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Toward hydro-social modeling: Merging human variables and the social sciences with climate-glacier runoff models (Santa River, Peru)

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SUMMARY

Glacier shrinkage caused by climate change is likely to trigger diminished and less consistent stream flow in glacier-fed watersheds worldwide. To understand, model, and adapt to these climate-glacier-water changes, it is vital to integrate the analysis of both water availability (the domain of hydrologists) and water use (the focus for social scientists). Drawn from a case study of the Santa River watershed below Peru's glaciated Cordillera Blanca mountain range, this paper provides a holistic hydro-social framework that identifies five major human variables critical to hydrological modeling because these forces have profoundly influenced water use over the last 60 years: (1) political agendas and economic development; (2) governance: laws and institutions; (3) technology and engineering; (4) land and resource use; and (5) societal responses. Notable shifts in Santa River water use—including major expansions in hydroelectricity generation, large-scale irrigation projects, and other land and resource-use practices—did not necessarily stem from changing glacier runoff or hydrologic shifts, but rather from these human variables. Ultimately, then, water usage is not predictable based on water availability alone. Glacier runoff conforms to certain expected trends predicted by models of progressively reduced glacier storage. However, societal forces establish the legal, economic, political, cultural, and social drivers that actually shape water usage patterns via human modification of watershed dynamics. This hydro-social framework has widespread implications for hydrological modeling in glaciated watersheds from the Andes and Alps to the Himalaya and Tien Shan, as well as for the development of climate change adaptation plans.

1. Introduction

Glacier shrinkage caused by climate change is likely to trigger far-reaching consequences for people living in and around mountain ranges worldwide due to ensuing water loss and streamflow variability, especially in dry times of the year. Various studies (e.g. Braun et al., 2000; Collins, 2008; Moore et al., 2009) show that, conceptually, glaciers produce an initial increase in runoff as they lose mass in conditions of continuous glacier retreat. The discharge then reaches a plateau called "peak water" and subsequently declines as the volume of glacial ice continues to decrease. This post-peak phase of water decline is characterized by decreases in the annual and dry-season discharge of glacier runoff, as well as simultaneous increases in discharge variability (Kundzewicz et al., 2007). The predicted trajectory of continued glacier shrinkage in the future has caused many researchers, policy makers, NGOs, and residents of glaciated mountain ranges worldwide to worry about potential dwindling of water supplies under various climate change scenarios (Akhtar et al., 2008; Bradley et al., 2006; Chevallier et al., 2011; Coudrain et al., 2005; Immerzeel et al., 2010; Kaser et al., 2010; Siegfried et al., 2012; Singh and Bengtsson, 2005; Sorg et al., 2012; Vergara et al., 2007). They worry that diminished and less consistent stream flow for hundreds of millions of people worldwide will generate problems for agriculture, irrigation, hydroelectricity generation, subsistence livelihoods, tourism economies, and also water quality as the dissolved and suspended load in the stream flow become more concentrated.

This paper contends that the only way to actually understand how climate change and shifting glacier runoff will affect human populations is to merge the social sciences with hydrology. This requires a consideration not only of the tools hydrologists typically bring to these studies, but also an investigation of the likelihood

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of water stress, changing water demands, problems of water allocation, and potential socio-political conflicts over water. A more accurate picture of climate change impacts on glacier runoff for downstream societies will result from a holistic, integrated analysis of both water *availability* (hydrology) and water *use* (social sciences). Understanding hydrological resource management and water use tends to fall into the domain of social scientists, who have the tools to analyze how and why societies use water in the ways they do. To date, hydrological models projecting both future water supply and usage scenarios below shrinking glaciers have only barely been explored, and mostly from a deterministic management perspective whereby water allocation scenarios are prescribed to balance demands and environmental watershed constraints (e.g. Water Evaluation and Planning model, WEAP) (Condom et al., 2012; Yates et al., 2005). Yet while the modeled relationship between climatic conditions and glacier mass balance may reveal the net quantity of runoff at the glacier snout, the farther water travels downstream the more human variables influence its flow, its management, and the actual use of the glacier runoff. Integrating the social sciences with hydrology can help illuminate how glacier runoff is actually utilized in downstream communities—and which factors influence that water use.

Hydrologists and other modelers have already recognized the importance of human variables in watershed dynamics. DeFries and Eshleman (2004) called for more attention to land use change in watershed dynamics, noting in particular how irrigation and urbanization alter water demands, how land use affects hydrological processes and water supplies, and how agricultural runoff and suburban development influenced water quality. To understand the role of land use in stream flow, they called for researchers to transcend traditional disciplinary boundaries and incorporate the social sciences. Harou (2009) offers the notion of a hydro-economic model to incorporate human values into hydrological models, thereby showing the importance of societal factors in the construction of models and the flow of water. Soboll et al. (2011) frame climate change impact research around the concept of global change because it combines climatic and societal forces undergoing change, thereby setting up a holistic multi-agent simulation that they believe more accurately captures interacting variables in combined social-ecological systems. Building on innovative, interdisciplinary studies like these will increase understanding of the impacts of changing glacier runoff on societies that inhabit mountain regions worldwide.

This paper aims to introduce the social sciences into hydrological modeling in glaciated basins by providing a historical case study from Peru's Santa River watershed that shows how human variables, along with the quantity of glacier runoff, affected both downstream hydrology (streamflow) and water use—and why these human variables must be considered among the underlying assumptions for climate-glacier-water models. Integrating historical data to simulate future scenarios helps avoid a tendency to model and construe future water scenarios through an environmentally deterministic lens (Hulme, 2011; Pahl-Wostl et al., 2008). The approach incorporates insights about coupled natural-human systems (Turner et al., 2003) and social-ecological systems (Folke, 2006; Young et al., 2006), as well as conceptualizing an integrated hydro-social watershed (Swyngedouw, 2009; Budds, 2009). Specifically, we identify the following five major human variables that must be considered for hydrological modeling because these forces have profoundly influenced water use over the last half century: (1) political agendas and economic development; (2) governance: laws and institutions; (3) technology and engineering; (4) land and resource use; and (5) societal responses. This hydro-social framework provides key conceptual insights into hydrological modeling that have implications beyond the Andes and even beyond glaciated basins.

