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Tracing Increasing Tropical Andean Glacier Melt with Stable Isotopes in Water

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Glaciers in the tropical Andes are undergoing rapid retreat with potentially devastating consequences for populations who rely on them for water resources. We measured stable water isotope ratios in synoptically sampled streams discharging from glacierized watersheds to associate hydroisotopic variation with relative changes in glacierized area. A total of 73 water samples were collected from hydrological endmembers including streams, glacier meltwater, and groundwater during the dry seasons of 2004–2006 in the Callejon de Huaylas, a 5000 km^2 watershed that drains the western side of the Cordillera Blanca in northern Perú. To differentiate the influence of elevation on isotopic values, we use samples from shallow groundwater springs and nonglacierized subcatchments to derive a local meteoric elevation effect. From published historical runoff data and satellite-mapped glacier cover, we estimate an average increase of 1.6 ($\pm$1.1)% in the specific discharge of the glacierized catchments as a function of isotopic changes from 2004 to 2006. These results confirm predicted short-term increases in discharge as glaciers melt and demonstrate the utility of stable isotopes in water for tracing relative glacier melt water contributions to watersheds.

Introduction

The future impact of a warmer global climate on snow and glacier water resources is complex, varies regionally, and is potentially socially disruptive (*1*). Greater than 80% of the fresh water supply for arid to semiarid regions of the tropics and subtropics originates in mountainous regions, affecting more than half of Earth's population, principally in the developing world (*2*). Globally, mountain glaciers are shrinking, and in some cases on the verge of disappearing completely (*3*). High elevations in the tropics such as the Andes in South America are particularly vulnerable to future warming (*4*), and the loss of glaciers in this region could pose future water supply crises (*5*).

In the tropical Andes the population relies on water resources that originate from glacier melt in a seasonally arid climate (*4*, *6*). Glaciers provide two primary positive functions for water resources—they decrease seasonal discharge variability and provide greater specific discharge. These functions mean that glacierized catchments have a less variable discharge throughout the year, particularly during drought or dry season conditions. Also, when glaciers experience negative net annual mass balance, the resulting decrease in size is hypothesized to result in increased meltwater discharge, at least in the short term. However, as glaciers reduce in size they become less significant seasonal reservoirs, and anticipated enhanced seasonality causes more runoff in the wet season and less in the dry under future climate warming scenarios (*6*, *7*).

To assess the role of glaciers in the hydrologic system, a measure of the meltwater discharge into the hydrologic system is required. For glaciers that lie in well defined, easily accessible watersheds, the flux of meltwater can be measured directly using a point measurement (*8*). In the tropics most glaciers are in remote, high elevation locations where continuous measurement is difficult, and permanent installations are prone to theft and vandalism (*9*). Changes in glacier volume (either from snow stakes or remote sensing) can also be used to assess the glacier meltwater discharge, although the high cost and logistical challenges of measuring the seasonal-to-annual volume change directly have limited the application of these methods to discontinuous intervals at very few sites. Quantifying glacier melt with point discharge measurements in streams is thus only logistically feasible in a limited number of small headwater catchments. Further downstream where social needs are greater, discerning the relative proportion of glacier meltwater is complicated by other components of the hydrologic system such as precipitation, evaporation, groundwater discharge, storage, and human induced changes such as dams and diversions for hydroelectric projects.

