersheds. We make use of various methods described here along the vertical course of water flow in each study watershed (see insets, Fig. 2).

Over glaciers, we have employed combinations of remote sensing (passive and active) at different scales and resolution (satellites, aerial photos, terrestrial photogrammetry, unmanned aerial vehicles (UAVs)) with other measurements of surface elevation changes (GPS) to constrain not only surface area but also volume changes (Huh et al., 2017; Mark and Seltzer, 2005; Wigmore and Mark, 2017a,b). Our direct and glacier-specific measurements of volume change permit us to compare volume-scaling approximations based on surface area (Chen and Ohmura, 1990; Bahr et al., 1997). At the ablating glacier snout at the head of the Quilcay valley we have also integrated time series of thermal and visible imagery with measurements of temperature, wind, radiation and humidity fluxes in, on and near the glacier to quantify energy fluxes (Aubry-Wake et al., 2015). We utilize previously unreleased historical photographs of glacier termini to illustrate recession over the 20th century from the personal collection of Alcides Ames, formerly a lead surveyor for the first Peruvian glacier inventory (Ames et al., 1989).

In the proglacial valleys below the Cordillera Blanca glaciers, we have used a combination of continuous automated instrument observations, near-surface geophysics (ground penetrating radar, seismic refraction, and electrical resistivity), high-resolution multispectral remote sensing with UAV, kite-borne aerial photography (KAP), terrestrial timelapse photography, and heat and geochemical tracing (Wigmore and Mark, 2017a,b; Somers et al., 2016; Baraer et al., 2015; Gordon et al., 2015). This has informed our previous analyses of water storage and flux between groundwater and streams on different spatial and temporal scales. Dry-season groundwater contributions to surface water were first investigated using hydrochemical and isotopic properties of potential hydrologic sources (Baraer et al., 2015). Observations of major ions and stable isotopes in 90 samples from streams, glacial melt and groundwater in 2008 and 2009 allowed for the characterization of the proglacial hydrology in four glacially fed watersheds within the Cordillera Blanca, including Quilcayhuanca and Llanganuco. The hydrochemical basin characterization method (HBCM) was applied to trace water sources at the outlet of the watersheds (Baraer et al., 2009). Similar methods have been applied to the valleys below the Huaytapallana glacier draining to the Shullcas River. In 2014, a total of 87 water samples from streams, glacier lakes, and springs were collected and analyzed following the HBCM to investigate the relative contributions of source waters to streamflow (Crumley, 2015). The study was designed to sample all major stream confluences in the Shullcas River basin during a short multi-week time frame at a very high spatial resolution. The study occurred during the dry season, and no major precipitation events occurred during the sampling time frame, making it possible to partition the baseflow constituents into glacier melt and groundwater contributions. Further investigation of groundwater contributions and stream-groundwater interactions have been done using dye tracing experiments and more detailed synoptic sampling of hydrochemistry in upper to mid-slope sections of the Quilcayhuanca and Llanganuco valleys (Gordon et al., 2015). More recently, groundwater-surface water interactions in the Quilcayhuanca watershed have been studied using paired dye- and heat-tracing experiments, and solute and heat-transport modeling (Somers et al., 2016). The combination of dye and heat tracing has allowed for characterization of gross versus net exchanges of stream and groundwater over different morphological features (e.g. moraines and meadows) in proglacial valleys.

We have embedded semi-permanent data-logging instruments measuring soil moisture, groundwater table height, streamflow and temperature, and atmospheric variables of wind, temperature, humidity and radiation within key study valleys along the range (Fig. 2). We have used these data in models to quantify hydrologic fluxes, e.g. groundwater-stream water exchange, discharge generation and evapotranspiration rates. We demonstrate here a novel integration of high spatial resolution, multispectral (visible, near infrared, thermal infrared) imagery collected from a UAV to explore spatial heterogeneity in the ecohydrology of the proglacial valleys. We use these data to calculate secondary indices, e.g. NDVI and Temperature Vegetation Dryness Index (TVDI) (Sandholt et al., 2002), to investigate spatial patterns of vegetation productivity, surface soil moisture and the impact of grazing animals. UAV and terrestrial thermal imagery are used to identify groundwater springs and seeps and corroborate theorized surface/subsurface hydrologic pathways (Wigmore et al., 2016).

### 3.2. Land cover change

Land cover in the study region is the result of an interplay of biophysical and landscape constraints, the ecological dynamics of plants and animals, and the land use of people (Young et al., 2017). Research questions included: (1) What are the dynamics of land cover over the past several decades, and (2) What biophysical and/or social processes were involved?

A land cover change analysis was carried out for the Cordillera Blanca region of Ancash using two Landsat TM images downloaded from the USGS Global Visualization Viewer (http://glovis.usgs.gov). We selected these images because they are the earliest and latest in the Landsat archive with no haze or clouds over the Santa river basin. Similarly, dry-season dates were chosen to minimize intra-annual phenological differences (path/row 8/67; 10 July 1990 and 2 June 2011). Both images are Level 1 T products with systematic radiometric and geometric correction. Standardized geometric accuracy is now common and improves efficiency for change detection studies because it reduces the amount of effort needed to create rectified time-series datasets (Hansen and Loveland, 2012). For Level 1T products, digital elevation models and a network of ground control points (GCPs) are used to obtain geometric and terrain accuracy. In this case, the GCPs are from the USGS Global Land Survey 2000 data set and terrain data is from the NASA Shuttle Radar Topography Mission. Pre-processing steps we carried out included clipping the original images to the area of interest, which measures 2323 $km^2$ and crosses the Cordillera Blanca (Fig. 2). Variations in atmospheric conditions affect indices applied to remotely sensed imagery (Jensen, 2015); therefore dark object subtraction was applied to the areas of interest for relative radiometric normalization (Chavez, 1988) (software used ERDAS Imagine 2014, Hexagon Geospatial, Madison, AL, USA).

Vegetation indices are used to remotely detect the presence of photosynthetic material, or green biomass (Jensen, 2015), and have been used in the study area for land cover mapping (Silverio and Jaquet, 2009). After pre-processing, the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Snow Index (NDSI) (Hall et al., 1995) were applied to both images independently (software used ArcGIS, Version 10.2, ESRI, Redlands, CA, USA). NDVI is expressed as (near infrared band − red band) / (near infrared band + red band) or (TM 4 − TM 3) / (TM 4 + TM 3). NDSI has been used in the study area to effectively distinguish glacier boundaries and changes through time (Racoviteanu et al., 2008; Silverio and Jaquet, 2005). It is expressed as (green − near infrared band) / (green + near infrared band) or (TM 2 − TM 5) / (TM 2 + TM 5). Glacier lakes were manually digitized for each of the time periods.

Vegetation classes were divided into 4 classes: No biomass, Low biomass, Medium biomass, High biomass. Class segmentation followed Silverio and Jaquet (2009) and class thresholds were determined by natural breaks in the NDVI values. The "no biomass" class is void of photosynthetic material; it is comprised of bare rock, exposed ground, barren substrate, scree, impervious cover, urban, mines, and roads. Low biomass is defined by puna grasslands and wetlands < 0.5 m in height, tussock grasses, herbs and forbs, and sparse vegetation mixed in with exposed rocky areas. Medium biomass includes shrubs > 0.5 m – 2.0 m in height, crops, and low-growing scrub. High biomass represents eucalyptus and pine trees > 2.0 m in height, woodlands, and deciduous and riparian forests. Snow and Ice is comprised of permanent ice and snowfields. Water is comprised of lakes. Snow and ice segmentation using the NDSI product was first attempted using a threshold of 0.51 from previous work on a Landsat ETM+ image (Silverio and Jaquet, 2009); however, after experimenting with various thresholds, it was determined that the NDSI 0.55 threshold more accurately represented Snow and Ice for 1990 and 0.30 for 2011. Next, the NDVI, NDSI, Glacier Lakes, and clouds were combined into a single thematic image for each date. The differences between the thematic images were calculated and from-to transitions from one class to another were identified (software used Land Change Modeler 2.0, Clark Labs, Clark University, Worcester, MA, USA).