2. Hydrology and humans in the Santa River basin

Peru's Santa River is one of the largest rivers by volume on the country's arid Pacific slope. It drains Peru's Cordillera Blanca mountain range, the most glaciated tropical mountain range in the world (Kaser and Osmaston, 2002). Approximately 70 percent of Cordillera Blanca glacier runoff discharges into the Santa River, which flows from the highlands to the Pacific Ocean (see Fig. 1). The Peruvian Glaciology and Hydrological Resources Unit's (UGRH) most recent inventory of glaciers shows that the range had 755 glaciers in 2003. But the coverage of these glaciers shrunk from 825 km^2 in 1930 to 723 km^2 in 1970 to 528 km^2 in 2003, a loss of 36% overall. Glacier runoff is responsible for 10–20 percent of total Santa River flow throughout the entire year. But during the dry season, glaciers contribute up to 66 percent of the water flow (Mark et al., 2010).

The Santa River flows north parallel to the Cordillera Blanca until it reaches Cañón del Pato, at which point the river turns west and descends rapidly though this narrow canyon before emptying into the Pacific Ocean (Fig. 1). Most of the upper section above Cañón del Pato is in the populated valley known as the Callejón de Huaylas with 267,000 inhabitants (Bury et al., 2011). Since 1958, electricity has been generated at the Cañón del Pato hydroelectric station, with the intake point at the opening of Cañón del Pato canyon and the generation house located 9 km downstream at Huallanca, where water is returned to the Santa River. Further downstream, the large-scale agricultural projects of Chavimochic and Chinecas have intake canals that divert Santa River water to their projects for irrigation, hydroelectricity generation, and drinking water. The population in the Santa River watershed, as well as in the adjacent watersheds served by the Chavimochic project, has grown markedly in the last half century and water demands have steadily escalated since the 1940s (Bury et al., 2013).

Most prior research on Santa River hydrology and Cordillera Blanca glacier runoff has focused primarily on the supply side of water resources. Researchers have sought to quantify water availability by trying to determine how glacier loss will alter Santa River hydrology (i.e., glacier melt that is not replaced in the annual hydrologic cycle is a net loss of water storage). Pouyaud et al. (2005) were among the first to report numerical model results for the glacierized tributary valleys of the Santa watershed. Juen et al. (2007) continued the study of highly glacierized catchments but utilized more adapted equations of mass and energy fluxes to account for water flowing through the system. Suarez et al. (2008) reported the use of a multi-reservoir based hydrological model to reproduce the outflows of the well-studied, highly glacierized Artesón/Parón basin. Baraer et al. (2012) modeled the hydrology of the whole Callejón de Huaylas area using a simple mass balance model. Additionally, Condom et al. (2012) advanced the WEAP model as the first hydrological model for the Santa River that integrates some human aspects of the watershed, such as reservoirs, canals, and hydroelectric facilities. Other attempts to include human factors into hydrological models have been announced for the region, but results have not yet appeared (López-Inojosa et al., 2012).

To understand the historical discharge and flow characteristics of the Santa River that are essential for constructing a hydrological model, historical observations of discharge have been acquired from government and private hydroelectric companies (e.g. Duke Energy) to compute trends over time, and these are related to the amount of glacier coverage (Mark and Seltzer, 2003). Given a relative lack of continuous discharge observations, hydrochemical tracers have been identified and used to quantify end-member contributions to discharge (Baraer et al., 2009; Mark and McKenzie, 2007; Mark et al., 2005). In recent assimilation of new observations from novel high resolution (15 min) discharge recordings,

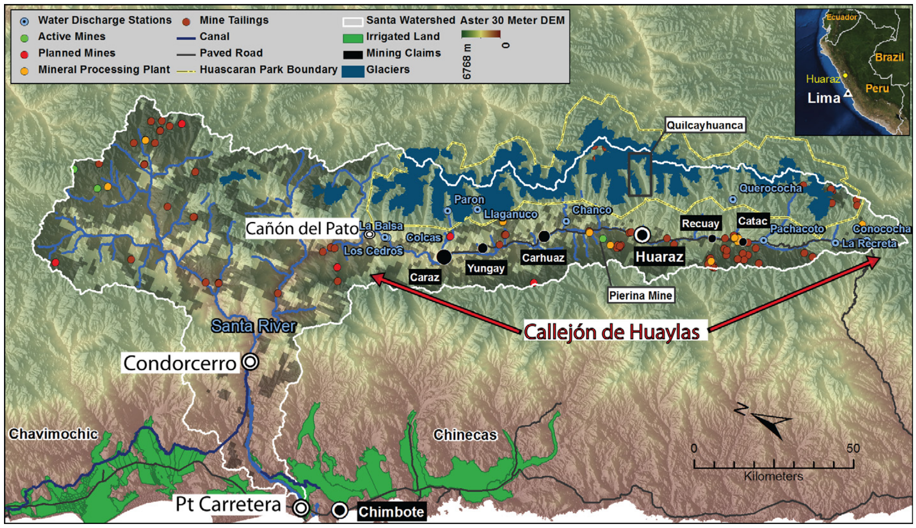

Fig. 1. Map of Santa River watershed.

basin-scale hydrochemical characterization, and model simulations of progressive glacier loss, researchers have demonstrated that the Santa River has likely passed the transient "peak water" caused as discharge from melting glacier storage provided higher flows but only for a time (Baraer et al., 2012).

However, water availability is characterized not only by the long term trends in river discharge, but also by the variability. Along with reduced river flows, decreased glacier coverage also results in more variable discharge—with greater ranges between maximum and minimum discharges—that more closely mimics the highly seasonal precipitation regime (Bury et al., 2011; Mark and Seltzer, 2003). Moreover, this Andean region is characterized by strong inter-annual fluctuations in precipitation. As the most pronounced cause of inter-annual climate variability on Earth, and centered off the Pacific Coast along Peru and Ecuador, El Niño events are a prime example. El Niño and La Niña are characteristic patterns of warm and cold Pacific sea surface temperatures that have been shown to impact stream flow and glacier mass balance in the Cordillera Blanca (Francou et al., 1995; Vuille et al., 2008). Another source of hydrometeorologic (including glacier mass balance) variability on a multi-decadal scale is the Pacific Decadal Oscillation, or PDO. The shift to positive PDO in 1976 (Giese et al., 2002) has been noted to accompany accelerated glacier loss and altered runoff in the western Andes (Casassa et al., 2009). In the Cordillera Blanca the PDO change ushered a shift to higher amplitude glacier mass balance changes less correlated to ENSO (Vuille et al., 2008).