A potential method to overcome these limitations and to assess glacier meltwater contribution to stream discharge is through the use of geochemical mixing models (*10*), although the scaling-up of mixing models is not simple (*11*). Stable isotopes of water (^{18}O, ^{16}O, ^{2}H, and ^{1}H) are commonly used in catchment-scale process studies because they integrate small-scale variability (*12*) within larger watershed scales (*13*). The stable isotopes of water are fractionated by naturally occurring hydrologic processes such as condensation, melting, and evaporation (*14*), which may help identify distinct end-member sources of water within a mountain hydrologic system. The hydrogen and oxygen isotopes tend to covary in ratios similar to meteoric waters, and consistent geographic variations are observed, including a general depletion of heavier isotopes with higher elevation (*15*). In studies of the hydrogen and oxygen isotopes in precipitation, a consistent decrease in δ^{18}O values with elevation is commonly observed and is interpreted as isotopic fractionation due to decreasing temperatures of precipitation at higher elevations. The altitude effect in precipitation generally ranges from −0.15 to −0.5‰ per 100-m rise in altitude (*14*). Shallow groundwater often mimics the altitude affect, most likely as a result of fairly short residence times and/or short flow paths (*16*).

Hydrochemical and hydroisotopic mixing analysis has been successfully applied to solving environmental problems of water source identification (*17*). The ratios of stable oxygen isotopes have been successfully used in a mixing model study to quantify glacier ice melt contributions to small headwater catchments in the Peruvian Andes (*8*). While this work identified a traceable glacier meltwater isotopic composition and demonstrated a quantifiable mass balance application, it was limited in spatial extent.

The purpose of this study is to demonstrate the application of stable isotopes in water to evaluate the relative change in

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glacier meltwater contribution to regional discharge, including the function of relative degree of catchment glacierization. A synoptic sampling scheme is used to measure the spatial distribution of stable isotope concentrations in surface and groundwaters in a large, multi-tributary Andean watershed (the Callejon de Huaylas) from the dry season (July and August) of 2004−2006. We then compile available geospatial and historical discharge data to correlate percentage of watershed area covered by glaciers to specific discharge. By considering a regional altitude effect from nonglacierized spring-fed streams, we are able to relate interannual changes in stable isotope values of glacier-fed streams to relative changes in discharge through a series of linear regression models.

Experimental Section

Study Area. Earth's most glacierized tropical mountain range, the Cordillera Blanca, trends NW-SE over 130 km between 8°−10° S latitude in Perú (*18*). The majority of the glacierized area in the Cordillera Blanca discharges to the Pacific Ocean via tributary streams to the Río Santa, which also collects runoff from the nonglacierized Cordillera Negra mountain range. The Río Santa starts at an elevation of 4300 masl, drains a total watershed area of 12 200 km^2 to the coastal city of Chimbote, and has the second largest and least variable annual discharge of all Pacific-draining rivers in Perú. Four hydroelectric plants along the lower canyon of the Río Santa supply power to mines and villages along its banks. The uppermost hydroelectric power plant at Huallanca (1800 masl) delimits the 5000 km^2 Callejon de Huaylas watershed (Figure 1). Our previous analyses have estimated that upward of 10−20% of annual (40% dry season) discharge to the Callejon de Huaylas is comprised of glacier melt that is not replaced in the annual hydrologic regime (*6*, *8*).

Only a few of the Río Santa tributary streams in the Callejon de Huaylas have been gauged to monitor discharge, and historical records are intermittent over the past 40 years with many ending in the late 1990s (*8*). Average monthly discharge from the gauged tributaries is highest in October through April, corresponding to the outer tropical wet season where ∼80% annual precipitation occurs (*8*). The monthly averaged air temperature remains relatively constant throughout the year, and the diurnal variation is larger than the annual variation, as is typical of the tropics. Through comparison of aerial photographs taken in 1962−1970 (*19*) and satellite remote sensing in 1990, the total glacier cover on the principal mountains of the Cordillera Blanca decreased by 14% (from 723 to 620 km^2) (*20*).

Water Sampling and Analysis. Synoptic sampling was used to assess the spatial variability of stable isotopes in surface and groundwater within the Callejon de Huaylas during the dry seasons of 2004, 2005, and 2006; stream sample locations are shown in Figure 1. Synoptic sampling in hydrologic studies is a sampling strategy whereby a large number of locations are sampled for water in a very short time span, providing essentially a snapshot of the spatial variability for a given parameter. This approach has been shown to be a very effective and economic method to elucidate hydrological processes at a regional scale (e.g., ref *16*).