### 3.3. Social processes

In order to examine human perceptions of glacier and hydrologic change and impacts of these processes on local livelihoods, a comparative analysis was conducted across three highland tributaries to the Santa River with different percentages of glacierized area where we were concurrently undertaking hydrologic analyses (the Querococha, Quilcay, and Llanganuco watersheds). We delineated study areas in each site ranging from highland pastures and farmsteads in the

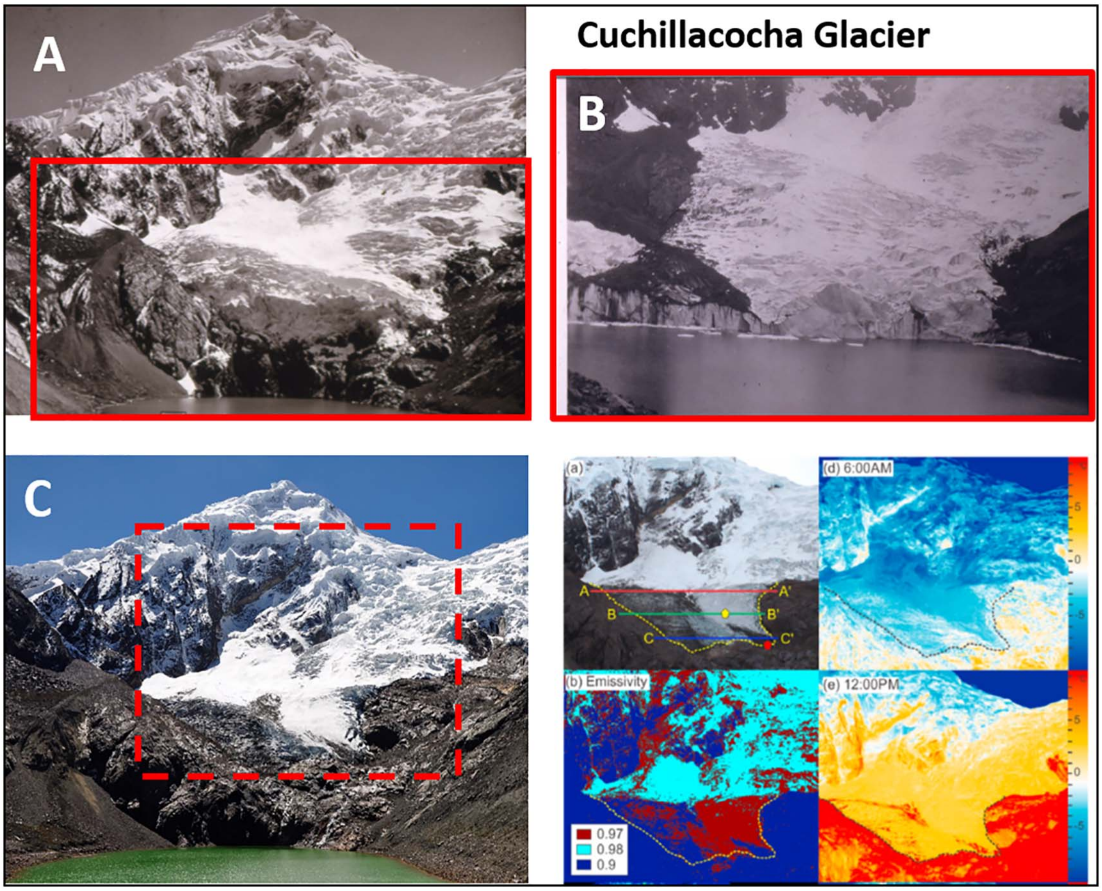


**Fig. 3.** Glacier changes to the Cuchillacocha glacier at the head of the Quilcay watershed. (A) Photograph taken in 1964 by Schneider (A. Ames collection). The red rectangle shows approximate area covered by (B), photograph from 1932 by Kinzl (A. Ames collection), showing that the glacier terminated in the Cuchillacocha lake. Photograph (C) taken in 2013 (B.G. Mark) showing thinning and recession of tongue, especially along L-lateral terminus where rock is exposed. Dashed rectangle indicates area photographed in IR (Aubry-Wake et al., 2015), as depicted in lower right panel, illustrating the meter-scale-resolution temperature distributions from different surface properties at subhourly intervals that can quantify heat flux from edges. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

headwater valleys of these drainages to their urban and peri-urban population centers (Catac, Llupa, and Yungay, respectively). To minimize selection bias, we developed a spatially-based, stratified random sampling frame utilizing high-resolution satellite imagery for the three watersheds to select households in which to administer semi-structured surveys. The anonymous surveys contained 32 structured and 18 open-ended questions grouped in sections covering environmental change, land resources, livelihood activities, personal data, and social resources to evaluate household access to and use of resources and to assess how recent environmental change such as hydrologic variability might be affecting household livelihood activities. Open-ended questions were transcribed and entered into qualitative databases for analysis and the structured question responses were coded across 234 variables for each survey and 9360 possible data points. The surveys were conducted in 2008 and 2009 and yielded a statistically significant and representative sample comprised of 125 households (40 from Querococha, 32 from Quilcay, and 53 from Llanganuco) that included 543 people (Bury et al., 2011; Mark et al., 2010).

In order to evaluate water use and management and upstream-downstream governance dynamics at the scale of the larger Santa watershed, an expanded set of methods was adopted. These methods included legal, institutional, historical, archival, and geospatial analyses drawing upon laws and regulatory frameworks; census data; news reports; resource management and planning documents from diverse levels of government and economic sectors; and policy and research documents from local universities, non-governmental organizations, and Huascarán National Park (Bury et al., 2013; Carey et al., 2014; French, 2016b; French et al., 2016). We also employed extensive formal and informal key-informant interviews with residents, public officials, state resource managers, and professionals from private-sector and civil-society organizations, as well as participant observation of formal meetings of local, regional, and watershed-scale organizations (Carey et al., 2012; French, 2015, 2016a).

Within the Shullcas watershed, perceptions and impacts of glacier recession and hydrologic change were pursued through ten semi-structured and unstructured interviews with informants including rural agropastoralists, periurban residents, local government officials, and water managers conducted over a period of six weeks in July and August 2014 and over two weeks in March 2015. Semi-structured and unstructured interviews were chosen because they allow participants to guide the question-and-answer process, while using their own words and vocabulary. Many of the interviews were conducted while walking or hiking among the Huaytapallana alpine meadows and periglacial environment because these 'walking interviews' are designed specifically to elicit stories that are profoundly influenced by landscape. These types of mobile interviews generate data that are simultaneously autobiographical in nature and rich with content about the surrounding environment (Evans and Jones, 2011). This cross section of the population was spatially, economically, and politically diverse in its experiences using and interacting with water in the region. Six of the ten informants were pastoralists that were intimately familiar with the periglacial environment due to collective land management and farming practices near the headwaters of the Shullcas River (Crumley, 2015). An additional survey of urban residential water access was carried out in 911 households within the city of Huancayo during December 2015.

## 4. Results

### 4.1. Pro-glacial hydrologic transformation

Our observations confirm an accelerating rate of glacier mass loss over recent years that is consistent with other analyses of satellite imagery (Burns and Nolin, 2014). The measured volume changes we derived from surface changes are superseding rates of volume loss expected from surface area alone (Huh et al., 2017). In the headwaters of Quilcay, the Cuchillacocha glacier is an over-steepened and avalanche-fed glacier that is relatively shaded in southern aspect. Nevertheless, recession is evident in historical photographs (Fig. 3). Using stereo-paired aerial photographs from 1962 and LiDAR from 2008, the surface area receded from 1.24 $km^2$ to 0.86 $km^2$, while the volume lost over this time is 0.02 $km^3$, equating to a mean surface lowering of ~10 m (Huh et al., 2017). This is relatively low compared to other glaciers in the region but shows clearly that rates of recession have accelerated; of the 31% loss from 1962 to 2008, 20% occurred in the 7 years from 2001 to 2008, as confirmed by time series of ASTER satellite imagery.

Notably, our investigation of volume change shows a 37% greater loss than predicted by surface area (Huh et al., 2017). We have observed a strong dependence of glacier loss on summit elevation and hypsometry of exposed glacier mass such that lower elevations are wasting faster than those with higher sources of mass accumulation (Mark and Seltzer, 2005; Rabatel et al., 2013). Our analysis of dry-season thermal regime at the Cuchillacocha glacier documents a strong feedback between thermal microscale processes at the glacier surface and margin related to low-albedo surface cover type that influences the temperature gradient at the glacier margins, enhancing mass loss (Aubry-Wake et al., 2015).