Arguably the limits to human water usage are given by considering this dry season flow, since this is the minimum in the distinct tropical wet-dry cycle. Yet the annual variability is also most relevant for management of a full range of flow conditions, and thus captures climatic variability in total input precipitation. To illustrate the relative water availability over time in the Callejón de Huaylas, a time series of dry season Santa River discharge and annual variability is provided in Fig. 2. The measures of dry season (May–October) averaged discharge at La Balsa, located just above the intake at Cañón del Pato, and the coefficient of variability (Cv) are computed from monthly mean observations. The discharge anomaly (Q anomaly) is computed as a difference of the annual average from the multi-year average discharge. While Fig. 2 shows a decreasing trend in dry season Santa River discharge, it also reveals a continued increase in hydroelectricity generation at Cañón del Pato. This increasing megawatt output demonstrates how water-use productivity is not merely dependent on water availability, hence the need to analyze both water supply and usage.

Over the past 60 years, human factors have affected the regional hydrology at different levels in the Santa watershed—and sometimes in even more pronounced ways than the influence of glacier retreat. For example, Fig. 3 shows minimum dry-season average discharges for the 1969–1999 (historical) period for the two lowest discharge measuring stations of the watershed: Condorcerro situated a few kilometers upstream of the Chavimochic intake point and Puente Carretera that represents the last station before the Santa River reaches the ocean. During that period, the average dry season discharges were 45 m^3/s and 49 m^3/s at Condorcerro and Puente Carretera, respectively. In absence of major withdrawals in that historical period, the downstream station showed expected discharge values slightly higher than the upstream ones. The situation was drastically different in 2011 and 2012, when measurements were conducted at the two station locations using an Acoustic Doppler Current Profiler (ADCP). According to these direct measurements, the Santa River discharge at Puente Carretera dropped by 37 m^3/s in 2011 and by 44 m^3/s in 2012 from the discharge at Condorcerro, equivalent to a withdrawal of 82% and 90%, respectively. These dramatic losses in Santa effluent to the Pacific are unprecedented in historical records, and correspond to volumes of water that are nowadays extracted from the Santa for human use, especially in the Chavimochic and Chinecas irrigation projects whose intakes are located between the Condorcerro and Puente Carretera discharge measuring stations.

Measurable influence of human intervention on stream flows is not limited to the lowest part of the Santa watershed. Since the 1940s, after three Cordillera Blanca glacial lake outburst floods that killed nearly 6000 residents, the Peruvian government has controlled dangerous glacial lakes, partially draining and artificially damming 35 of them (Carey, 2010). In one case at Lake Parón in a highly glacierized catchment above the city of Caraz, lake drainage for security reasons stimulated the installation of floodgates to control the lake's outflow for enhanced hydroelectricity generation at Cañón del Pato. By regulating the lake's discharge, human interventions have influenced lake outflow variability. Fig. 4 shows that, even at the scale of monthly averages, the discharge variability for Parón has been reduced for both high and low flows. At the downstream Santa River discharge measuring stations and the Lake Parón outflow, human variables influenced both water availability and use.

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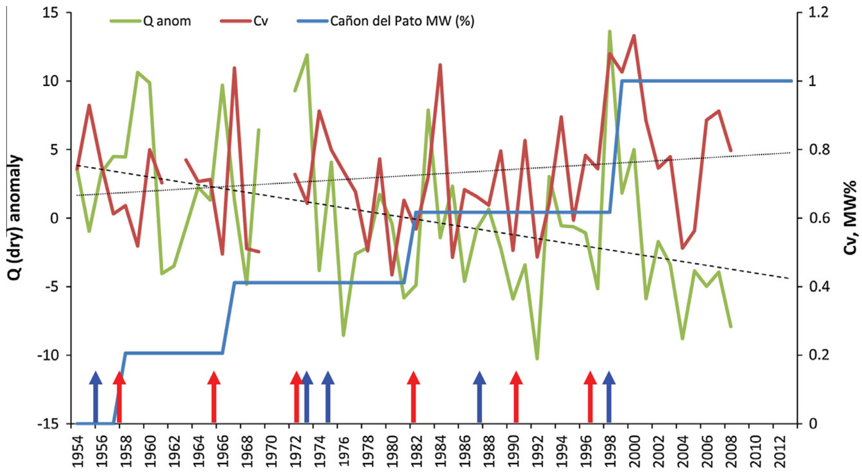

Fig. 2. Timeline showing representative metrics of Santa River availability and usage. Availability: Dry season discharge anomaly (Q anom, black) and annual coefficient of variability (Cv, light grey) for the Santa River at La Balsa (data from 1954-2008). The decreasing trend in dry season discharge (bold dashed line) is very significant ($p = 0.0023$), while the slightly increasing trend in Cv is not significant. Usage: Cumulative hydropower capacity (blue) at the Cañón del Pato plant as % of maximum capacity of 243 MW (1999). Also depicted for measure of natural precipitation variation: Vertical arrows indicate strong El Niño (black) and strong La Niña (grey) events, as recorded on the Ocean Niño Index (http://ggweather.com/enso/oni.htm).

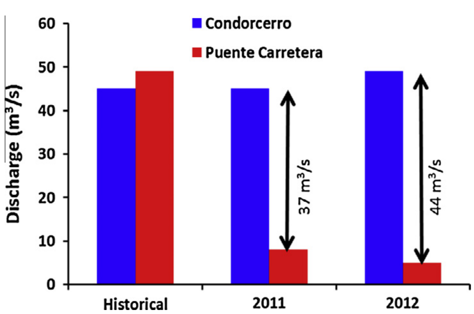

Fig. 3. Comparison between historical dry season minimum discharge records (1969-1999) and recent spot measurements upstream and downstream of the most important water intake installation in the lowest portion of the Rio Santa: Condorcerro (dark/black) and Puente Carretera (light/grey).

