New Geographies of Water and Climate Change in Peru: Coupled Natural and Social Transformations in the Santa River Watershed

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Projections of future water shortages in the world's glaciated mountain ranges have grown increasingly dire. Although water modeling research has begun to examine changing environmental parameters, the inclusion of social scenarios has been very limited. Yet human water use and demand are vital for long-term adaptation, risk reduction, and resource allocation. Concerns about future water supplies are particularly pronounced on Peru's arid Pacific slope, where upstream glacier recession has been accompanied by rapid and water-intensive economic development. Models predict water shortages decades into the future, but conflicts have already arisen in Peru's Santa River watershed due to either real or perceived shortages. Modeled thresholds do not align well with historical realities and therefore suggest that a broader analysis of the combined natural and social drivers of change is needed to more effectively understand the hydrologic transformation taking place across the watershed. This article situates these new geographies of water and climate change in Peru within current global change research discussions to demonstrate how future coupled research models can inform broader scale questions of hydrologic change and water security across watersheds and regions. We provide a coupled historical analysis of glacier recession in the Cordillera Blanca, declining Santa River discharge, and alpine wetland contraction. We also examine various water withdrawal mechanisms, including smallholder agriculture, mining, potable water use, hydroelectric power generation, and coastal irrigation. We argue that both ecological change and societal forces will play vital roles in shaping the future of water resources and water governance in the region. *Key Words: agriculture, climate change, coupled systems, hydrology, mining, Peru.*

对于未来全球冰河山岳的水资源稀缺之预期, 已经发展到极度紧迫的状态。儘管水的模式化研究已着手检视改变中的环境因素, 但却鲜少将社会情境纳入分析。但人类的用水和需求对于长期的调节、降低风险和资源配置而言相当重要。对于未来供水的考量, 在秘鲁的乾旱太平洋斜坡中特别显着。在此处中, 上游冰河的退缩伴随着急速且大量耗水的经济发展。模型预测未来还需数十年才会面临水资源的缺乏, 但在祕鲁桑塔河流域中, 因为实际或预期的水资源缺乏, 已开始产生冲突。模拟的起始点与历史事实并不相符, 因而指出必须对结合自然和社会的改变驱力进行更为广泛的分析, 以更有效地理解流域中发生的水文变迁。本文将秘鲁这些水资源及气候的崭新地理变迁置放在当前的全球变迁研究讨论中, 证明未来的结合研究模式如何得以提供资讯给流域和区域中关乎水文变迁和水资源安全的更大尺度之问题。我们提供对布兰卡山脉冰河退缩、减少中的桑塔河流流量, 以及高山溼地缩减的结合性历史分析。我们同时检视众多取水的途径, 包含小型农业、矿业、饮用水的使用、水力发电以及沿海灌溉。我们主张, 生态变迁和社会驱力在形塑区域水资源与水资源管理的未来中, 将同时扮演重要的角色。 *关键词: 农业, 气候变迁, 结合系统, 水文, 矿业, 秘鲁。*

Las proyecciones de futura escasez de agua en las cadenas montañosas glaciadas del mundo son cada vez más alarmantes. Aunque la investigación que trabaja en la modelización del agua ha comenzado a examinar los cambiantes parámetros ambientales, la inclusión de escenarios sociales ha estado muy limitada. Sin embargo, el uso humano del agua y la demanda son vitales para adaptación a largo plazo, reducción del riesgo y asignación de recursos. Las preocupaciones sobre los futuros suministros de agua son particularmente pronunciadas en las áridas

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vertientes pacíficas del Perú, donde la recesión de los glaciares situados corriente arriba ha estado acompañada de un rápido desarrollo económico intensivo en términos del uso del agua. Los modelos pronostican déficits de agua para décadas del futuro, pero ya han estallado conflictos en la cuenca del Río Santa en el Perú, debido a escaseces reales o percibidas. Los umbrales modelados no concuerdan bien con las realidades históricas y por ello mismo sugieren que se necesita un análisis más amplio de los agentes de cambio naturales y sociales combinados para comprender más efectivamente la transformación hidrológica que está ocurriendo a lo ancho de la cuenca. Este artículo coloca estas nuevas geografías de cambio climático e hidrológico en el Perú dentro de las actuales discusiones de investigación sobre cambio global, para demostrar cómo los futuros modelos de investigación acoplada pueden llegar a contemplar cuestiones de escala más amplias del cambio hidrológico y de seguridad del agua a través de cuencas y regiones. Nosotros entregamos un análisis histórico acoplado sobre la recesión de glaciares en la Cordillera Blanca, la declinación del flujo del Río Santa y la contracción de los humedales de tipo alpino. Examinamos, además, varios mecanismos de extracción de agua, incluyendo agricultura de pequeños cultivadores, minería, uso de agua potable, generación de energía hidroeléctrica e irrigación costanera. Sostenemos que juntos, el cambio ecológico y las fuerzas sociales, desempeñarán papeles vitales en la configuración del futuro de los recursos hídricos y la gobernanza del agua en la región. *Palabras clave: agricultura, cambio climático, sistemas acoplados, hidrología, minería, Perú.*

Water is critical for both ecological and social systems, and its storage, movement, and use are determined by complex interrelationships among them that are temporally contingent, spatially variable, and shifting at nonlinear rates. Most water research, however, is done by scientists and engineers working within their disciplinary boundaries, and it thus lacks the integrated socioecological framework necessary for understanding such complex systems. To understand the ways in which these combined factors are influencing the flow of water across landscapes, new "coupled" or interdisciplinary theoretical and methodological approaches are needed that facilitate more comprehensive evaluations of complex and interrelated systems. These approaches must be flexible enough to foster the development of integrated assessment frameworks that incorporate the temporal and spatial dimensions of the multiple phase changes of water as well as the fact that water can be simultaneously categorized as both a human resource and as part of a natural process.