A total of 73 samples were taken from glacierized tributary streams ($n = 11$) of the Cordillera Blanca, groundwater springs ($n = 9$) of the glacier-free Cordillera Negra, and nonglacierized streams ($n = 3$) from both ranges. The glacierized tributary streams were sampled where the stream intersects the principal roadway paralleling the Río Santa along the valley floor, often near original historical discharge gages. Groundwater springs from the Cordillera Negra were sampled at elevations ranging between 3600 and 4200 m, located in consultation with local farmers and an agricultural engineer from Huaraz. In all years the majority of the synoptic samplings took place over 2 consecutive days, with a few samples collected within 1 week of the major samplings. All samples were collected in 60 mL nalgene bottles and were kept refrigerated at 4 °C whenever possible. Sample locations and elevations were recorded using Trimble GeoExplorer II GPS receivers.

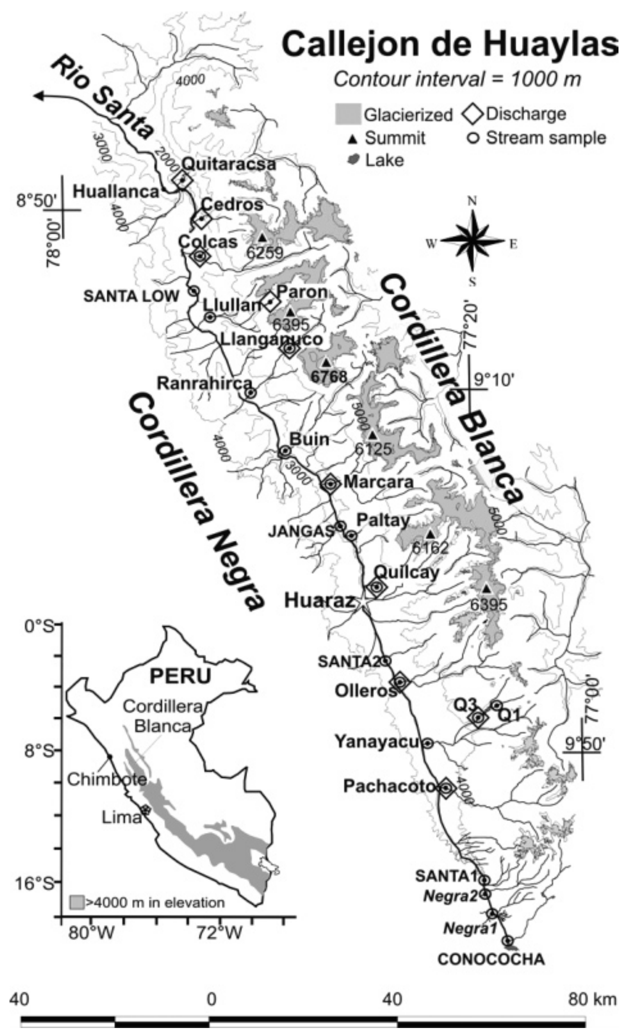

FIGURE 1. Map of Callejon de Huaylas, with sampling locations.

Values of $\delta^{18}O$ and $\delta^{2}H$ were measured with a mass spectrometer (Finnigan MAT Delta Plus coupled to a HDO water equilibrator) in the Ice Core Paleoclimatology Lab at the Byrd Polar Research Center at The Ohio State University, Columbus, OH. Stable isotopes results are reported using the δ-notation reported relative to the Vienna-Standard Mean Ocean Water (VSMOW) standard, with an accuracy of ±0.2‰ for $\delta^{18}O$ and ±2‰ for $\delta^{2}H$, such that

$$\delta^{18}O_{sample} = \left(\frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{VSMOW}} - 1\right)\cdot 1000‰ \quad (1)$$

$$\delta^{2}H_{sample} = \left(\frac{(^{2}H/^{1}H)_{sample}}{(^{2}H/^{1}H)_{VSMOW}} - 1\right)\cdot 1000‰ \quad (2)$$