3. Human variables influencing models of water use and hydrology

Since the development of the first rainfall-runoff model in the nineteenth century, hydrological models have evolved to encompass a broad range of complexities and approaches (Bourdin et al., 2012). Despite major advances, the human factors remain under accounted for in many hydrological models, especially those assessing climate change impacts on mountain water resources and glacier runoff. Mountainous catchment simulation is already a challenging task in itself because the environment is characterized by highly variable morphology, soil, and vegetation types, as well as by pronounced temporal and spatial variations in climatic elements (Viviroli et al., 2009). These difficulties are exacerbated by the presence of glaciers in catchments. Moreover, tropical glaciers have unique characteristics that make some traditional

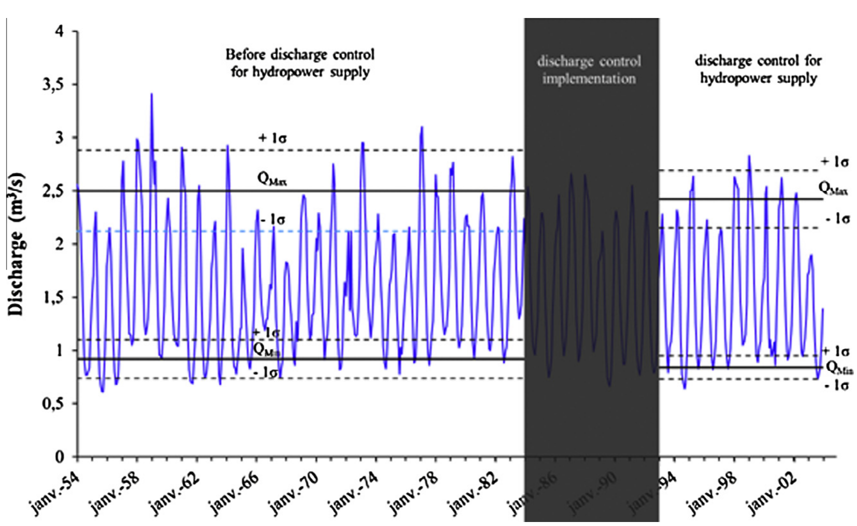

Fig. 4. Decrease in monthly discharge variability, Paron 1954-2003. Measured monthly discharges are compared to the yearly max and min average for the periods before and after the implementation of a discharge control system at the lake outlet. Max and min averages (black thick line) are presented with one standard deviation intervals (black dashed lines) representing discharge variability.

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modeling techniques such as degree-days unrealistic in tropical environments (Juen et al., 2007). Energy balance based models are more appropriate for glacierized tropical catchments but require large amounts of input data that often limit their application to small areas (less than 100 km^2). Modellers also have limited ability to upscale small-scale hydrological models to large-scale fluxes given the coarse availability of observations for validation (Pechlivanidis et al., 2011). Human influences, impacts, and changes in water management practices and demands are also very hard to quantify and model because of insufficient data and information (Nijssen and Schumann, 2012).

Such challenges and complexities have led to recent refinements and even some reinterpretations of the effects of glacier loss on water resources. In the greater Himalayan region, for example, observations of rapid glacier loss have offered dire forecasts about the effects of glacier loss on downstream water supplies (e.g. Kehrwald et al., 2008). But new research shows that glacier recession in the Himalayas is not as uniform or rapid as previously suggested (e.g. Cogley, 2012) or that local residents rely more on snowpack than glaciers for potable water (McDowell et al., 2013). The US National Academy of Sciences (2012) concludes that "the contribution of glacier meltwater to water supply in the Hindu Kush Himalayan region may have been overestimated in the past" because of the varied landscape, divergent climate change impacts across the region, and failure to differentiate between snow and glacier contributions to water supplies, among other issues. The report also says that groundwater depletion and increasing human water use (not glaciers) will reduce low-elevation water supplies, thus signaling that human forces intersect with climate, glaciers, water, and topography to influence downstream hydrology.

By linking hydrology and the social sciences, we move beyond theoretical, climatically-determined simulations of water supplies below shrinking glaciers to account for forces that influence actual water use and management in downstream communities (see Table 1). These human variables include how politics and economic development shape water use practices, how land use changes affects hydrology, how technology and engineering alter both water dynamics and the capacity for water use, and how new water laws affect stream flow as well as allocation and demand. Grounding the data in "real world" contexts with details from historical trajectories is essential because, as Le Masson and Nair (2012) assert, any analysis of environmental change must incorporate not only climate data and models, but also local perceptions and knowledge, land use practices, and development trends. Contextualizing Santa River water use and management in this historical case reveals that water use has significantly expanded in the last half century even as water supplies have declined (see Fig. 2 and Table 1). We thus contend that various social factors, though largely overlooked in existing models, profoundly shape the ways societies will perceive, frame, and grapple with the influence of climate change and glacier retreat on hydrological resources.

Although we have identified five human variables that influence both hydrological conditions and water use, we recognize complexities and challenges associated with the identification of these variables. For one, factors within particular categories are often interrelated, overlapping, and co-productive in reality. Based in social relations, these factors are inherently dynamic and unpredictable. The factors also display cross determination and thus are constantly influencing one another directly and through feedbacks. Additionally, knowledge, culture, perceptions, and values shape how people respond not only to changing water supplies but also to new water engineering projects, government water laws and policies, hydroelectric company activities, and international consumer preference for agricultural products grown with glacier-fed irrigation canals. Many local residents in glaciated watersheds have already begun to perceive the impacts of shrinking glaciers and dwindling water supplies (Brugger et al., 2013; Bury et al., 2011; Mark et al., 2010). Responses, however, vary substantially. Some communities in response to private company water management and weak governance amidst glacier retreat have gone so far as to seize control of a local reservoir (Carey et al., 2012). Others place their faith in spiritual forces to maintain future water supplies (Drew, 2012). These characteristics make human variables particularly difficult to handle in models and likely contribute to the dearth of efforts to include them in existing modeling efforts. Nevertheless, these variables have fundamental impacts on how water is channeled, appropriated, and used in socio-ecological systems.

3.1. Political agendas and economic development

Political agendas and economic development have exerted considerable influence on both water use and flows of downstream glacier runoff in the Santa River watershed since the 1940s. First, Import Substitution Industrialization (ISI) was an international political-economic agenda that emerged following the worldwide economic crisis of 1929 and was particularly important in Latin America from the 1940s to the 1970s. The goal of ISI was to make Latin America and other countries in the developing world (Global South) more independent from Europe and the United States, hence the substitution of imports from abroad with nationally produced goods and resources. In Peru, the country embarked on an ambitious program to build iron and steel industries, expand ports and exports, increase roads and railroads, and become more energy self sufficient through the construction of new hydroelectric stations. In 1943, the country began construction of the Cañón del Pato hydroelectric facility, which tapped the glacier-fed Santa River to provide energy for coastal development. The hydroelectric

Table 1
Major turning points, listed chronologically, in Santa River hydroelectricity and irrigation development. Key for Drivers/Variables: PAED = political agendas and economic development; G = governance (laws and institutions); TE = technology and engineering; LRU = land and resource use; SR = societal responses.