Our studies on the importance of groundwater in proglacial valleys have all converged to the conclusion that the contribution of groundwater to dry season discharge cannot be neglected at the watershed scale. The HBCM results show that groundwater is a major component of discharge during the dry season and that groundwater contributions to outflow were > 24% in all of the four studied valleys in 2008 (Baraer et al., 2015). Likewise, analysis of the 2014 dry-season Shullcas River watershed streamflow estimated that between 83.4% and 91.1% originated as groundwater (Crumley, 2015). Dye-tracing experiments have shown how different geomorphologic features, such as cross-valley moraines and talus slopes, impact the interaction of surface water and groundwater. Almost all of the water exiting the proglacial tributary catchments spent some time in the subsurface (Gordon et al., 2015) and about a third of the water exiting the mid-slope Quilcayhuanca valley derived from groundwater discharge (Somers et al., 2016).

As we move away from the heads of proglacial valleys, meltwater is progressively diluted by groundwater input. Meltwater production in the dry season is mainly driven by glacier extent, temperature and solar radiation. As these parameters are somewhat stable from year to year, meltwater volumes remain relatively stable. Given the hydrogeological constraints of both thin soils and coarse debris deposits leading to limited retention capacities, groundwater yields in high valleys are dependent upon recent (1 to 3 years) precipitation (Baraer et al., 2009). These characteristics lead to sensitivity to precipitation variability increasing from the high valleys to the lowest part of the watershed. In addition, it can be expected that groundwater yield gradually decreases from the high valleys to the Pacific coast, mainly reflecting the precipitation gradient of the Andean rain shadow.

Preliminary results from our embedded sensors and high resolution imaging (UAV and terrestrial) suggest that soil moisture content is closely tied to the level of the groundwater table, which is maintained through complex subsurface hydrologic pathways and includes inputs from glacier melt and seasonal recharge of groundwater aquifers. UAV imagery for the Llanganuco study site shows that surface soil moisture is highly heterogeneous within these systems (Fig. 4), with the wettest areas corresponding to perennial groundwater springs. When not fed by groundwater springs, the soil moisture content of these systems exhibits a strong seasonal signal tied to the precipitation regime (Fig. 5A). Calculated rates of evapotranspiration at the three study sites are high, and evapotranspiration appears to be the primary mechanism through which soil moisture is removed from the system - i.e. not much is left for percolation and subsurface flow that can then contribute to the deeper groundwater system and ultimately downstream water supply (Fig. 5B,C). Measurements of volumetric water content (VWC) of up to 90% were measured before soil saturation occurred. Soil samples from the 'bofedales' systems revealed low bulk densities and high organic content: it is these characteristics that give these soil their 'sponge like' characteristics.

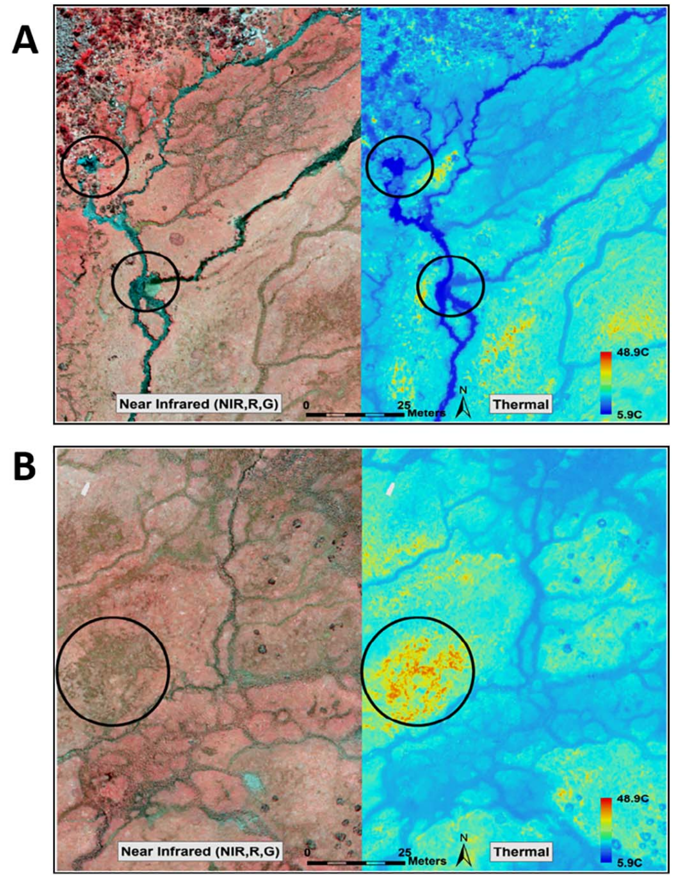


**Fig. 4.** Surface temperature (Ts) analysis from UAV-born infrared sensor over proglacial valley meadows. (A) Groundwater springs exiting the talus field (top circle). The colder water temperature here compared to the main stream channel (right of confluence in lower circle) indicates supply from groundwater. NOTE: Near infrared is displayed at its maximum 5 cm resolution and Ts data is at its maximum 20 cm resolution. (B) Overgrazing causes soil compaction and destruction of the unique plant assemblages that support the health of the wet meadow. Resulting dramatic increases in Ts (circled) likely enhances evaporation and aridification.

Along the course of the Santa River, water quality is affected by both natural and anthropogenic contamination. Highly acidic water resulting from pyrite oxidation (Fortner et al., 2011) mobilizes metals from the regional bedrock, particularly the Chicama Formation of metamorphic rocks into which the regional granodioritic batholith of the Cordillera Blanca intrudes. This creates high concentrations of naturally sourced dissolved metal concentrations in a few Santa River tributary streams. At other locations, mainly situated below valley cities, mines and abandoned mine tailings, diffuse but high metal concentrations enter tributaries or the main river (Guittard et al., In Review). The Santa River accumulates loads from both natural and human origins mainly in the form of river-bed sediments. The absence of proper sewage treatment systems from the valley cities also accumulates