Geospatial and Discharge Data. We compiled geographical data on the regional topography, glacierized area, and historical discharge. Topographic maps and satellite imagery of the study region were processed within a geographic information system (GIS: ArcGIS 9.0) to delineate watershed areas according to the catchment pour-point sample loca-

TABLE 1. Water Sample Sites, Altitude, and Isotope Values (both δ^{18}O and δ^2H Given in ‰) for the 3 Years (2004−2006) Categorized by Glacierized Condition or Location[a]

site name	altitude (m)	2004 δ^{18}O	2004 δD	2005 δ18O	2005 δD	2006 δ18O	2006 δD
Glacierized							
Querococha(Q3)	3980	−13.5	−103	−13.4	−100	−14.2	−106
Pachacoto	3765	−13.6	−106	−14.0	−104	−15.3	−115
Yanayacu	3705	−13.4	−102	−13.8	−103	−14.1	−105
Olleros	3540	−13.6	−99	−14.3	−105	−15.2	−113
Quilcay	3150	−14.1	−104	−14.6	−108	−15.1	−111
Pariac	3144	−14.3	−105	−14.4	−105	−15.0	−111
Marcara	2923	−14.6	−96	−14.6	−106	−14.6	−115
Paltay	2884	−13.8	−101	−14.3	−104	−14.9	−110
Buin	2632	−13.3	−102	−14.3	−105	−14.1	−103
Ranrahirca	2525	−13.6	−104	−14.4	−106	−14.7	−108
Llullan	2350	−14.2	−101	−14.2	−103	−14.4	−109
Glacier-Free							
Q1	4020	−14.0	−105	−14.0	−106	−14.4	−109
C. Negra 1	4004	−14.3	−109	−13.9	−109	−13.4	−109
C. Negra 2	3973	−14.6	−118	n/a	n/a	−14.1	−117
Río Santa							
Conococha	4020	−4.5	−51	−4.9	−55	−8.8	−84
Río Santa 1	3800	−12.3	−99	−12.2	−95	−12.7	−100
Río Santa 2	3462	−13.1	−103	−13.6	−101	−14.1	−108
Río Santa Jangas	2807	−13.4	−100	−14.0	−102	−14.0	−107
Río Santa Low	2000	−13.5	−102	−13.7	−101	−14.3	−112
C. Negra							
Punta Callan	4120	n/a	n/a	−14.0	−108	−13.8	−108
Santo Torib	4022	n/a	n/a	−13.6	−105	−14.3	−108
Paccha	3989	n/a	n/a	−14.0	−106	−14.5	−114
Paccha #2	3968	n/a	n/a	−14.3	−111	−14.7	−113
Cancha Cuta	3948	n/a	n/a	−12.9	−99	−13.7	−108
Matara#2	3742	n/a	n/a	−12.4	−99	−12.5	−102
Canshan	3676	n/a	n/a	−11.7	−95	−11.6	−98
Matara#3	3646	n/a	n/a	−11.1	−88	−11.4	−95
Matara#1	3631	n/a	n/a	−11.0	−92	−11.4	−96

[a] Samples from the Cordillera Negra (C. Negra) category are all discharge from groundwater springs.

tions. 1:100 000 scale topographic maps published by the Peruvian Instituto Geografico Nacional with 200 m contour interval were digitized and used as the basis for a 100 m digital elevation model (DEM) of the Cordillera Blanca. The DEM was georeferenced to UTM zone 18, to match two rectified 1997 Landsat satellite image scenes covering the range. Cordillera Blanca tributary watersheds were demarcated from GPS mapped sample locations, based on the stream channels and flow paths in the DEM, and glacierized coverage was digitized from the satellite imagery. Historical stream discharge data largely predating the late 20th century privatization (*21*) of the regional hydrologic observation network exist for a number of stations (marked with diamonds in Figure 1) (*8*).