Recently, new global change research initiatives have emerged to facilitate more comprehensive and integrated evaluations of complex interrelated system changes. This approach has also been highlighted as a federal research priority over the next decade by the U.S. Global Change Research Program (USGCRP) and as a global concern by many international organizations (Food and Agriculture Organization 2006; USGCRP 2012). Key thematic foci of recent research supported by these initiatives include water security, biodiversity, and the adoption of cross-scalar analytical frameworks and spatial units such as watersheds to evaluate the anthropogenic and biophysical drivers affecting water resources (Vörösmarty et al. 2010).[1]

This article seeks to build on these new global change research efforts in several different ways. First, we seek to deepen the thematic focus of this research on water resources and security by examining the rapidly shifting geographies of water resources and security in the central Peruvian Andes. In addition, we adopt a similarly broad spatial unit of analysis by focusing on the Santa River watershed region in Peru to examine the complex interactions among global, regional, and local processes of anthropogenic and biophysical drivers of hydrologic change across the watershed that are significantly affecting these emergent geographies. Furthermore, our integrated and collaborative empirical examination of recent climatic and social change in this watershed highlights the need for interdisciplinary approaches to more thoroughly address the complex effects of these changes on current and future water security and ecosystem processes.[2] Finally, our coupled analysis informs long-standing environment–society research debates within geographic studies as it demonstrates the need to avoid overly environmental deterministic explanations of global change that neglect the historical social and political factors that shape both hydrologic processes and hydraulic resource management (Hulme 2011). Overall, our combined analysis seeks to provide new insights for geographers seeking to understand the unique role of water in shifting, dynamic, and integrated socioecological systems.

Our analysis of new geographies of water and climate change in the Santa River watershed begins by reviewing how glacier recession is transforming downstream hydrology and alpine wetlands. It then continues with an evaluation of key social drivers of change that include smallholder agriculture, mining, potable water use, hydroelectric power generation, and coastal

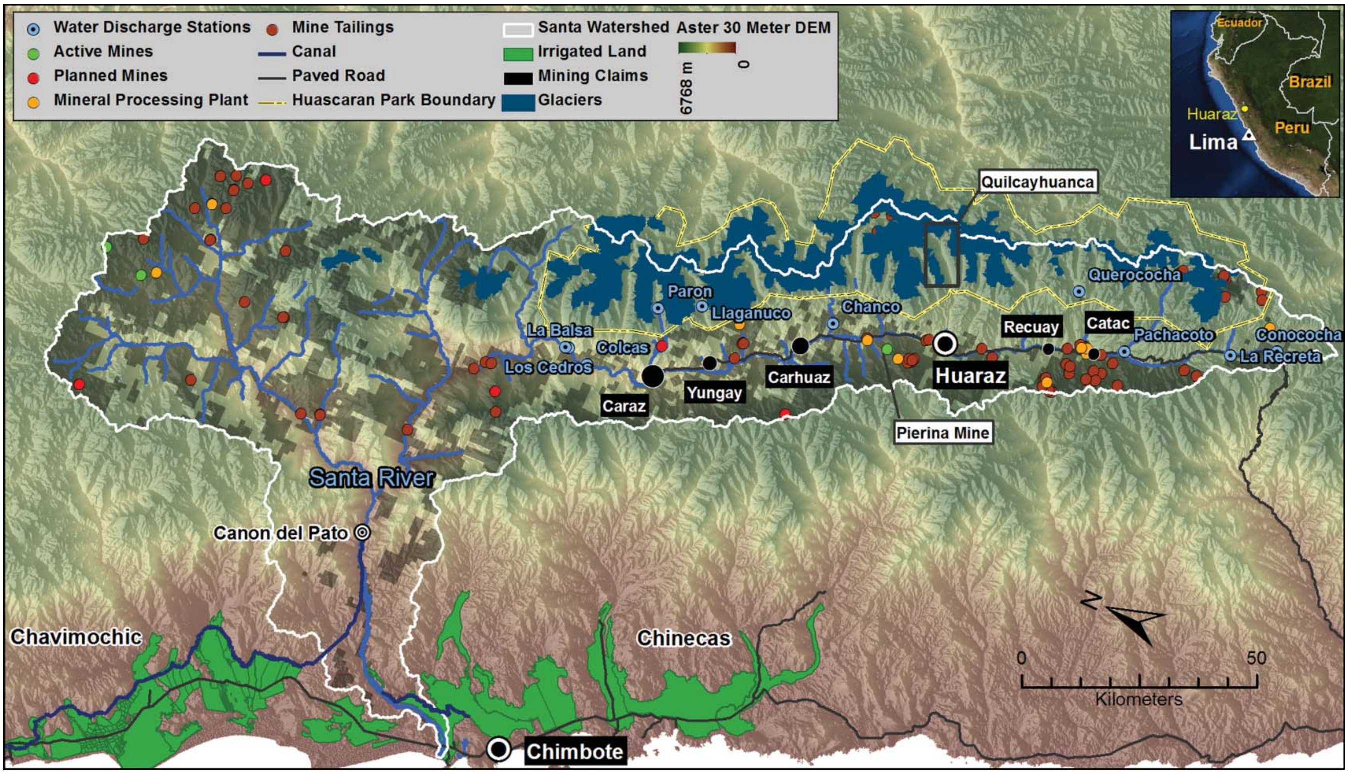

Figure 1. The Santa River Basin. (Color figure available online.)

irrigation. Finally, a brief conclusion discusses recent shifting cross-scalar water governance activities across the region and key research questions for the future.