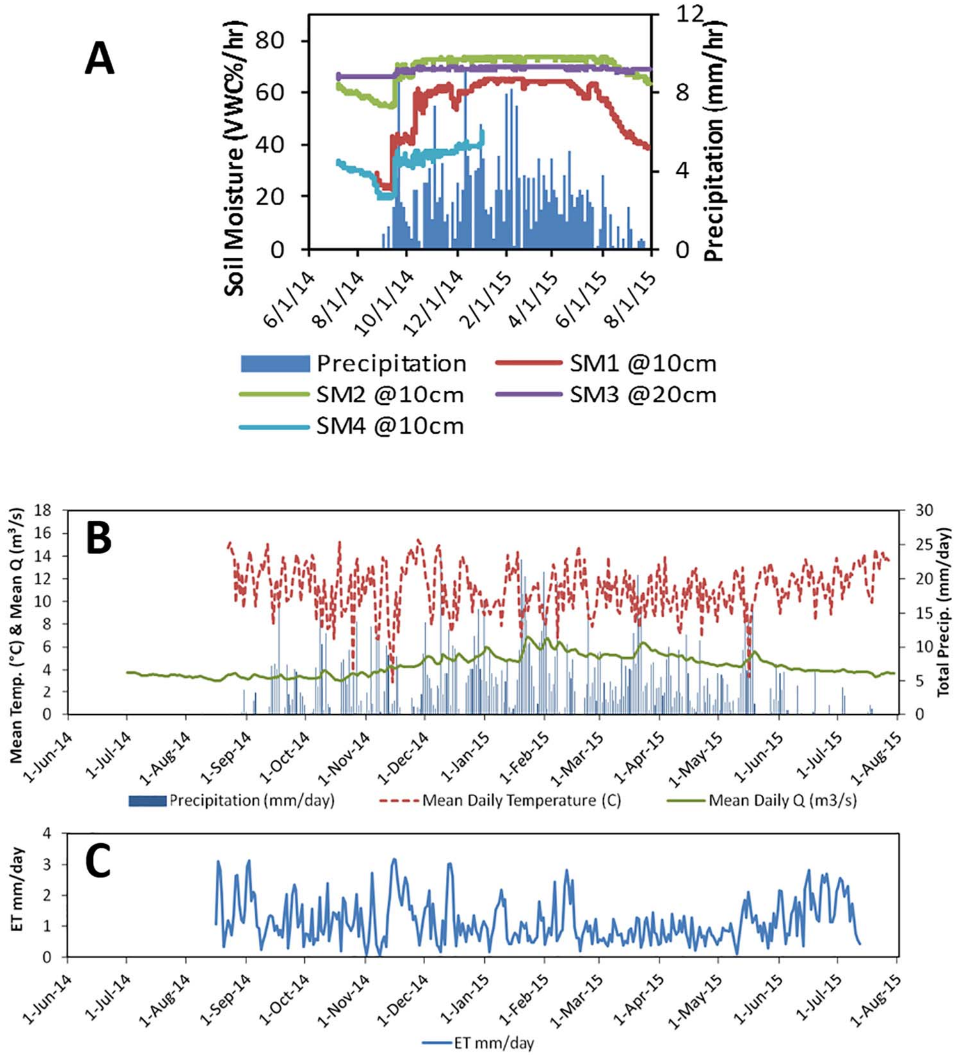


**Fig. 5.** (A) Hourly soil moisture values as VWC% soil moisture probes installed in the glacierized Llanganuco valley of the Cordillera Blanca, located to the north of Quilcay. SM probes 2 and 3 are co-located at different depths. (B) Llanganuco daily mean precipitation, temperature, discharge (Q); and (C) calculated evapotranspiration (ET). NOTE: aggregated from hourly data for display.

contaminant metals, nutrients and organic loads to the Santa River. Part of this contamination is eliminated from the water by natural processes such as oxidation or sedimentation, while part transits through the river to the watershed outlet. A few tens of kilometers before the Pacific Ocean outlet, the river receives substantial contaminants from its last large tributary (the Tablachaca River) (Guittard et al., In Review).

### 4.2. Land cover change

Our new analysis of land cover change shows that while glacier recession is an important driver, it is but one agent of change acting upon these highland environments. In fact, the predominant kind of change had to do with an increased "greening" signal as evidenced by increases in medium biomass (195 $km^2$ net gain) and high biomass (217 $km^2$ net gain) and decreases in low biomass ($-$ 398 $km^2$ net loss) (Fig. 6). Based on fieldwork and additional analyses (Young et al., 2017), we interpret increased biomass below 3600 masl to be due to denser shrublands and, nearer settlements, to the planting of eucalyptus plantations. There are also larger areas in urban land cover, and two notable places that were denuded for open pit mining. Above 3600 masl, and especially within Huascarán National Park, we have found that areas exposed by glacier retreat are in some cases being colonized by vascular plants, while grasslands and scree slopes are increasingly dominated by native shrubs. In imagery from within the park, Young et al. (2017) found that a substantial portion of the park area was in some kind of land cover transition from 1987 to 2010, including a recent loss of wetlands. Although representing a relatively small surface area, the wetlands of the park are of particular interest because presumably their change trajectory will follow the "peak water" curve expected for water availability as controlled by glacier recession (Baraer et al., 2012), and further documented in Polk et al. (2017).

### 4.3. Social processes

#### 4.3.1. Perceptions of changing water availability

Water users at diverse scales in the Santa River basin have perceived an overall decline in dry-season hydrologic resources during recent years. Our analyses highlight that the extent of these shifts and the resulting impacts to water availability are, however, variable inter-annually and spatially within the watershed (e.g. with extent of remaining glacial cover). Surveyed residents in the catchments in the upper watershed are nearly universally aware of the marked glacier recession underway. While most respondents perceived declining water availability during recent dry seasons, respondents reported the highest awareness of these declines in the least glaciated catchments and the lowest awareness of them in the most glaciated areas (Table 1). Across all areas surveyed, $< 10\%$ of respondents indicated water shortages for direct consumption during recent dry seasons, while approximately 25% reported shortages for irrigation water (Mark et al., 2010). Respondents across surveyed locations also mentioned reduced output or disappearance of local springs, which required additional effort (e.g. in

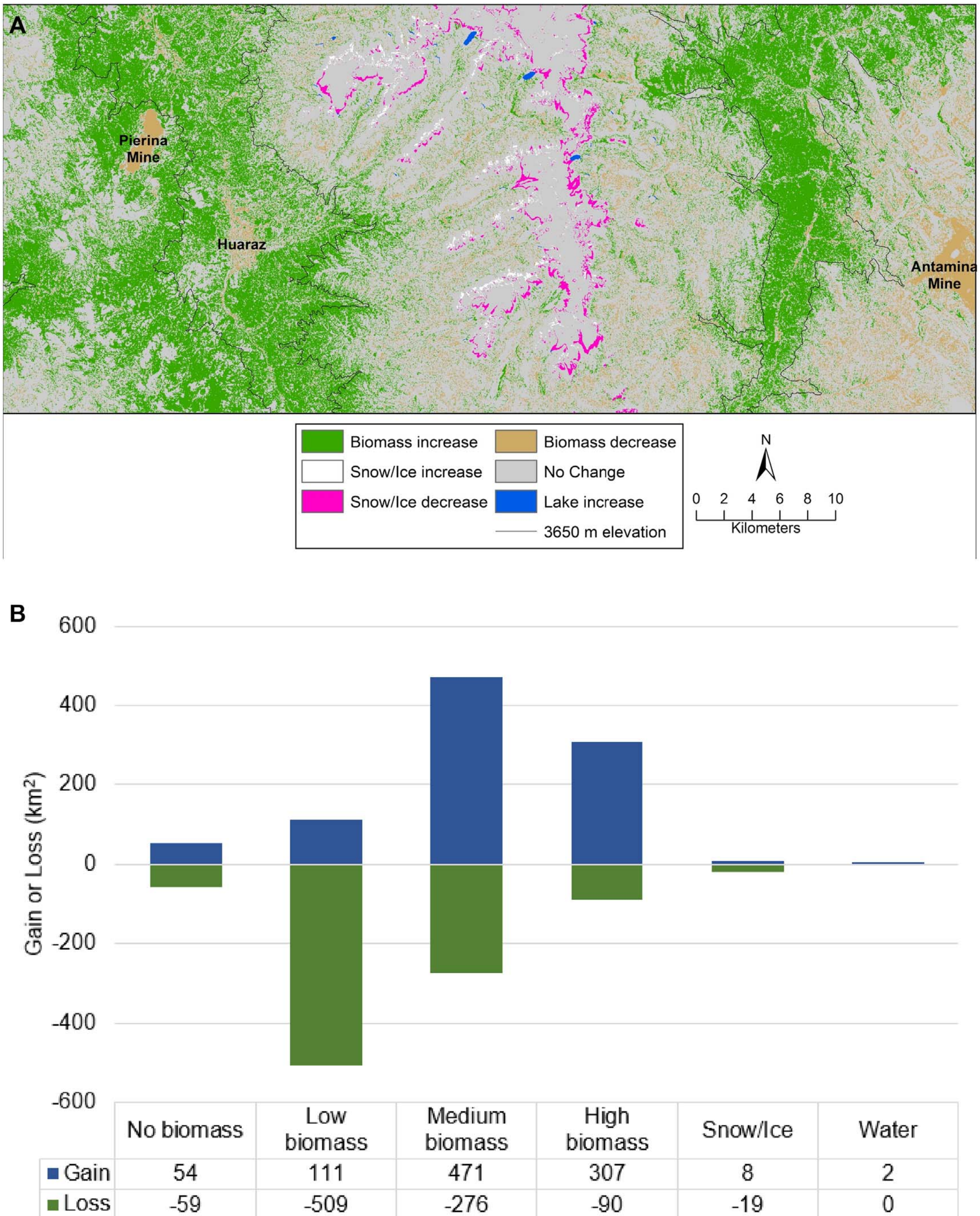


**Fig. 6.** A) Principal landscape transformation processes across the transect (located in Fig. 2) from 1990 to 2011; B) Increases and decreases in area from 1990 to 2011 for six land cover classes suggests a "greening" signal and glacier recession as important drivers of landscape change.