Results

Isotopic Variability. The δ^{18}O and δ^2H values measured for water samples collected in 2004−2006 are provided in Table 1. The samples with the highest (most enriched) values for all years were from Conococha (4020 masl), a very shallow (<3 m), high evaporation lake at the head of the Río Santa. The lowest (most depleted) values were samples from glacierized tributary streams which varied from year to year and had δ^{18}O values 8−10‰ lower than Conococha.

The averaged isotopic concentrations for the 3 years are plotted on a bivariate plot according to the groups from Table 1 (Figure 2). All of the water samples fall along a linear fit oriented slightly below the global meteoric water line (MWL: $\delta^2\text{H} = 8\,\delta^{18}\text{O} + 10$), with a lower slope of 5, usually indicating the influence of evaporation (*22*). The glacierized tributaries of the Cordillera Blanca cluster closer to the MWL, while the Cordillera Negra samples and the groundwater samples fall on a line with a lower slope than the meteoric water line, as would be expected for waters that have a significant shallow groundwater component or waters that have undergone evaporation (*14*). Of the Río Santa samples, Laguna Conococha (not shown on Figure 2) and Río Santa 1 (circled) have less negative $\delta\ ^{18}$O values and thus are further extended to the right along the evaporation line, reflecting their geographic location nearer the headwaters of the Callejon de Huaylas watershed before the river enters the main portion of the Cordillera Blanca where glacier melt inputs are expected to be more significant.

Annual repeat sampling of the same sites allows the range of interannual isotope variability to be assessed. Most of the glacierized tributaries and Río Santa samples progress toward more negative values over the range of measurements from 2004 to 2006. Moreover, the largest interannual range of isotopic values is seen for the glacierized tributaries (except for the outlying Conococha site), which have an average variability of 0.85‰, over twice the magnitude seen in the spring-fed samples (0.39‰).

Degree of Glacierization. The geospatial and historical discharge data used in this study are summarized in Table 2, showing the percentage surface area covered by glaciers within the watershed defined by the discharge station. Those sites located near the road along the Río Santa which we were able to sample for isotopes are in bold text. There is a significant ($P = 0.008$) correlation between percent watershed area glacierized and specific discharge (Figure 3a).

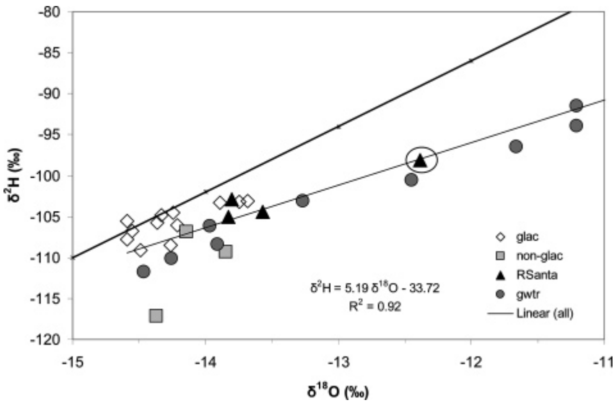

FIGURE 2. Isotopic ratios δ^{18}O vs δ^2H of all samples, averaged for the 3 years, grouped by Table 1 categories (glac = glacierized; nonglac = glacier-free; RSanta = Rio Santa; gwtr = C. Negra groundwater) with global meteoric water line (MWL, dark line). Regression line (linear (all)) is fit to all the sample points and forms an evaporation line (light line) with slope ~5, shown diverging from the MWL. The circled site is Río Santa 1, exposed to more evaporative enrichment at the headwaters of the Callejon de Huaylas.