Event	Date	Water use impact	Driver/variable
Cañón del Pato construction	1943	None	PAED, G,TE
Cañón del Pato opened	1958	50 MW generated; 45 m^3/s used	TE
Cañón del Pato expanded	1967	100 MW generated	TE
Chavimochic established	1967	None	PAED, G
Cañón del Pato expanded	1982	150 MW generated	TE
Chavimochic Phase 1	1986	Diverted up to 105 m^3/s from Santa; 58,000 ha irrigated	PAED, G, TE
New reservoirs (Parón, Cullicocha)	1992	65×10^6 m^3 total storage	PAED, TE
Chavimochic Phase 2	1993	Continued 105 m^3/s Santa diversion; 23,000 ha irrigated	PAED, G, TE
Cañón del Pato expanded	1999	243 MW generated; 72 m^3/s used	PAED, G,TE
New reservoir (San Diego)	2001	665,000 m^3 storage	PAED, TE
Cañón del Pato expanded	2002	263 MW generated; 72 m^3/s used	TE
Reservoirs opposed (Shallap,Auquiscocha)	2003	Not quantified, not implemented	SR
Reservoir lost (Parón)	2009	Lost up to 5 m^3/s and 50×10^6 storage	SR, PAED

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station opened in 1958 at 50 MW capacity. This was the first major hydroelectric facility in the Santa watershed, and today it is the seventh largest hydroelectric station in the country. Currently, the Cañón del Pato plant requires 72 m^3/s of water to generate at full capacity (263 MW). During the dry season when Santa River streamflow drops to 30–40 m^3/s, the station relies on artificial reservoirs to augment water flow into the facility (see Section 3.4 below). The growth in water use stemmed not from changing water supplies in the river, but rather from the new international ISI political-economic agenda that put coast-centered development plans into action with water from highland Peru.

Second, a national-level impetus for increased agricultural development and export-oriented agriculture in the 1980s was implemented by the American Popular Revolutionary Alliance (APRA) political party, thereby demonstrating how a national political-economic agenda could also influence the flow of Santa River water. Longstanding plans for the Chavimochic irrigation project to divert Santa River water into adjacent watersheds with a 267 km mother canal from the Santa to the Chicama Valley north of Trujillo became a reality once APRA leader Alan Garcia became president in 1985 and rewarded his support base in La Libertad and Trujillo. Construction of the Santa River intake with a capacity of 105 m^3/s began in 1986 (Chavimochic, 2009; Landeras Rodríguez, 2004). This significant alteration in river flow and expansion of water use to irrigate up to 81,000 ha of agricultural land—as well as generating more than 16 MW of electricity and providing drinking water for the city of Trujillo—did not emerge because of increased glacier runoff. In fact, glacier runoff into the Santa River decreased during this same period (Baraer et al., 2012). Chavimochic irrigation, hydroelectricity generation, and drinking water provision were thus driven by human variables: the APRA-focused agriculture and irrigation in La Libertad. Further, these political-economic variables shaped hydrology at all points downstream from the Chavimochic intake because the diversion withdraws a significant amount of water from the Santa River that is not returned (Fig. 3).

Third, the neoliberal era of international economic development and related policy making triggered profound impacts on water use in the watershed after the 1990s. As part of President Fujimori's structural adjustments that involved the privatization, decentralization, and deregulation of industries and social services throughout Peru, he privatized the Cañón del Pato hydroelectric station in 1996, which led to its acquisition by the US multinational company Duke Energy International. Once managing Cañón del Pato, Duke expanded its water use at the hydroelectric station from 48 m^3/s to 72 m^3/s. The company also increased hydroelectric generation from 150 MW to 263 MW, especially after building several new reservoirs to regulate the Santa. Overall, neoliberalization led to the restructuring and privatization of Peru's energy sector in the 1990s and ultimately to a 57 percent boost in electricity generation at Cañón del Pato. A typical hydrological model estimating downstream water volumes based only on glacier mass balance and runoff would not be able to detect increased water use and hydroelectricity generation without considering these human variables influencing the station's capacity. Correspondingly, it would be an oversimplification to predict increased hydro-social infrastructure construction on demand variables like population or GDP.

3.2. Governance: laws and institutions

Governance—in the form of shifting laws and institutions—is another variable that has profoundly affected hydrology and water use. In 1943, the national government passed a law to create the Peruvian Santa Corporation (CPS) that ultimately built Cañón del Pato, expanded irrigation on the Ancash coast, promoted mining, and invested in infrastructure development in and around the Cordillera Blanca and Santa River watershed. Without the CPS, the hydroelectric station would not have been constructed when it was. Management of the station changed in 1973 when Peru's military government dissolved the CPS and wrote legislation to create a new national energy company, Electroperú, that managed Cañón del Pato (among other facilities) until 1996. The creation of Electroperú stimulated hydrologic changes in the Santa watershed because the company invested in reservoir construction, transforming Lakes Parón and Cullicocha into water-regulating reservoirs in 1992 with capacities of 50×10^6 m^3 and 15×10^6 m^3, respectively (Unidad de Glaciología e Hidrología, 1990). Operating Lake Parón, for example, as a reservoir to assist in peak-hour energy production in the dry season significantly altered the flow regime in the Llullán River, which connects Lake Parón to the Santa River. While the maximum average discharge in the Llullán River for the 30 year period from 1954–84 was 2.55 m^3/s, Electroperú's license permitted them to discharge up to 8 m^3/s, which was reduced to 5.5 m^3/s in 2006 while Duke Energy was operating the station. At both levels there were destructive consequences for downstream users. In fact, complaints about Duke Energy's management of the outflow from Lake Parón have come from a variety of stakeholders as a result of the company's inconsistent water management during the past decade (Carey et al., 2012; Lynch, 2012). Another law, the 1992 Electricity Concessions Law, had important consequences for Santa River water use because it provided the groundwork for hydroelectricity privatization, which after 1996 brought Duke Energy to Cañón del Pato. Moreover, Duke Energy benefited from a new law passed in 2001 that increased the company's water right from 48 m^3/s to 79 m^3/s.

Governance factors and new laws have also influenced water use and hydrologic flows related to export-oriented agriculture in the Chavimochic and Chinecas irrigation projects. In 1967, Peruvian Law No. 16667 created the Special Project Chavimochic (PECH), and the 1980 law D.L. 22945 identified Chavimochic as a "preferred national interest." Once operational in 1990 due to APRA political support, Chavimochic's 88 km mother canal diverted up to 105 m^3/s of Santa River for irrigation (Gobierno Regional La Libertad, 2012). The 1991 Legislative Decree No. 653 further enhanced Chavimochic because the law dedicated national government funds to the development of agricultural sectors more broadly. The law also removed previously established limits on landholding size, which allowed large companies to purchase extensive tracts of desert land in the Chavimochic region that would be converted to export agriculture using irrigation water diverted from the Santa River. Institutional and legal support for Chavimochic led to the construction of an additional 66 km of the mother canal, which expanded irrigation by 12,700 ha on new land and improved 10,300 ha. Overall, both specific laws and changes in the political parties controlling national politics have fueled the growth (or stalling) of the Chavimochic irrigation project, which diverted significant water out of the Santa River watershed into neighboring basins.