**Table 1**
Household perceptions of recent climatic and hydrologic changes, 2008–2009 (95% confidence interval).

| Catchment (% glacierized) | Querococha (3%) | Quilcay (17%) | Llanganuco (36%) |
|---|---|---|---|
| Perceptions (% of households reporting) | | | |
| Significant recession of nearby glaciers | 100 | 94 ± 4 | 98 ± 3.8 |
| Decreasing water supplies during the dry season | 93 ± 3.6 | 81 ± 6.54 | 76 ± 11 |

distance traveled or infrastructure development) to maintain continued access.

Industrial-scale water users in the middle and lower watershed also perceive an overall decline in dry-season water availability, as well as greater inter-annual variability in dry-season river discharge (Chavimochic, 2013; Duke, 2011). This declining and less predictable water availability alongside growing water demand in the lower watershed—driven largely by economic objectives to maximize hydroelectric energy production and boost agricultural production and exports—has stimulated construction of new infrastructure (e.g. Chavimochic's Palo Redondo reservoir and Duke Energy's San Diego reservoir).

Survey results from the Shullcas watershed also indicate widespread

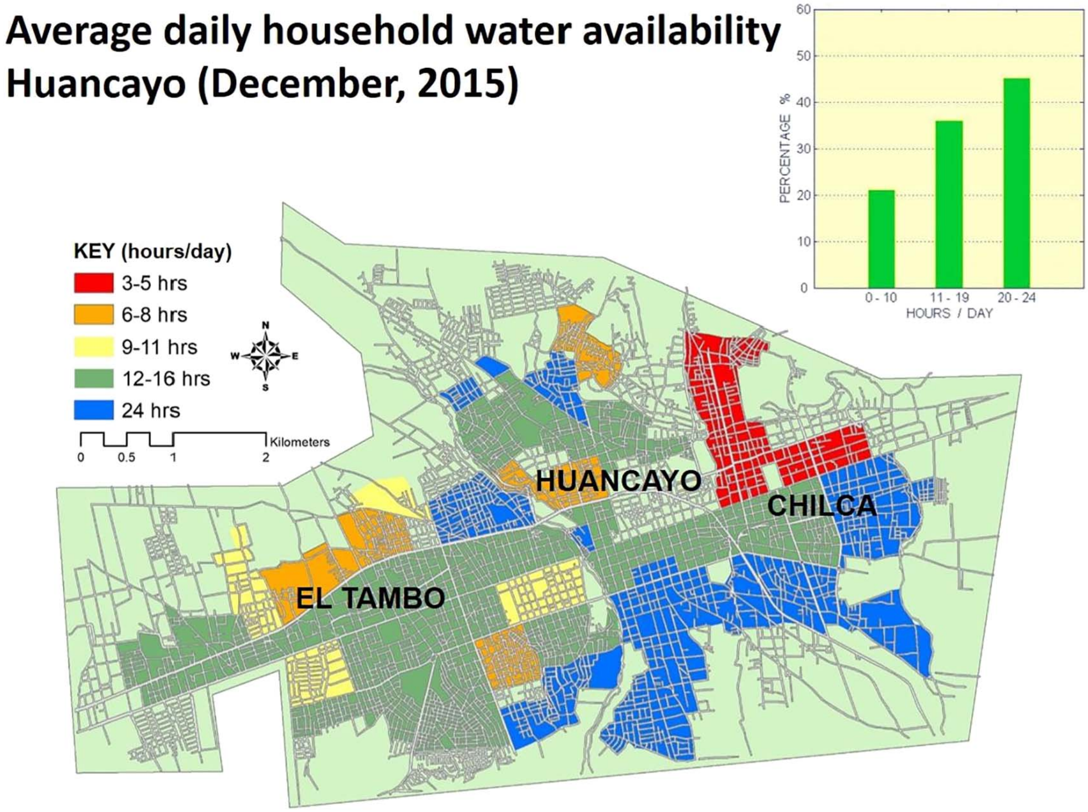


**Fig. 7.** Mapped results of household survey ($n$ = 911 residences) showing daily hours of water access (excluding homes with built in reservoir tanks).

awareness of increasing regional hydrologic variability. All respondents interviewed in the upper watershed perceived both decreased snow and ice cover and declining water availability. Surveys of > 900 households in Huancayo in 2015 revealed that < 50% had constant (20–24 h per day) access to water while approximately 20% had < 10 h of water access per day (Fig. 7).

*4.3.2. Water use and infrastructure in local and regional economies*

Diverse factors influence the capacities of both local households and larger-scale water users in the Santa and Shullcas basins to access water for their economic activities. In the least developed rural contexts, the spatial location of landholdings is a key determinant of water access, with households typically relying upon water from streams and springs—and to a lesser degree irrigation infrastructure—proximal to property claims (e.g. household plots or community-granted grazing allotments). The region's high environmental heterogeneity thus strongly influences both the quantity and quality of available water resources. In high-elevation pasturelands, for example, some grazing allotments lie near perennial springs or surface flows while other parcels may lack such direct access, necessitating a reliance on water of lower quality or the movement of livestock over greater distances. Those without access to springs depend more heavily on surface flows, such as glacier-fed streams. Similarly, the region's complex topography and varied hydrogeological conditions produce spatially variable and unequal household access to irrigation water. While reduced water access may inflict hydrologic risk on households, they are sometimes able to overcome water stress or limit vulnerability to water scarcity through diverse livelihood choices, such as modifying cropping decisions or engaging in contract labor, seasonal tourism-service provision, and small-scale commercial activities (instead of relying on agriculture and pastoralism for subsistence). These off-farm activities can help buffer the impacts of reduced water supplies–as well as other climate change-related impacts–on livelihood security (cf. Eakin, 2006) by providing household access to forms of virtual water (Allan, 1998) that may help to compensate for declining glacier-fed water flows crucial for agriculture and animal husbandry.

In the highland tributaries of the Santa basin, recent growth in the mining sector coupled with contamination from earlier extractive activities creates additional water-access risks for both local and downstream water users through impacts on water quality (Himley, 2012; Romero et al., 2010). According to the Ministry of Energy and Mines' National Inventory of Mine Impacts, the political department (Ancash) in which most of the Santa basin is located had the highest number of impacted sites (1284) in the country in 2016, with the Santa watershed containing 885 of these sites (MINEM, 2016). Respondents in our Querococha valley survey underscored the negative impacts of the area's multiple ore-processing plants on water quality and availability, and conflicts between these facilities and local residents have erupted in recent years (e.g. Peru, 2014). At the basin scale, commercial irrigators have long stressed the cumulative impacts of upstream mining contamination (INADE, 2001), and in 2010 concerns over water-quality impacts contributed to coordinated efforts between upstream and downstream actors to block development of a new mine in the basin's headwaters at Lake Conococha (ANA, 2011b). In addition to mining impacts, water-quality concerns are linked to the lack of wastewater treatment systems throughout the watershed and to high levels of naturally occurring heavy metals (cf. Fortner et al., 2011) and suspended sediments, which damage hydroelectric and irrigation infrastructure (INADE, 2001).

At regional scales, and especially at lower elevations and greater distances from key water sources, water infrastructure plays a critical role in overcoming the challenges of spatial heterogeneity of water availability and poor water quality. Spatial analysis of water systems indicates extensive development of water-transport, storage, and treatment infrastructure to offer more dependable water supplies to population centers and priority economic uses. As urban areas and local and regional economies have grown in both the Santa and Shullcas watersheds, this infrastructure development has expanded substantially, creating new linkages and dependencies across each basin and beyond their physical boundaries.

This development is most notable in the agriculture and hydroelectric sectors. For example, the Chavimochic irrigation project diverts up to 105 $m^3/s$ from the Santa River for agriculture in adjacent watersheds on the arid coastal plain, most of which produces non-traditional crops for export (e.g. asparagus, avocado, and blueberries). After Stages I and II of Chavimochic, approximately 81,000 ha have come under cultivation using Santa water for irrigation in the Chao, Virú, and Moche valleys, and the project simultaneously provides much of the coastal city of Trujillo's potable water supply. The vast Chavimochic infrastructure—in this case the Santa River intake and the 154 km mother canal (projected to extend to 267 km with completion of Stage III)—demonstrates how new technologies and engineering projects affect the spatial distribution of water and access to water within and even beyond glacier-fed watersheds (Chavimochic, 2012).

Currently, the entire dry-season streamflow is diverted from the Shullcas River for human use, split between urban municipal water supply for Huancayo and agricultural irrigation. Yet regional water shortages continue even with complete dry-season Shullcas water diversion. These ongoing shortages have triggered the construction of additional infrastructure: in urban Huancayo 18 wells have been established for groundwater extraction, 15 of which supply water year-round.