TABLE 2. Summary of Cordillera Blanca Tributary Glacierization and Historical Discharge[a]

station	period of record	watershed area (km^2)	% glaciated area (1997)	av annual discharge ($m^3 s^{-1}$)	av specific discharge (ma^{-1})
Paron	1953–1995	49	52	1.89	1.22
Llanganuco	1953–1997	85	36	2.99	1.11
Marcara	1953–1997	221	22	8.80	1.26
Cedros	1953–1983	114	18	3.54	0.98
Quillcay	1953–1983	243	17	7.41	0.96
Olleros	1970–1997	175	10	4.77	0.86
Pachacoto	1953–1983	194	8	4.40	0.72
Quitaracsa	1953–1997	383	7	10.97	0.90
Querococha (Q3)	1956–1996	62	3	1.70	0.87

[a] Sites included in isotope synoptic sampling are emboldened. Average annual discharge is the mean discharge for the period of record for a given site, and average specific discharge is mean discharge for the period of record divided by watershed area.

Elevation Effect. To evaluate the effect of sample elevation on the isotopic values, we computed a regional elevation effect by using the average δ^{18}O for nonglacierized Cordillera Negra spring samples and spring-fed streams. We use a linear regression to derive an expression predicting the sample δ^{18}O from the elevation. The slope of this regression line ($P < 0.001$) defines an altitude effect of −0.7‰ per 100 m rise in elevation that closely matches those expected for precipitation values, indicating precipitation as the predominant source of streamwater in the absence of glacier melt.

Applying this relationship to our glacierized tributary isotope samples, we can compute a predicted sample elevation (E_p) in meters (m) based on a sample δ^{18}O value by inverting the equation of the regression line:

$$E_p \text{ (m)} = -127 * \delta^{18}\text{O} + 2213 \qquad (3)$$

The difference in elevation (ΔE) between the actual (E_a) and predicted sample elevations ($\Delta E = E_a - E_p$) can then be related to glacier cover using a linear regression. We find a very good correlation ($P < 0.0001$) between the average ΔE and percentage glacier cover in a catchment calculated using the geospatial data (Figure 3b). This relationship yields an equation to predict glacier cover (G_p) as a function of ΔE:

$$G_p \text{ (\%)} = -0.014 * \Delta_{\text{elevation}} + 2.99 \qquad (4)$$

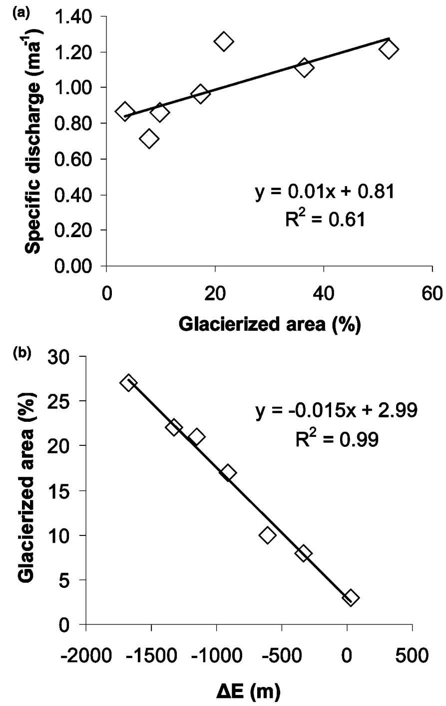

FIGURE 3. (a) Historical specific discharge predicted by percentage glacierized area computed from a 1997 Landsat image. (b) Plot of ΔE, the difference in elevation between the actual (E_a) and predicted sample elevations ($\Delta E = E_a - E_p$) versus percent of subcatchment area glacierization.

Changing Glacier Melt Contribution. The predicted glacier cover (G_p) is related to the average annual specific discharge (Table 2) by the regression shown in Figure 3a, allowing for specific discharge to be predicted. The year-to-year difference in predicted specific discharge (ΔQ_{sp}) for each glacierized tributary sampled gives a quantified estimate of change in glacier meltwater yield, as summarized in Table 3. Overall, the glacierized streams show an average increase in specific discharge of 1.6 ± 1.1% from 2004 to 2006. The different sample positions along the Río Santa also show an increase in specific discharge over the observation interval, which generally increases downstream to a maximum of 1.4%.