Hydrologic Change in the Santa River Watershed

Hydrologic systems in the tropical Peruvian Andes are currently situated at the confluence of a number of significant ecological and social transformations. Rapid and accelerating glacier recession due to climate change, new mineral extraction activities, shifting human populations, and agricultural intensification are all impacting mountain hydrology, regional water supplies, and human security across the region (Zierl and Bugmann 2005). Historically, glaciers have buffered stream flows to the country's arid Pacific coast, where the majority of the population resides (Vuille et al. 2008). Because future scenarios predict more pronounced increases in warming rates in the Andes, however (Bradley et al. 2006), the cascading effects of these changes will have significant impacts on downstream glacial lakes, biodiverse wetlands, hydrologic outflows, glacier-related hazards, human vulnerability, and water resources (Carey 2005; Mark et al. 2010; Bury et al. 2011; Carey, French, and O'Brien 2012).

The Santa River drains a total watershed of 12,200 km^2 (Figure 1) and is the second largest river along Peru's Pacific Coast (Mark et al. 2010). The upper watershed, above the Cañon del Pato hydroelectric generation plant that is fed from Santa River input at La Balsa, is more than 5,000 km^2 and captures runoff from the majority of the glacierized valleys of the Cordillera Blanca. The glacier coverage of the Cordillera Blanca has declined from 800 to 850 km^2 in 1930 to slightly less than 600 km^2 at the end of the twentieth century (Georges 2004). In this tropical latitude, average temperatures do not vary throughout the year, but the precipitation seasonality is very pronounced (Figure 2). Glacier melt water is thus an important buffer to runoff, providing 10 to 20 percent of the total annual discharge in the Santa River, and exceeding 40 percent in the dry season (Mark, McKenzie, and Gómez 2005). This buffer is also important for irrigation and other land use activities as it has historically extended agricultural production.

In this context, the central question for our hydrological assessment has been how glacier recession is impacting water supplies (Mark et al. 2010; Bury et al. 2011). Theoretically, glacier recession initially will

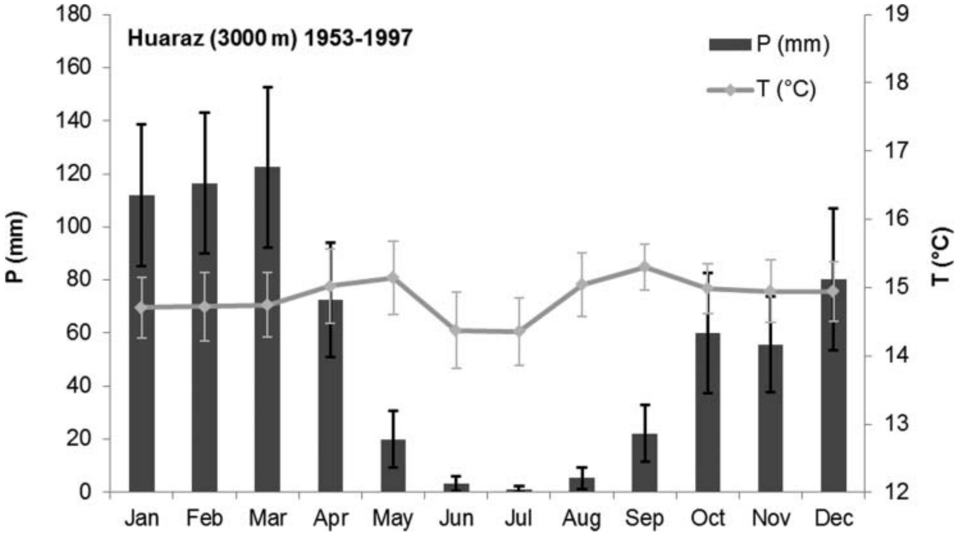

Figure 2. Historical monthy precipitation (P) and temperature (T) averages for Huaraz, Peru (error ranges span 1 standard deviation).

increase stream discharge as a result of the melted ice mass being released from storage (e.g., Chen and Ohmura 1990; Jansson, Hock, and Schneider 2003; Huss et al. 2008). Regionally increased glacier melt has been observed in the glacierized tributaries of the Santa River by changes in interannual isotopic variability (Mark and McKenzie 2007). Similarly, our hydrologic budget calculations in the Yanamarey glacier watershed showed significantly altered mass balance changes over time, with sustained negative mass balance (i.e., more melt and release of glacier water storage) resulting in higher and more variable discharge over time (Bury et al. 2011). The nature of this glacier melt alteration to stream discharge is largely a function of glacier coverage and watershed scale, however (Mark and Seltzer 2003). With less glacier coverage, either by comparing across different tributaries or extrapolating over time (i.e., Mark et al. 2010), annual stream hydrographs conform more closely to the shape of precipitation curves (e.g., Figure 2). Furthermore, contradictory research conclusions about how glacier recession ultimately impacts present and future Santa River discharge have been published based on different model studies and incomplete observations. These results indicate that mean annual total Santa River runoff will either remain almost unchanged, while discharge seasonality will be considerably amplified, or that there will be increases for several decades to come (Pouyaud et al. 2005; Juen, Kaser, and Georges 2007; Vuille et al. 2008). Nevertheless, our analysis of (incomplete) historical annual discharge for the upper Santa River at La Balsa showed statistically significant declines over multiple decades (Mark et al. 2010). These inconsistencies partly reflect the fact that Peruvian state-run stream stage and precipitation gauges fell into disarray after the hydroelectric plant was privatized during the 1990s (Carey 2010). By 2000 only three of an original set of twenty stations remained in operation or had been reactivated after an interruption of several years.