Shifting national water laws have also affected water management and use, such as the 1969 water law that turned water into a national resource, put the central government in control of water rights, and redistributed water allocation not only in the Santa basin but throughout Peru (Oré, 1998; Oré et al., 2009). But it is important to recognize that there was always a gap—what modelers often refer to as a "lag"—between the laws passed in Lima and the actual practices of water management. Water laws and actual governance, in other words, are distinct. This same gap continues today in response to the 2009 water law, which despite being almost 4 years old remains in its early stages of implementation in many rural areas of Peru. While it may be too early to detect actual impacts of this recent law on Santa River streamflow or water use, through formalization of rural farmers' water rights and promotion of the paradigm of Integrated Water Resource Management, the law sets the stage for a profound shift in Santa River water management practices. Factoring in these various gaps between laws and practice, as well as the differences between authoritarian (President Odría in the 1950s, Velasco from 1968 to 1975, and Fujimori in the 1990s) and democratic regimes, reveals that the laws and institutions affecting Santa River hydrology change significantly over time, altering hydrology as well as the landscape of water users, who put distinct and sometimes radically different constraints or expansions on Santa River water use.

3.3. Technology and engineering

Technology and engineering can increase water use capacity or divert water as it flows through a watershed. The implementation of technology and engineering depends on available economic resources and political support (at local, regional, and national levels), as well as the existing state of global technological capacity. Along the Santa River, hydroelectricity generation has escalated from zero megawatts before the facility opened in 1958 to 263 MW today. Part of the increase stems from additional water intake, but also from the installation of new turbines. When Cañón del Pato opened in 1958, its capacity was 50 MW. It increased output to 100 MW in 1967 and to 150 in 1982. Throughout that time, the company's water right was maximized at 48 m^3/s, thereby showing how technological improvements—rather than changing streamflow or an increase in Cordillera Blanca glacier runoff—influenced hydroelectricity generation. Duke Energy did expand its water right to 79 m^3/s in 1999, which helped boost generation to 243 MW at that time, with a subsequent increase to 263 MW. Production during the dry season is challenged, however, by river flows that typically drop to 30–40 m^3/s. Overall, it was the installation of new stations and new turbines at Cañón del Pato to enhance the watershed's hydroelectric capacity that most affected how water was exploited downstream from the glaciers.

To partially address the dry-season deficit in water demand, Duke relies on reservoirs the company built over the last decade. It built the San Diego Reservoir, a two-basin complex along the Santa River just above Cañón del Pato that holds more than 665,000 m^3, and converted Lakes Rajucolta and Aguascocha into water-regulating reservoirs in the upper Santa River catchment. Lake Parón was only transformed into a reservoir with the construction of a 1.2 km drainage tunnel through solid bedrock (Carey, 2010). In conjunction with the Santa's flows, these highland lakes can be used to refill the San Diego Reservoir on a daily basis, which can be emptied at volumes up to 50 m^3/s, thereby allowing the plant to operate at full capacity for three hours at a time (Duke-Energy, 2002; Hernández Espinoza, 2006). While this system has been important in addressing growing energy demand, it has changed the dry-season discharge regime of the downstream Santa River considerably, not in terms of total volumes but in the timing of flows. More than doubling the river's flow for several hours in the evening during peak-energy demand has proven problematic for some downstream irrigators, who have requested that Duke Energy construct a compensatory regulating reservoir below Cañón del Pato at Huallanca where the water is returned to the Santa River (ANA, 2011).

A similar analysis of the impacts of technology and engineering on hydrology is essential for understanding irrigation demands in the Santa River basin. For example, engineers working on the Chavimochic project constructed the intake to withdraw up to 105 m^3/s of Santa River water, as well as building 154 km of the mother canal. Without these engineering projects that diverted Santa River water, streamflow below the intake would have been much higher. While Chavimochic is a crucial example of this irrigation infrastructure, there is also the Chinecas coastal irrigation project, as well as small-scale irrigation canals that subsistence farmers, individuals, and companies utilize throughout the Santa River watershed. Consequently, canal capacity is a crucial determining factor for whether water stress will result from glacier shrinkage under future climate change scenarios, even though this variable has not been incorporated into existing models.

3.4. Land and resource use

Changes in land and water resource use have also altered water pathways in the greater Santa River watershed. One important shift in water resource use across the region is due to the rapid increase of mining activities during the past two decades (Bebbington and Bury, 2009; Bury et al., 2013). Since 1990, more than 90 percent of all mining claims were placed in the Santa watershed (See Fig. 5). In 2010, there were three large mining operations in the watershed, 6 new planned projects, 12 mineral processing facilities, and 1848 active mining claims that covered approximately 52% (6111 km^2) of the drainage. Most of the active mines

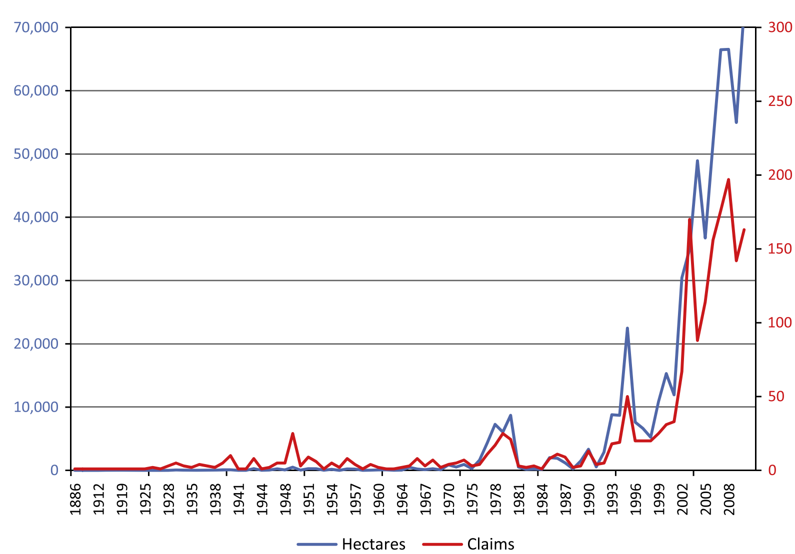

Fig. 5. Mining Claims in the Santa Watershed 1886–2011.