Hydroelectricity producers are also longstanding and influential water users in both the Santa and Mantaro River basins. The Cañon del Pato facility, for example, was completed on the Santa in 1958 with a 50 MW capacity, but expanded several times in the ensuing decades to its current capacity of 263 MW. This growth has necessitated an increasing reliance on the Santa River's base flow, as well as on water stored in highland lakes and constructed reservoirs in the upper watershed (Carey et al., 2014).

While this infrastructure is critical to regional economies, water users managing hydroelectric and irrigation infrastructure underscore the risks that geophysical hazards and extreme weather events pose to their water access, including seismic events, glacial lake outburst floods (GLOFs), avalanches, and El Niño Southern Oscillation (ENSO)-linked phenomena (Chavimochic, 2013; Duke, 2011). The Santa basin in particular, and especially the Callejón de Huaylas, has a long history of GLOFs and avalanches, including a 1950 GLOF that destroyed much of the nearly constructed Cañón del Pato hydroelectric station and a 1970 earthquake and associated avalanche and debris flow that buried the city of Yungay and killed approximately 6000 inhabitants (Carey, 2010; Evans et al., 2009). Extreme precipitation associated with El Niño events (e.g. in 1997–98 and 2017) has also damaged water-delivery and treatment infrastructure, causing service disruptions and substantial expenses across sectors (CAF, 2000; French and Mechler, 2017). For example, landslides and flooding during the “coastal El Niño” of early 2017 severely damaged the Chavimochic “mother canal” and associated infrastructure, cutting off the delivery of the project's irrigation water as well as the drinking water for Trujillo's 800,000 inhabitants (Industria, 2017). The 1997–1998 ENSO event also damaged Chavimochic's mother canal intake on the Santa River (CAF, 2000). Both cases underscore the vulnerability of regional economies and human populations highly reliant on infrastructure to convey highland-sourced, glacier-fed water to more arid downstream reaches.

#### 4.3.3. *Water rights and governance*

While rapid growth in regional economies and urban centers has driven increasing lowland reliance on highland water sources in the Santa and Shullcas basins, there is still little formal coordination in basin-scale water governance in these regions. State-led efforts to promote watershed-level management processes through the formation of a multi-sectoral watershed council were initiated in the Santa basin in 2010 but have stalled—due largely to regional and inter-regional political problems—and this process of institutional development remains incipient in the Mantaro basin (French, 2015). Nevertheless, the politics and economics of inter-sectoral water management play a key role in how water is distributed to various stakeholders throughout the watersheds, thus indicating the need to analyze the governance of water allocation alongside water availability.

In the absence of integrated water management institutions at the basin scale, inter-sectoral conflicts and temporary water scarcity problems (typically occurring at the peak of the dry season) have been handled on an ad-hoc basis. For example, during the 2011 dry season, large-scale coastal irrigators and central government authorities came together to create a contingency plan for managing severely reduced water flows in the Santa River and to discuss strategies for obtaining additional water from specific tributaries in the upper watershed (ANA, 2011a), but this coordination ceased with the arrival of the rainy season. Similarly, a longstanding conflict between local residents and the hydropower sector at Lake Parón—the largest lake in the Cordillera Blanca that was converted into a regulating reservoir in the early 1990′s—has been managed periodically and largely on the basis of risk-reduction criteria rather than for water provisioning (Carey et al., 2012; French, 2016a). These specific cases notwithstanding, downstream water demand still has relatively little direct impact on water availability and management practices in most highland tributaries. Efforts by lowland water users to influence upland water allocation, however, are growing as the hydroelectric and export-agriculture sectors that rely on Santa River water pursue diverse strategies to exert economic and political force regionally and nationally.

One prevailing state-led strategy to address burgeoning water demands and water-related conflicts among end-users is the universal formalization of water-use rights via volumetric allocations. This process is a key element of the integrated water management regime established under Peru's 2009 Hydrologic Resources Law (Law N° 29338), and has proceeded under the direction of the Program for Water Rights Formalization (PROFODUA) with financial support from the World Bank and the Inter-American Development Bank (French, 2016b). The government has prioritized this rights-allocation process on the Pacific slope, especially in large and economically important watersheds like the Santa. A long-term objective of the process is the reduction of the complexity of access entitlements that have developed since the 1969 agrarian reform through overlapping systems of usufruct rights held by small-scale users and state-issued licenses primarily for large-scale and industrial users (Boelens et al., 2010; Guillet, 1992).

This ongoing process of water rights formalization—which legally structures water access in the Santa and other catchments but remains nascent in implementation and influence in most settings—has provoked a range of responses from end users. Some small- and medium-scale irrigators, for example, worry that the 2009 water law represents an initial step towards eventual water privatization, with likely reduced or more contested water access (Oré and Rap, 2009). State water managers and large-scale water users, however, argue that precise allocations will support more efficient water use and more effective integrated planning (Peru, 2009). In the Santa watershed, some rural, upper-basin irrigators have refused to register for formalized rights, instead insisting that the government uphold their customary uses (PROFODUA, 2011). Others have accepted formal allocations but find their volumetric character abstract and lacking impact on quotidian water management (Parón-Llullán, 2011). Such perspectives are understandable in this context where most highland catchments and irrigation systems still lack precise gauging infrastructure and actual water allocations remain under the control of community-level institutions (French, 2016b; Rasmussen, 2015). Nevertheless, industrial-scale water users in the coastal reaches of the watershed have requested the completion of the rights-formalization process in the upper basin in order to improve estimates of downstream water availability (Chavimochic, 2013). Although the long-term effects of water-rights formalization remain uncertain, disputes over overlapping legal and customary water rights have already affected water distribution downstream from glaciers (French, 2016a; Lynch, 2012) as water demand increases and dry-season water availability gradually declines and becomes more variable with the passing of "peak water."

## 5. Discussion

At the heads of the highland watersheds in our study, glaciers that provide critical water supply to moderate seasonally variable streamflow are accelerating not only in the rate of frontal recession, which has been mapped from many different scales, but more in volume loss. The total volume loss of individual glaciers quantified with repeat high resolution surface mapping (Huh et al., 2017) exceeds the volume estimated by using scaling factors for predicting volume loss as a function of surface area (i.e. Bahr et al., 1997). Because these results derive from comparisons on a limited number of individual glaciers, they should not be generally applied over larger scales. Further, we acknowledge that there are other methods using 3D flux/stress/slope-related thickness that could be used to provide better estimations of regional volume change (Colonia et al., 2017; Haeberli, 2016). Nevertheless, this lack of conformity implies that regional estimations of remaining glacier water reserves based on glacier surface-area scaling might be incorrect and likely too high. Similarly, our new mapping with IR digital photography allows for the magnitude of hypothesized radiative feedbacks from exposed rock surfaces at the edges of retreating glacier termini to be quantified. We suggest that more glacier mass has already melted than previously discerned, and that future projections should account for this additional mass sensitivity. Moreover, as the remaining glaciers are higher, local topography will play a larger role in moderating the mass loss.

Emergent system characteristics that impinge on water access can be depicted along a vertical gradient (Fig. 8). Fig. 8a, adapted from Baraer et al. (2012), illustrates the partitioning of surface water origin between meltwater and groundwater sources for the dry season. Sensitivity to annual precipitation that depends on the water origin is conceptualized in Fig. 8b. Within the proglacial valley environment, as glaciers melt, human access to water will be more susceptible to the seasonal availability of precipitation and groundwater recharged by precipitation runoff. The hydrogeologic characteristics of the region also lead to increasing levels of inter-annual variability in the lower parts of the watershed. Access to groundwater supplies is dependent upon the heterogeneous local subsurface composition, flow paths, and permeability, and groundwater reserves are crucial not only for maintaining base flow to streams, but also for water quality. Groundwater-streamflow interactions increase the influence of subsurface conditions on water quality. Even though upwards of half of the total outflow from our study watersheds originated as groundwater downstream of the glacial lakes, the original sources of groundwater (local precipitation or stream water lost to the subsurface up-hill), as well as groundwater residence time and age, are not always obvious or known. Glacier melt collected in proglacial lakes can provide important recharge to the groundwater in valley meadows, emerging in concentrated springs that are important sources of water for human and livestock consumption and for supporting the pasturage of domestic animals, as well as for wider ecosystem processes (Gordon et al., 2015).