To address these inconsistencies and evaluate discharge changes for the entire Santa River watershed, we made new measurements of stream discharge from glacierized tributaries throughout the watershed, and from the main Santa River channel, to analyze for trends and test a model of glacier hydrologic evolution (Baraer et al. 2012). In collaboration with both researchers from the French Institute of Research and Development (IRD) and the Peruvian Office of Glaciology and Water Resources in the National Water Authority (ANA-UGRH), we deployed new prototype stream stage recording devices (Solinst^{TM} digitally logging pressure transducers) to either rehabilitate or extend the historic stream gauging station network. These devices were calibrated with discharge measurements (using traditional cross-sectional area and velocity profiling methods) at high and low flow conditions. We also reanalyzed new daily-resolution historical discharge data from seventeen stations beginning in 1952. Ultimately, only nine stations were selected for analysis after quality control to prevent interpretation errors (Table 1, Figure 1). We related trends to the evolution of glacier hydrological influence through the use of a water balance–based model that generates synthetic hydrographs from the watershed area, the glacierized surfaces, and the annual fractional loss of ice area as computed from previously published data

Table 1. Discharge measurement points, drainage basins, and discharge time series and interpolations

Station	Stream	Basin area (km^2)	Period of records	Number of years available	Number of years selected	Number of years with interpolations	Linear interpolation (%)	Polynomial interpolation (%)
Chancos	Marcara	221	1953–2009	48 (1)	40	22	2.0	4.6
Colcas	Colcas	237	1954–1999	46	37	15	1.5	4.2
La Balsa	Rio Santa	4768	1954–2008	55	50	21	1.13	3.2
La Recreta	Rio Santa	297	1952–2009	48 (2)	41	10	0	1.4
Llanganuco	Llanganuco	85	1954–2009	55 (1)	44	31	1.4	7.4
Los Cedros	Los Cedros	114	1952–1999	48	41	16	1.1	3.9
Pachacoto	Pachacoto	194	1953–2009	46 (2)	41	22	0.4	2.4
Paron	Paron	49	1953–2009	43	30	13	1.0	3.2
Querococha	Querococha	62	1953–2009	47 (1)	43	19	0.8	3.0

Note: The numbers in parentheses, where shown, are the number of years of data from the rehabilitated stations.

extending to 1930 photographs (Georges 2004) and two epochs of available satellite imagery (2001–2003 and 2009–2010) spanning the entire mountain range.

The results of our study are summarized in the conceptual hydrograph (Figure 3) that traces the evolution of discharge over time through four impact phases: (1) release of glacier storage by melt increases dry-season and yearly average discharges above initial equilibrium discharge level; (2) annual and dry-season average discharges continue to increase but slow as they reach a peak ("peak water"); (3) a pronounced decrease in discharges is accompanied by increasing variability of discharge; and (4) the end of the glacier influence as discharge flattens out at a lower equilibrium level, but with increased variability (i.e., Fountain and Tangborn 1985). Results from the phase allocation demonstrate that seven out of the nine studied watersheds are at Phase Three, La Recreta is at Phase Four, and Paron is still at Phase One. With an overall (linear regression–based) increase in variability and decrease in annual and dry season discharges, La Balsa exhibits characteristics of a watershed in Phase Three, having likely passed the peak water transition from Phase Two around the year 1970.

Alpine Wetlands Transformations

One key driver of coupled ecological and social change affecting water resources in the Santa River Watershed is related to biogeographic transformations taking place beneath the rapidly receding glaciers. The relatively flat glacial valleys of the high Santa River Watershed in the Cordillera Blanca serve multiple land use goals, which include biodiversity protection in Huascaran National Park, livestock grazing, recreation, and water supply (Byers 2000). In July 2011, several