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include global mining corporations such as Barrick, Milpo, Placer Dome, Lumina Copper, Anaconda, and Gold Fields (MEM, 2010). These new mining and mineral processing activities have become significant users of water resources in the watershed because current extraction technologies such as cyanide heap leach gold mining, mineral flotation and concentration require large quantities of water. For example, in 2008 Barrick's Pierina cyanide heap leaching gold mine—the largest mining operation in the watershed—extracted 29.7 million tons of rock and utilized approximately 10 million cubic meters of fresh water to produce 400,000 oz of gold (Barrick, 2008). Each ounce of gold thus required 25 m^3 of water. These and other mines are diverting water from the Santa River and its tributaries, while also causing understudied and poorly understood impacts on water quality in these catchments. Given the increased mining claims and operations since neoliberal reforms in the 1990s, significant new water use has occurred in the last two decades while Santa River stream flow has declined.

Shifting agricultural production is another important factor affecting water resource use in the Santa watershed. While the total population of the watershed has increased over the past three decades, the total area of land cultivated in the Ancash Department declined between 1972 and 2008 (MINAG, 2010). Subsistence crops such as alfalfa, barley, potatoes, and wheat have declined consistently during this period; yet, as shown in Fig. 6, the production of commercial and export crops such as asparagus, rice, and sugar cane has increased rapidly (Bury et al., 2013). These transformations in agricultural activities shift where water flows in the watershed, where irrigation is needed, and where in the watershed water is diverted. Cultivation in the coastal desert with water-intensive export crops (Rundel et al., 1991), such as at Chavimochic (Bury et al., 2013), has increased evapotranspiration-related water use and, as previously mentioned, diverted Santa River water for these changing land-use practices.

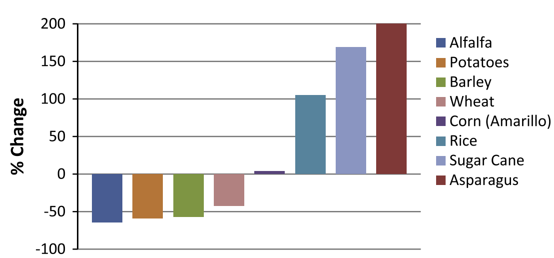

Fig. 6. Percentage Change in Agricultural Production in the Department of Ancash between 1960 and 2000.

Other land use patterns have influenced hydrology. Demographic changes and urbanization in highland towns and cities have led to an increase in urban water use on the order of 150–180% (Bury et al., 2013). The highest elevations of the Cordillera Blanca, including most of its glaciers, exist within Huascaran National Park, established in 1975 (Young and Lipton, 2006; Young and Rodriguez, 2006). The park is managed for biodiversity conservation and the role of the glaciers as sources of ecosystem services is recognized, thus demonstrating how even national park creation as a form of land management has implications for both hydrological conditions and the use of glacier-fed rivers and streams. All of these examples of land use change have implications for water transfers, but are caused by interactions of regional and global social and biophysical processes.

3.5. Societal responses

In addition to the national and international human variables described above, more localized societal forces such as local residents' responses to new and existing projects or laws also affect both water use and hydrology. The impacts of these societal responses are particularly evident in the case of recent reservoir construction. Since the late 1990s, Duke Energy has attempted to build 5 new streamflow-regulating reservoirs at Lakes Auquiscocha, Shallap, Rajucolta, Aguascocha, and the artificial San Diego Reservoir. Additionally, the company has continued to manage 2 existing reservoirs (Lakes Cullicocha and Parón). Of these seven reservoirs, three were contested and either defeated or seized by local residents: Auquiscocha, Shallap, and Parón. Residents of Hualcán near Lake Auquiscocha challenged the reservoir in part due to their cultural values and beliefs that construe the lake as a sacred part of their surroundings (Carey, 2010). Duke Energy also attempted to transform Lake Shallap above the region's largest city, Huaraz, into a reservoir to regulate Santa River water flow rates. In this case, residents resisted the project in 2003 because they feared the new reservoir with much more water than the existing lake would create a significant risk of glacial lake outburst floods, thereby endangering tens of thousands living in Huaraz.

At Lake Parón, which was initially transformed from a lake to a reservoir by Electroperú in 1992, Duke Energy began managing the reservoir in the late 1990s but has clashed with residents for more than a decade. Various local stakeholders have protested against what they considered to be the company's mismanagement of the lake, especially related to the timing and quantity of its water releases. A combination of local values, environmental impacts, irrigation needs, cultural perceptions, frustration with government management, concerns about future water supplies, and

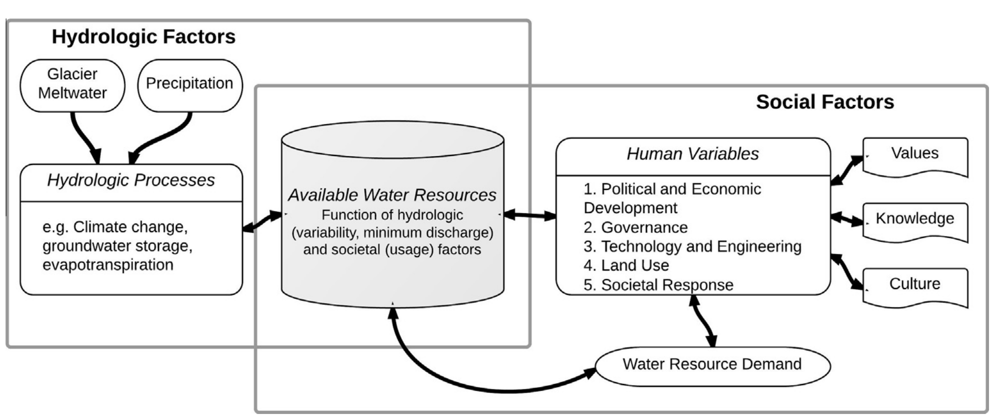

Fig. 7. Interaction of hydrologic processes and human variables influencing water resource availability, while also demonstrating the interaction of socio-ecological forces in water use and water availability.

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opposition to a foreign company fed local resistance to Duke's operation of Parón (Carey et al., 2012). These local constituencies seized control of the reservoir in 2008, leading to an ongoing conflict over water flow rates from Parón. For several years, water releases in the dry season from Parón have been limited at approximately 1 m^3/s instead of the previous 5.5 m^3/s, demonstrating how societal responses—not only at Parón but also at Shallap and Auquiscocha—affected both downstream water supplies and water usage. In the end, only about half of the reservoirs that Duke pursued were constructed due to local opposition.