Given the influence of subsurface composition on the spatial heterogeneity of water sources within individual valleys, as well as variability in precipitation and glacial cover between valleys, water availability and risks related to shifting water supplies are already diverse and will continue to change in non-uniform ways as glacier recession proceeds and precipitation becomes increasingly important. Adding to this physical heterogeneity in water distribution and the resulting hydrologic risks are the varied social and economic resources and capacities of different end users, which generate unevenness in their levels of vulnerability to ongoing hydrologic change. For example, as glaciers disappear and seasonal precipitation becomes more critical, water access, storage, and transport infrastructure (e.g. wells, reservoirs, and canals) will likely become more necessary in highland catchments, requiring investments in infrastructure development and access to formal water allocations in centralized distribution systems, as well as the negotiation of complex political dynamics (Rasmussen, 2016).

At the regional scale of the Santa watershed, where most hydroelectric generation and large-scale agricultural production takes place, the peak-water transition has likely already passed, increasing the risks associated with variable precipitation regimes and droughts (Baraer et al., 2012). In this context, energy producers and agro-export firms have constructed water storage and transport infrastructure and have secured formal water rights to river flows to buffer seasonal variability. Similarly, in the Shullcas basin, glacier melt is presently contributing a minor (< 20%) share of even the dry season baseflow to streams. The entire Shullcas discharge is diverted for human use and is still inadequate for urban domestic supply. Numerous wells have been drilled

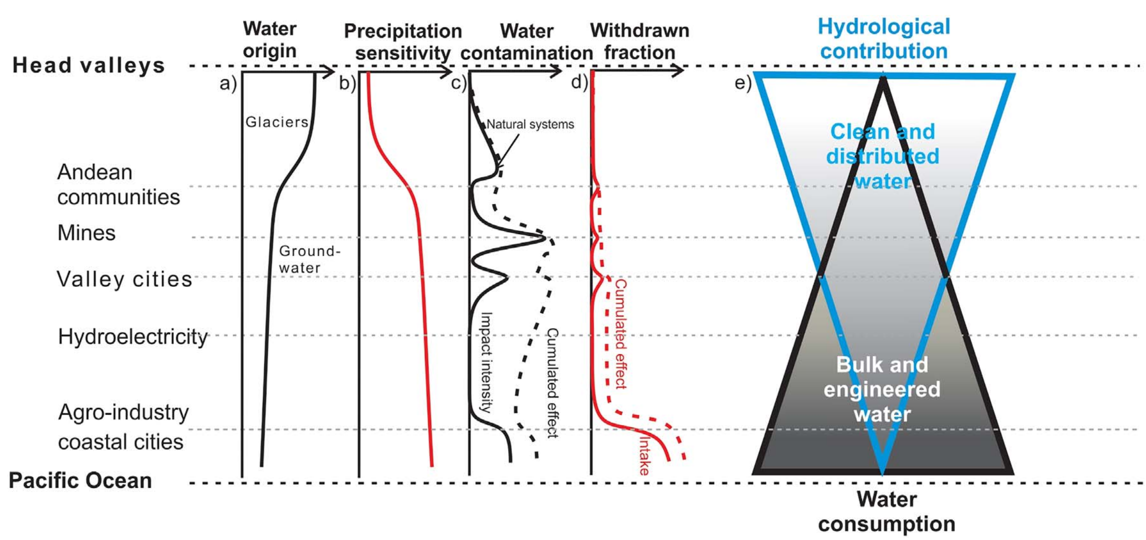


**Fig. 8.** Conceptual model of vertical arrangement of watershed characteristics impinging on water access. Nominally oriented from upper catchments (top) to the coast (bottom), each vertical figure illustrates a characteristic with relative scale, aligned L-R sequentially: (a) illustrates the partitioning of surface water origin between meltwater and groundwater sources for the dry season; (b) represents the sensitivity to annual precipitation for the dry season flows; (c) presents relative impacts of water contamination, affected by both natural water-rock interactions and anthropogenic activities along the course of the Rio Santa; (d) illustrates water withdrawal amounts; and (e) provides a visual interpretation of the symmetrical imbalance that exists between the water supply and the demand through the watershed during the dry season.

to augment urban water supplies. In the Santa watershed, these expanded utility developments have led to increased power generation capacity and expansion of coastal agriculture despite gradually declining river flows. These changes, however, have also created new multi-level dynamics and dependencies that come with new risks. These risks include the exposure of assets to natural hazards and declining water access due to inter-sectoral social conflicts and increasing upstream water withdrawals (Carey et al., 2014). Through interconnections such as the national energy grid, global agricultural markets, and dependence on the Santa's flows for potable water in Trujillo, these risks extend to an array of end-users within and beyond the physical boundaries of the watershed.

How water flows over and through the proglacial landscape as determined by interacting hydrogeologic and social processes has a variety of other direct and indirect impacts on both ecosystems and linked hydro-social systems. In highland valleys, changes in soil moisture content linked to reduced quantities of glacier meltwater or groundwater or human-caused modifications to drainage patterns may impact the productivity of proglacial meadows with feedbacks on soil characteristics and the quality of livestock fodder. Surface soil moisture is highly heterogeneous and depends on a number of local factors that are hard to detect without extensive instrumentation networks, high resolution imagery, and/or geophysical studies, but that have important implications for access, particularly the presence of groundwater springs (Fig. 4A) and overland flow which are responsible for maintaining year round wetlands at saturation (80–90% VWC). However, the low bulk density and high field capacity of these soils likely reduces overland flow and provides a seasonal supply of water for the meadow and wetland systems within the proglacial valleys when they are not fed by surface water springs. The productivity of these wetland systems is likely dependent on these soil properties being maintained i.e. high year-round soil moisture. Overgrazing can compact the soil surface and change the vegetation composition (Fig. 4B), potentially reducing the soil's water-storage capacity. It also can increase direct evaporation through exposure of bare ground. Through these processes, overgrazing can thus lead to rapid drying of the land surface, which is evident in our high resolution soil moisture maps (Fig. 4B). Overgrazing may also have interactive effects on ecosystem dynamics and services. Soil compaction may increase flashiness of watershed response to precipitation events, enhancing surface runoff and reducing the amount of water available to the meadow and wetland systems through the dry season. Furthermore, reduced soil moisture storage capacity may lower the groundwater table as vertical transport is increased to support the high rates of evapotranspiration, or, alternatively wetland plant species may dry out and disappear.

Our land cover change analyses have identified ecological shifts in these dynamic landscapes, including significant flux near the snowline as glacier retreat exposes bare substrates that can be colonized by plants while altering hydrologic flows. This leads to expanding lakes and wetlands early in the "peak water" curve, and reduced flows later on that result in shrinking lakes and drying wetlands. Other studies have reported widespread ecological threshold changes in Andean lake environments (Michelutti et al., 2015): as glaciers are removed and temperatures change, diatom assemblages have altered dramatically, suggesting patterns in thermal stability that counter nutrient access and hinder productivity. Likewise, ecological shifts in other flora and fauna will affect land use, often with implications for local livelihoods.

The biggest land cover changes we observed in Junin and mapped in Ancash (Fig. 6), however, had to do with other landscape agents of change. In both sites, urban areas are expanding and areas denuded for mining activities have increased, processes reflective of predominant demographic and industrial trends at the national level. There is also a strong "greening" signal in the land cover change, suggesting that, at least for Ancash, the dominant change has to do with increased woody vegetation, a change reported elsewhere in the tropical Andes as well (Aide et al., 2013; Young, 2015). This landscape-scale increase in biomass, which we attribute to increased tree plantations and grasslands invaded by shrubs, will lead to more leaf area and hence larger total amounts of evapotranspiration. In principle, this could cause increased interception of rainfall by vegetation and could decrease infiltration and eventually streamflow, thus further altering hydrologic connectivity in these landscapes (Ponette-González et al., 2014). Changes to landscape albedo, soil moisture, and soil temperatures could also be affected through feedback loops among increased vegetation cover/biomass and these factors. Near glaciers, much water flux is mediated through groundwater, so the changed above-ground biomass may not be the critical factor. However, elsewhere in these landscapes, increased shrubland and tree plantings are probably significant new fluxes in regional water balance.