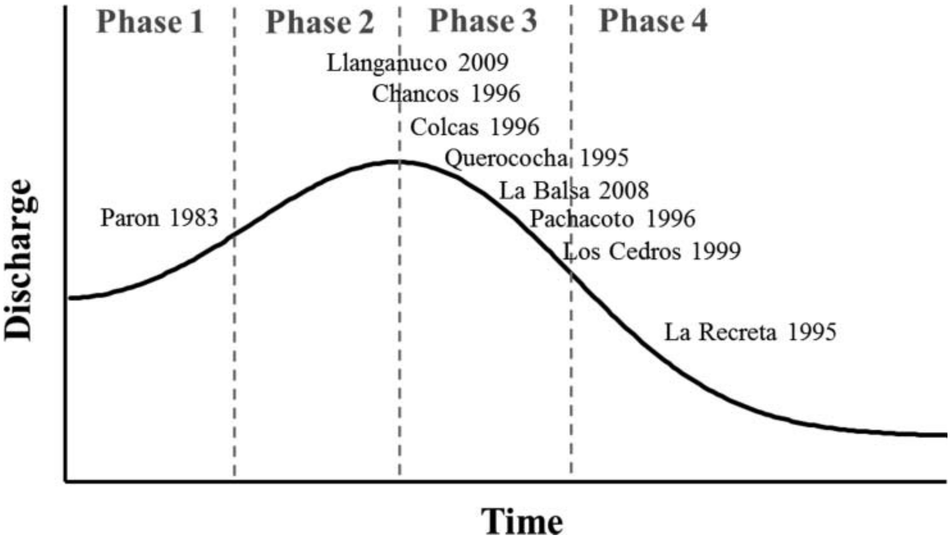

Figure 3. Conceptual hydrograph showing relative change in discharge (*y*-axis) over time (*x*-axis). This provides a synopsis of the discharge trend analysis results. Dates that appear following the station names represent the year for which the phase allocation is valid.

Table 2. Change in extent and landscape configuration of high-elevation wetlands in the Quilcayhuanca valley from 2000 to 2011

	2000	2006	2011
Wetland extent, ha (%)	191.7 (2.03)	141.93 (1.51)	158.67 (1.68)
Nonwetland extent, ha (%)	9,230.04 (97.97)	9,279.81 (98.49)	9,263.07 (98.32)
Number wetland patches	135	141	118
Wetland patch density (per 100 ha)	0.6211	0.6487	0.5429
Largest wetland patch index (%)	37.64	12.59	25.17
Mean wetland patch area (ha)	1.42	1.0066	1.3477
Isolation: Mean Euclidian nearest neighbor (m)	149.2265	122.824	142.8998

hundred sheep, horses, and cattle were observed in one case-study watershed, the Quilcayhuanca valley, where wetlands were studied (Figure 1) and where previous hydrological studies were done (Fortner et al. 2011). The valley floor is dominated by *Plantago rigida* and a variety of short grasses and sedges. The slopes of the valley have tussock grasslands admixed in some places with shrubs.

Change detection of the Quilcayhuanca wetlands was done using Landsat TM imagery from relatively cloud-free (<20 percent coverage) dry season dates: 21 July 2000, 8 September 2006, and 2 June 2011. The classification scheme was simplified from those developed during previous research in the general study area (Lipton 2008; Silverio and Jaquet 2009) to stress wetland–nonwetland differences. After trials with a supervised classification, a principal component analysis, and various vegetation indexes, best separation was obtained with an unsupervised clustering algorithm (ISODATA) using bands 1 through 5 and 7 (ERDAS Imagine 2011 software) and separating spectrally similar pixels into 100 classes (2000 and 2011) or 200 classes (2006). Visual interpretation was done using false-color images, combined with information on land cover from more than 100 Global Positioning System (GPS) points collected in July 2011. Accuracy assessment of the 2011 wetland–nonwetland classification was carried out using 200 random stratified points on the 15-m panchromatic band of a 28 July 2011 Landsat ETM+ image; the accuracy was highly acceptable with a producer's accuracy of wetland of 98.89 percent (nonwetland 90.0 percent); a user's accuracy of 89.0 percent (nonwetland 99.0 percent); an overall classification accuracy of 94.0 percent; and a kappa (KHAT) statistic of 88.0 percent (with a conditional kappa of 80.0 percent for wetland and of 97.78 percent for nonwetland). In follow-up fieldwork done in July 2012, the three largest areas of mapped change from wetland to nonwetland were verified to be nonwetland at that point in time. Several landscape metrics were computed for wetlands greater than four pixels in size with FRAGSTATS 3.3 (McGarigal et al. 2002).

If the wetland area responds directly to glacial retreat, then the expectation would be for area to track the shape of the hydrograph with a peak in discharge followed by a gradual decline (Figure 3). From 2000 to 2011, wetland extent in the Quilcayhuanca valley shrank by 17.2 percent (33 ha; Table 2). The 2006 classified image revealed that most of this overall loss occurred early in the decade, as there was a slight increase in wetland extent from 2006 to 2011. Wetland loss from 2000 to 2006 included an increase in habitat fragmentation, with smaller, more numerous, and more clustered wetland patches. By 2011 there were only 118 wetland patches, because many of the small isolated patches had vanished. The "from–to" changes illustrated in Figure 4 show that a number of processes were involved: From 2000 to 2011 much of the wetland loss in the valley bottoms was due to contraction, implying less total water moving through valley bottom substrates and possibly some cutoffs in surface flow. The valley sides and higher elevations had the loss of isolated wetlands, implying that springs or small streams once connected to uphill glaciers were drying out. There was some wetland expansion, spatially constrained to valley bottoms and presumably caused by new surface flows to those particular places.