4. Discussion

Water management, we have shown, is an issue of distribution, not just glacier size and runoff rates. More importantly, this case study reveals that the drivers of changing water use do not map well onto the history of stream flow patterns and water availability, which is the more common and often sole focus in hydrological models of glacierized basins under climate change scenarios. Notable shifts in water use—including major expansions in hydroelectricity generation, large-scale irrigation projects, and other land use practices—did not stem from changing glacier runoff or hydrologic shifts, but rather from human variables such as political agendas and economic development, new laws and institutions, technology and engineering, changing land use, and societal responses to all of these other forces.

The hydro-social framework for modeling that we provide depicts not only the quantity of water flowing into a hydroelectric station or irrigation canal, but also how, why, and when the amount of hydroelectricity generated at that facility or hectares irrigated have changed (see Table 1 and Fig. 7). Of course there is a significant challenge resulting from the different response times of human and natural variables, including leads and lags that confound deterministic cause-and-effect links between supply and demand. Human infrastructural modifications facilitating altered water use are subject to socio-economic factors that are offset in timing from natural forcings impacting water availability. These operate at widely divergent frequencies, from the relatively instantaneous (e.g. glacial lake outburst floods, earthquakes, ENSO) to the multi-decadal (PDO) and secular changes of climate change (glacier melt). Nor can human behavior or cultural values be easily predicted or simulated in future projections. We are concerned both with how much water is available to generate hydroelectricity or irrigate crops as well as the factors that influence the capacity of a hydroelectric station or irrigation canal—the variables that lead to expanded water use regardless of how much water is available.

While our study shows the importance of merging the social sciences and hydrology to understand watershed and glacier runoff dynamics, the next step, of course, is to design a hydrological model that can actually incorporate these human variables. Modelers could follow several paths to integrate human factors into projections of water resources. The easiest way is possibly to use water demand scenarios as model inputs. These scenarios are built independently from the hydrological model, based on realistic assumptions about how human factors evolve. The Intergovernmental Panel on Climate Change (IPCC, 2000) carbon emissions scenarios is one of the well-known examples of such a modeling method. Several benefits can be expected from the use of these scenarios. For example, scenarios allow for integrating human factors without increasing the complexity of hydrological models. They also offer full transparency for tracing scenarios' justifications. A drawback, however, is that demand scenarios lack the dynamic interaction between hydrological and water-use parameters, not allowing reactive human adaptation measures to be simulated.

Another modeling option involves integrating decision algorithms for the different human factors into the model. Used primarily in hydrological network management simulations (e.g. Park et al., 2007; Senthil Kumar et al., 2013), these models allow simulations of interactions between decision making and hydrological responses, and vice versa. Extending this type of modeling to include social, cultural, political, and economic variables, however, makes the development of accurate decision algorithms extremely complex, and transparency in the decision-making processes is often lost. Interactive modeling represents another alternative to the two previous methods. These models allow interaction between both the evolution of human factors and hydrological characteristics (e.g. Nolin, 2012; Zhang et al., 2013). They offer the possibility of multiple iterative simulations where human variables or management options can be gradually tested and virtually modified based on previous simulation results. While these possible modeling approaches offer ways to merge human variables and the social sciences into the existing world of hydrological modeling, we also recognize (and hope) that the development of entirely new approaches to modeling will also emerge as trans-disciplinary collaboration occurs and researchers from across disciplines recognize the importance of social sciences in hydrology.

5. Conclusions

This paper's merging of the social sciences with hydrology to analyze the intersections between water use and water availability enriches not only the understanding of glacier runoff and hydrology, but also the implications of climate change for human societies and the types of adaptation agendas that might be pursued. We have shown by critical review of historical realities that water runoff originating in glacierized watersheds conforms to certain expected trends predicted by models of progressively reduced glacier storage. However, human realities shape the legal, economic, political, cultural, and social forces that ultimately influence water usage patterns via human modification of watershed dynamics. The future trajectory of water availability will feature increased variability, and therefore more uncertainty, risk, and vulnerability. Physical science is limited in the ability to diagnose the nature of resulting water access, and also limited in capacity to inform social response. Hence closer adherence to historically informed social science variables is essential in modeling scenarios of water use.

Discerning all of these issues requires collaboration among social scientists and hydrologists. Moreover, it is useful to plan for climate change adaptation agendas, to produce more accurate hydrological models, to show how hydro-social or social-ecological systems are dynamic and not static, and to recognize how science and engineering are place-based, not easily modeled without in-depth social scientific and scientific investigations. Milly et al. (2008) asserted provocatively that stationarity was dead in part because of ongoing global climate change and transitory regional climatic conditions, but also because of ever-changing, dynamic human impacts on hydrology, such as through water infrastructure, channel diversions, drainage projects, and changing land-use practices. Other researchers such as Budds (2009) show the limitations of hydrological models in the context of changing policies and institutions, especially those stimulated by neoliberalism. This Peruvian case study demonstrates the need to address these concerns particularly for glacier runoff under climate change scenarios. It also reinforces Gober's (2013) point that there is only limited capacity to predict climate change, and therefore the emphasis in water management planning should shift to human actors and social dynamics in the water system. Our findings also confirm what Braden et al. (2009) emphasized: that the hydrosphere and social sphere must be analyzed in tandem and across space and time in order to understand watershed dynamics and be able to forecast water scenarios for the future. Uncovering the human variables at work in the Santa River shows the necessity of merging water use and water availability analyses. Moreover, the case also suggests that each watershed in each spatial and temporal context will be distinct. Science, engineering, and modeling should thus be tied to particular places and contexts (Finnegan, 2008; Livingstone, 2003; Reuss, 2008).

While it is critical for hydrologists to understand the importance of integrating the social sciences and human variables into hydrological models, the burden of collaboration and cross-disciplinary interaction does not of course rest solely on water scientists and engineers. In fact, social scientists have often failed to reach out and pursue collaborative relationships, instead offering critiques of science, technology, and engineering or modeling without proposing solutions. The funding structure that allows scientists to build labs and acquire grant funding is certainly one obstacle that social scientists face (Braden et al., 2009). But there also needs to be a cultural shift across the water-related disciplines—not simply, and hegemonically, folding the social sciences into hydrology, but rather through systematic efforts by various disciplines typically divided into the social sciences and environmental sciences to collaborate and find new ways of making their data intersect. This special issue on social sciences in hydrology should help achieve that goal.

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