Discussion

This synoptic survey provides a quantitative measure of the relative magnitude of changes in glacier melt runoff from the world's most glacierized tropical mountain range using stable isotopes where actual discharge measurements are insufficient. The methodology of sampling water during the dry season is employed to characterize the contributions to runoff when precipitation inputs are minimal to the hydrologic system. Our samples (Table 1, Figure 2) show greater isotopic variability than is usually seen in meteorological or small catchment studies. This scatter is expected given the wide variety of water sources sampled from a large region. Moreover, sampling the same sites over multiple years enabled us to explore interannual variability. We are able to track a change in the overall regional isotopic ratios that can be related to glacier cover, corroborating previously published observations of increased glacier melt.

TABLE 3. Summary of Relative Change in (%) Specific Discharge Based on Predicted Elevation and Glacierization

site name	ΔQ_{sp} (%) 2004−2005	2005−2006	2004−2006
	Glacierized		
Querococha (Q3)	−0.3	1.7	1.4
Pachacoto	0.9	2.7	3.6
Yanayacu	0.9	0.6	1.5
Olleros	1.6	1.7	3.3
Quilcay	1.1	1.0	2.0
Pariac	0.2	1.2	1.5
Marcara	1.0	1.0	2.0
Paltay	0.1	0.1	0.2
Buin	1.8	−0.2	1.6
Ranrahirca	1.3	0.6	1.9
Llullan	0.0	0.4	0.4
	Río Santa		
Río Santa 1	−0.1	1.0	0.9
Río Santa 2	1.1	−0.8	0.3
Río Santa Jangas	1.1	−0.1	1.1
R Santa Low	0.3	1.1	1.4

Other hydrologic factors, such as variability in precipitation amount, may also account for some of the regional shift in isotopic ratios. Observations of precipitation in Africa and the Central Andes of Boliva have demonstrated that the amount of precipitation has a predominant effect on interannual isotopic variation in the tropics (*23*). Specifically, larger amounts of precipitation lead to decreased isotope values. Previous work in the Cordillera Blanca shows that streams have an annual oxygen isotope variation of close to 9‰, reflecting the contribution of glacier meltwater and precipitation amount (*8*). While there is limited current data on precipitation amounts for the region, a station maintained at Llanganuco (3850 m) since July 2004 in collaboration with the University of Innsbruck provides some incomplete data (due to technical problems) for comparison during the study period. The results do not show excessive amounts of precipitation above average historical monthly totals from a totalizing gage on the same site from 1953 to 1997. From January to July of 2005 there was 389 mm total precipitation, compared to an average historical monthly total of 409 mm. From October 2005 through June 2006, the total rainfall was 808 mm, larger than the average historical monthly total for the same months of 565 mm but almost within the 200 mm standard deviation for the same interval. Furthermore, the historical totalizing gage should be considered a minimum since it is more susceptible to evaporation and has not been calibrated to the gage installed in 2004. Future work involving ongoing sampling during additional dry seasons and/or wet seasons is required to improve our understanding of the system dynamics.

Hydrothermal waters have been observed in the Cordillera Blanca region and were considered a potential endmember that might influence isotopic values in streams. We sampled two hot springs over 3 years and measured $\delta^{18}O$ values ranging from −5.4 to −10.8 and $\delta^{2}H$ values ranging from −80 to −89. These are slightly higher than other surface waters but not as high as evaporatively enriched lake waters and represent a small proportion of discharge. Furthermore, since these inputs would tend to decrease the overall isotopic values of streams, our glacier melt estimates can be considered conservative.