Although Lipton (2008) reported a 330 percent increase from 1987 to 2001 in area covered by high-elevation wetlands in Huascaran National Park, we instead found much wetland loss, especially from 2000 to 2006. These findings and the hydrological modeling reported here imply that much of the water originating from glacier retreat has already moved downslope, temporarily increasing wetland area but now leading to its reduction. Our findings agree with observations of local people who reported that smaller streams and springs were becoming intermittent or

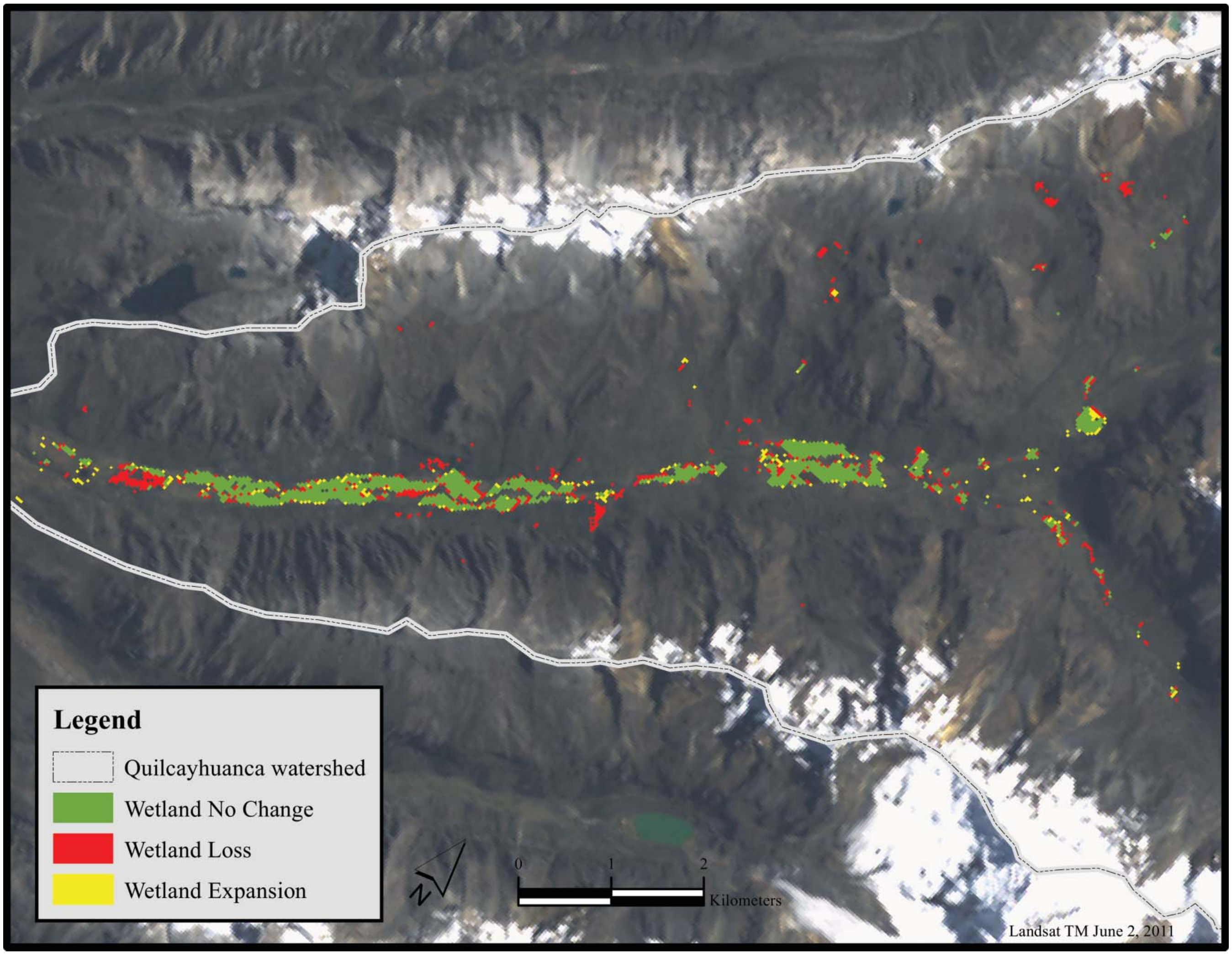

Figure 4. Wetland change in glaciated Quilcayhuanca valley from 2000 to 2011 based on TM satellite imagery. (Color figure available online.)

disappearing in Quilcayhuanca (Mark et al. 2010; Bury et al. 2011). Consequences for park managers would be that wetland habitat is now more limited in extent; the increased habitat fragmentation will further amplify negative biodiversity effects. The hydrological role of the wetlands in slowing throughflow will be altered (Buytaert, Cuesta-Camacho, and Tobón 2011). In addition, organic matter once maintained as peat under reduced conditions will begin to oxidize and decompose in drying soils of the upper valleys.

Smallholder Agriculture

Human agricultural activities across the Santa River watershed are also a key driver of coupled transformations affecting the Santa River watershed. Over the past fifty years, rural smallholder agriculture in the region has declined significantly. Although the total population of the Santa watershed increased, between 1970 and 2000, the rural population decreased by 10 percent. The total area of land cultivated in the Ancash Department also declined by 19 percent between 1972 and 2008. Agricultural areas adjacent to rapidly growing urban centers declined even more rapidly. For example, area utilized for agriculture near the city of Huaraz declined by 68 percent between 1993 and 2005 (Ministry of Agriculture 2010). Over the past few decades, as Table 3 illustrates, the cultivation of livelihood subsistence crops such as alfalfa, barley, potatoes, and wheat have consistently declined since the 1960s. Yet as smallholder crop production has declined, commercial and export crop production has increased. For example, asparagus, rice, and sugar production have increased significantly

Table 3. Decadal averages of harvested crops (in hectares) for the Department of Ancash, Peru, 1960–2010