Water contamination is another factor impinging critically on access (Fig. 8c), including through health risks and infrastructure costs. With anthropogenic activities such as mineral ore processing adding contamination loads on top of a natural background, the Santa River's waters surpass drinking-water standards for trace metals before the river reaches the first large city on its course, Huaraz. Despite natural processes such as particle settling that attenuate slightly the contaminant concentrations in water downstream of the contaminating points, the Santa's waters remain laden with heavy metals from Huaraz to the Pacific Ocean. Andean communities have adapted their water consumption patterns to the natural contamination occurring in the highlands by selecting non-polluted sources, but, in the context of growing demand, such selective water use is increasingly difficult, especially for downstream users. The city of Huaraz, for example, must at times mix naturally contaminated water from the Quilcay River with non-contaminated flows to supply the city with a sufficient amount of fresh water during some annual dry seasons. The contamination level of the Santa River itself prevents it from being considered as a potential water supply along most of its course. On the arid coastal plain, where the Santa comprises the only source of water with adequate volume to meet demands, the river's waters are used for irrigation and potable water provision, necessitating expensive water-transfer and treatment infrastructure that is vulnerable to heavy sediment loads and natural hazards. Access to non-contaminated water in this context is thus dependent on the interacting effects of spatial location, the rights to use particular water sources, and the ability to construct and maintain effective infrastructure.

Water withdrawal patterns show a great imbalance at the watershed scale (Fig. 8d). While the majority of the water is produced in the upper and middle reaches of the watershed, including in the glaciated subcatchments of the Cordillera Blanca, the largest volumes of water are extracted in the lowest portion of the watershed for large-scale coastal agriculture and urban water provision. Withdrawn volumes in this coastal area can represent up to 90% of the Santa's discharge just above the intakes during the dry season (Carey et al., 2014). A conceptual synthesis of the four first graphs of Fig. 8 (a, b, c, d) is given in Fig. 8e. It shows this characteristic imbalance between water supply and demand in the watershed during the dry season. Most of the water originates in the high valleys where glacier melt and proglacial springs supply nearby populations with relatively consistent flows, although residents in valleys with low levels of remaining glacier cover already report noticeable impacts on both surface and groundwater availability during some dry seasons. Water demand from highland communities closest to these distributed sources is typically significantly lower than the total water available, while, in the lower reaches of the watershed, the situation is reversed as water is supplied by a quasi-unique source to a distributed and dense population whose demands far exceed the region's yields. Water that has been contaminated during its journey to the coast requires costly distribution systems to reach end users. With increasing demand for clean water, downstream populations and water-intensive economic activities become progressively more vulnerable to upstream watershed management practices. This vulnerability of downstream water users to upstream water management is prevalent on

Peru's Pacific slope and contributed to the passing in 2014 of a law governing payments for ecosystem services (PES) (Law N° 30215). Under the PES framework, various pilot schemes involving downstream water users compensating upstream users for watershed conservation measures have developed, and explicit discussions of such arrangements in the Santa basin have been promoted by large-scale coastal water users since at least 2013, though no such arrangements have yet been formalized (Chavimochic, 2013).

Currently, the existing water supply and demand dynamics are shifting across the spatial scales of the Santa and Shullcas watersheds, driven by a combination of interacting biophysical changes linked to glacier recession and social processes including urban and industrial growth and changing livelihood pursuits. In these contexts, the water needs of expanding cities and large-scale users like mines, electricity producers, and export agriculturalists will increasingly compete with those of small-scale agro-pastoralists and rural communities. While these latter users are located close to principal water sources, new institutional arrangements such as formal volumetric allocations and expanded water-transfer infrastructure are being developed to distribute water resources across the watersheds in new ways that will reduce risks for some users while increasing them for others. Such dynamics are increasingly prevalent across the tropical Andes and in other glaciated regions worldwide, suggesting that the conceptual framework presented here could be adapted to a range of hydro-social systems undergoing complex and interacting processes of global change.

## 6. Conclusions and implications

In this paper, we have shown that interacting biophysical processes and social dynamics at diverse scales shape environmental risks and resource entitlements for different water users in multi-level hydro-social systems. The biophysical dimensions of our analysis have examined how glaciers, glacierized landscapes, and pro-glacial hydrologic systems are changing in the context of climate change, and we have estimated how much glacier melt actually contributes to diverse end users' water supplies across the physical watershed at different times and via what forms of water (e.g. surface water and groundwater). In complement, the social component of the analysis has examined how water is incorporated into the livelihoods, economic activities, and institutional arrangements of different end users and how access to water resources and related hydro-social risks are shaped not only by hydrologic conditions, but by complex factors including geographical location, livelihood diversity and food- purchasing options, ties to market economies, and access to and control over resources such as technology and capital (in the form of infrastructure) and political authority and power (in the form of legal rights and institutions) (cf. Ribot and Peluso, 2003). By linking these analyses of biophysical water availability and the social and technological elements structuring water access, our findings provide insights into the interactions and feedbacks between system components and the ways in which these dynamics differentially shape the risks and vulnerability of diverse end users within and beyond the watershed to shifting hydro-social conditions.

Our integrated observations and conceptual modeling of this coupled hydro-social system over multiple scales elucidate certain characteristics of such a dynamic system that can present challenges to ongoing management of water resource access. First, climate and glacier changes may be triggering hydrologic changes in the system well before scientists, engineers or local residents can detect them. The glaciers in the tropical Andes are no longer in mass equilibrium, and detecting the actual net glacier loss from storage presents challenges without intensive monitoring and means to discern melt from precipitation. Feedbacks exist that further decouple mass loss from the resulting signal of streamflow changes. For example, our TIR measurements at the melting glacier edge show how exposed bedrock proximal to receding glaciers induce radiative feedbacks that have likely enhanced melting. This can help explain how actual measured volume loss has exceeded the amount predicted using previous formulations.

Second, emerging risks to water access and associated vulnerabilities are not uniform in space or time, but instead are extremely heterogeneous, even at small spatial scales, and should be seen as conjunctural outcomes produced by the interactions of diverse local and supra-local conditions and processes. These factors may include shifting quantities and qualities of water over spatial and temporal scales, proximity to particular sources of water and contaminants, formal and informal entitlements to use water in specific ways and at specific times, access to water transport and treatment infrastructure, and access to additional resources that provide “virtual water” alternatives to offset changes in actual water access. As we have shown, such factors are conditioned by a wide range of processes and characteristics (e.g. glacier recession, drought, overgrazing, household location, diversity of livelihood pursuits, regional economies, political decisions, income levels, etc.). The analysis of risks and vulnerabilities associated with hydrologic change therefore entails much more than the consideration of shifting physical access to a particular source or volume of water or simple material measures of poverty.

Third, risks to water access may be generated at spatial scales far beyond the physical bounds of single catchments or even much larger watersheds (e.g. the Santa River basin). Such cross-scale effects are seen in the global drivers of climate change and glacial recession as well as through the incorporation of global economic actors into regional economies and the influence of global policy paradigms on national- to local-level laws and institutions. Practically, the diffusion of impacts far beyond the melting glacier means that water access is often situated where direct loss of glacier ice is not the dominant control over readily available streamflow, and other factors of groundwater residence and water-rock interactions impacting water quality emerge as different risks to water resources. Nevertheless, a differentially greater proportion of populations poised close to the margin of extraction means they are reliant on small margins of supply, and thus more vulnerable to glacier loss.

The complexity of the factors influencing risks to water access under ongoing processes of global climatic and economic change argues for their evaluation across the broader hydro-social systems in which particular watersheds and localized systems of water use are embedded. Through multiple stages of coupled biophysical and social analyses in the Santa River watershed, we have developed an approach and a framework for this type of multi-scalar systemic analysis that may be of use in similar systems in the tropical Andes and elsewhere, with the understanding that specific contexts will always present their own particular dynamics and complexities. Embedded observations with creative use of high-resolution environmental sensors and modeling of processes over different scales can be maintained collaboratively and sustainably with in-country collaboration. Yet ultimately, understanding the interacting risks impacting water resource access and management in this context of rapid climatic and socio-environmental change requires a close coupling of disciplinary approaches through scientific teams working in context to develop and refine integrated hydro-social perspectives.

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