	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009	% Change (1960s–2000s)
Alfalfa	16,758	18,959	10,431	4,662	6,039	−64
Asparagus	8.75	250	785	721	1,382	15,692
Barley	28,575	29,363	12,984	10,600	12,282	−57
Corn (Amarillo)	15,622	15,866	12,321	8,869	16,200	3.7
Rice	1,730	694	2,576	1,764	3,539	105
Potatoes	26,625	22,376	14,656	11,430	11,004	−59
Sugar cane	2,101	1,992	2,042	2,430	5,645	169
Wheat	28,098	30,381	19,117	13,892	16,310	−42

since 1960. Large agricultural projects along the coast account for the vast majority of these increases and are thus also largely responsible for increases in hydrologic demand for agriculture over the course of the past two decades. Overall, this transition in smallholder agriculture illustrates that although human populations in the upper watershed might have increased, new pressures on water resources are not simply a function of demographic changes as the complex political and economic factors transforming agriculture—and thus water use—in in the region have also been critically important.

Mining

Mining activities are also affecting water resources in the Santa River watershed, particularly because they have increased significantly during the past two decades (Bebbington and Bury 2009). Since 1990 more than 90 percent of all recorded mining claims were placed in the watershed. In 2010, there were three large mining operations in the watershed, six new planned projects, twelve mineral processing facilities, and 1,848 active mining claims covering approximately 52 percent (6,111 km^2) of the drainage area (Ministerio de Energía y Minas [Ministry of Education and Mines (MEM)] 2009).

Mining and mineral processing activities have become significant users of surface and subsurface water supplies in the watershed largely due to current extraction technologies such as cyanide heap leach gold mining and mineral concentration that require large quantities of water. In 2008 Barrick's Pierina gold mine above the city of Huaraz extracted 29.7 million tons of rock and 400,000 ounces of gold and consumed approximately 10 million cubic meters of freshwater (Barrick 2008). Mining also places indirect demands on water resources through hydroelectric power generation. For example, in 2007 Pierina consumed 296 GW of energy, which accounts for 18 percent of the Cañón del Pato output (1,606 GWH). Other forms of water demand from mining include new pressures on surface waters near new mineral processing activities.

The historical legacy of mining in the region has had a significant impact on water resources in the Santa River watershed, particularly on the quality of water resources for downstream populations. Water monitoring studies were conducted throughout the watershed in 1981, 1999, and 2000 (Instituto Nacional de Desarrollo [INADE] 2001). Of the contaminants that were measured in each study, current Peruvian water quality standards for either human and animal consumption or agriculture were exceeded on a frequent basis (Ministerio del Ambiente 2008). This includes arsenic (89 percent of measurements), iron (48 percent of measurements), lead (76 percent of measurements), manganese (53 percent of measurements), and zinc (24 percent of measurements). This toxic legacy poses critical challenges for future water resources planning and human well-being.

Potable Water Use

As the population of the Santa River watershed has increased since the mid-1900s, the number of water users and quantity of water used has also increased, even as glaciers have shrunk. Although comprehensive historical data are not available, case studies provide representative examples of increased Santa River water consumption over time. Given the past half-century of rural-to-urban migration, it is likely that urban populations have grown more than rural populations, and there has been overall population growth in the region since the 1940s as well. In Huaraz, the urban population has grown from 11,054 residents in the 1940 census (Instituto Nacional de Estadística e Información [INEI] 1947) to 96,000 in 2010 (INEI 2007; Mark et al. 2010). It is likely that such large population growth has corresponded with increased potable water use, although there are no data to precisely quantify per person water use over time. Evidence since 1999 from the water company EPS Chavín (2011) does, however, clearly show that total accumulated water delivery in Huaraz increased from 3.2 million m^3 in 1999 to 4.8 million m^3 in 2010. In the city of Caraz, potable water consumption rose from 502,000 m^3 in 1999 to 896,000 m^3 in 2010 (EPS Chavín 2011). The potable water came from glacier-fed Santa River tributaries. In addition, a significant amount of the potable water supply for the city of Trujillo also relies on Santa River water, transported to the city through the Chavimochic mother canal. Since this water plant opened in 1996, it has produced 300 million m^3 of potable water. In 2009 the potable water plant provided a monthly average water flow for Trujillo of 0.8 m^3/second (Chavimochic 2009). Overall, the use of potable water across the watershed demonstrates the complex interrelationships that exist among water management practices, population, consumption patterns, and water supplies from glacier runoff.

Hydroelectricity

One of the most important uses of water in the Santa River watershed for regional populations is the generation of hydroelectricity at the Cañón del Pato hydroelectric station located in the middle reaches of the Santa River watershed near the town of Huallanca. Millions of people depend on Santa River water for their household, industrial, and agricultural energy needs. The use of Santa River water for hydroelectricity generation has increased markedly during the last half-century, despite sustained glacier shrinkage and decreased glacier runoff during the same period. The Cañón del Pato hydroelectric station is the largest energy generator in the Santa River watershed, currently has an installed potential of 264 megawatts, and is the seventh largest hydroelectric station in Peru (MEM 2009). In addition to energy output, water use at Cañón del Pato has also increased from 45 m^3/second when the facility opened in 1958 (Ramírez Alzamora 1996; Electroperú 1980) to 79 m^3/second after 1999, when Duke Energy Egenor took control of Cañón del Pato (Duke Energy International 2001). Twelve additional hydroelectric stations in the Santa River watershed have been built since the 1950s, including three stations recently completed by the Chavimochic irrigation project in La Libertad that generate approximately 84 megawatts (Chavimochic 2009; MEM 2009).

Beyond increased water intake, the various hydroelectric companies have also managed Santa River water flow and increased water usage by using four large Cordillera Blanca reservoirs at Lake Aguascocha near Recuay, Rajucolta just south of Huaraz, Lake Paron near Caraz, and Lake Cuchillacocha near Los Cedros, which were constructed since the early 1990s, and the smaller, artificial San Diego Reservoir adjacent to the Santa River also near Los Cedros that was built in 2001 (Duke Energy 2002). Use of the reservoirs demonstrates how economic investment, engineering projects, and technology (human variables) can affect hydrology and help overcome water supply barriers. The reservoirs affect hydrology throughout the watershed, from the reservoirs themselves at the foot of glaciers to the Cañón del Pato plant intake, to Huallanca where the water is returned to the Santa River after generating hydroelectricity, to the Pacific where the Santa empties into the ocean. Models that neglect human initiatives, responses, and adaptation measures are thus inadequate because they neglect important human variables.

Coastal Irrigation

Two large-scale coastal irrigation projects use water from the lower Santa River watershed to irrigate extensive agricultural areas (Figure 1). Despite an overall decline in Santa River water flow, both projects have utilized increasing amounts of Santa River water since they were established. Since its canal construction after the 1980s, the Chinecas project expanded to capture enough Santa River water to irrigate approximately 30,000 ha of farmland in Ancash, benefitting 600,000 inhabitants. The project has generally been diverting at least 35 m^3/second from the Santa River (INADE 2003; CHINECAS 2004). The Chavimochic project also began canal construction in the 1980s and now plans to irrigate approximately 144,000 ha of agricultural land in La Libertad (Huaranga Moreno 2008; Gobierno Peruano 2011). In 2009, Chavimochic used 553 million m^3 of Santa River water, a dramatic rise in water use from the pre-Chavimochic era of the 1980s when there was no canal and thus no Santa River water use (Chavimochic 2009). The 174,000 ha of cultivated land that will be using the Santa River water stands in sharp contrast to a 1958 estimate of 7,500 ha irrigated in this same coastal region (Santa María Calderón 1958). Again, the marked increase in water use during the period of declining glacier runoff suggests that water use is not solely dependent on the amount of water in the Santa River, even though many future water use projections neglect to account for these human and technological variables (e.g., Vergara et al. 2007).

Conclusions

The multiple vectors of ecological and social change transforming the tropical Peruvian Andes that our research highlights are also leading to more complex and conflicted hydraulic governance across the Santa River watershed and in many other parts of Peru's arid Pacific slope. A wide variety of struggles over Santa River water have recently emerged that illustrate the broadening range of actors linked by these flows as well as the diverse, and often incompatible, geographies of development that these actors promote (Adger, Lorenzoni, and O'Brien 2009; Carey, French, and O'Brien 2012). In general, competing claims over water resources have burgeoned during the last two decades in a context of increasingly unclear and overlapping institutional and legal arrangements for water governance in Peru (Ore et al. 2009). In the face of these governance challenges that are linked to rapidly growing multisectoral hydrologic demand as well as real and perceived shortages of water supply during the dry season, Peruvian legislators passed a new water law in 2009 to promote a model of integrated management (Autoridad Nacional del Agua [National Water Authority] 2009). The law mandates the formation of watershed councils in large basins like the Santa to confront the functional interdependencies that increasingly link water users across scales (Brondizio, Ostrom, and Young 2009). In theory, the watershed councils will provide a platform for dialogue and collaboration between sectors, but their ability to represent diverse users with competing hydrologic needs and to shape and enforce policy remains unproven (Del Castillo 2011). This uncertainty demonstrates the need for new coupled natural–human investigations to further examine the ongoing politics and geography of water in the Santa watershed.

Meanwhile, our work suggests that glacier recession is accelerating in the Cordillera Blanca. Our studies indicate that the Santa River and many of its tributaries have crossed a critical transition with regard to water yield and now exhibit decreasing annual and dry-season discharge. The La Balsa station, which measures discharge from the upper Santa River, is undergoing a decline in dry season flow that probably began during the 1970s and will continue for many decades. If the glaciers were to melt completely, the dry season discharge could be as much as 30 percent lower than present. Our wetlands analysis of the Quilcayhuanca valley also indicates that peak discharge has already passed through this system, illustrating the cascading effects of this hydrologic transformation on biodiversity and habitat and suggesting that further decreases in high-elevation wetland areas are likely.

Yet, rather than seeing these hydrologic changes as driving predetermined water shortages or conflicts, our coupled analysis demonstrates that water use responds to a variety of social and ecological factors, including both physical changes in water supplies and the political economy of water management and use. In light of these findings, we conclude that future adaptation to changing hydrologic scenarios will depend as much on understanding and responding to social values and perceptions, economic development, and governance as it will on the physical supply of glacier runoff or river flows.

Notes

1. This research has been supported by several of these programs, including the National Science Foundation's Geography and Spatial Sciences Directorate, the National Science Foundation's Coupled Natural and Human Systems Program (CNH), and the National Aeronautics and Space Administration (NASA).
2. The collaborative research findings presented in this article draw on several years of field research and a wide variety of quantitative and qualitative methods. Whereas this article focuses on the combined synthetic findings of this research, more extensive discussions of our research methods can be found in Carey (2010), Mark et al. (2010), Bury et al. (2011), and Baraer et al. (2012).

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