Located at the pour points of the glacierized tributary watersheds to the Río Santa, our samples represent catchment average discharge with varying degrees of glacier melt, depending on the percentage of area glacierized. An analysis of the historical discharge available (Table 2) shows positive correlations between glacier coverage and average annual and specific discharge, while greater percentage glacierization moderates extremes of discharge (*8*). During the dry season, base flow is buffered by glacier melt, and catchments with larger glacier cover therefore discharge a greater portion of glacier meltwater to the Río Santa. The statistically significant linear relationships (eqs 3 and 4) predict an "effective" percentage of glacier ice cover contributing to discharge with a measured isotopic ratio. This predicted glacier cover (G_p) is simply a function of the isotopic content in the stream, relative to the isotopic values in tributary streams with measured glacier cover at a specific point in time (1997 satellite image date). Although the predicted glacier cover does not have a physical value, it does provide an indication of how predominantly glacier meltwater contributes to total discharge.

This analysis must be constrained to an assessment of relative change, given the implicit assumptions. First of all, we assume that the relative offset between glacierized tributary sample elevation and expected elevation is related to isotopically distinct ice melt. However, the effects of elevation and glacier cover are inter-related—catchments that have a greater glacier cover usually have a higher maximum elevation, which also impacts the isotopic values of the runoff. Our approach addresses this concern by accounting for a regional predicted elevation effect based on samples taken exclusively from spring-fed sources. We make the assumption that the elevation effect calculated from the Cordillera Negra shallow groundwater is applicable for the Cordillera Blanca, given the close (<50 km) maximum separation distance. Although the glacierized tributary stream samples are an integration of water from throughout a given subcatchment, the elevation correction is applied only to the bulk sample at the elevation of the catchment outflow. Also, there is a discrepancy between the number of sites we were able to sample given logistical constraints (poor access) and the historical discharge data available (Table 2). In the field, Cedros and Quitaracsa sites were inaccessible to sample, and Paron has had a dam installed in 1992, so we did not include it for isotope sampling. This means that our linear correlations depicted in Figure 3 include slightly different data. Yet the trends are robust, since both sets cover a broad range of glacier cover. Furthermore, the glacier cover data is from 10 year old imagery. Nevertheless, because the model is purposed to quantify relative changes, it does not rely on precisely accurate or current values of glacier cover.

Although the glacier-derived meltwater has a strong influence on the control of water isotopes, the observed altitude effect from glacier elevations down to the Río Santa indicates that wet-season precipitation is potentially important as an antecedent source of water during the dry season. The elevation effect is commonly applied to precipitation samples along a topographic transect, and the effect can sometimes be observed in shallow groundwater systems (e.g., ref *16*). We propose that the presence of this trend during the dry season is an indication that the streams are receiving groundwater discharge, possibly near-surface through-flow that is lagged from the preceding wet season. The Q1 stream drains a nonglacierized valley catchment continuously through the year. Therefore, during the dry season this high-elevation stream must be receiving groundwater discharge of some sort. A possible site for temporal storage may be pampas—treeless plains that are formed from paludified moraine dammed lakes. The composition of the pampas' fill material appears to be primarily low permeability, organic rich unconsolidated material. The exact hydrologic role of these unique geomorphic features is not fully understood and warrants further study.

Significance. In the Callejon de Huaylas there are many critical hydrologic research and policy questions, including what is the role of glacier melt in the hydrologic budget, what portion of the dry season water budget is from glacier melt, and what will be the future impact of glacier recession on water resources? This study demonstrates the utility of stable isotopes in water for addressing these questions. Within the large, multi-tributary Callejon de Huaylas watershed the Río Santa is the primary channel draining both the glacier capped Cordillera Blanca and the relatively dry Cordillera Negra. The isotopic results verify that the Río Santa is predominately derived from the glacierized tributaries of the Cordillera Blanca (*6*) and that these tributaries are increasingly supplying glacier meltwater in proportion to their relative degree of glacier ice coverage. In this context, there is corroborating evidence for the predominance of glacier meltwater in the Callejon de Huaylas based on a dissolved ion mixing model that estimated 66% of dry season Río Santa discharge originated from the glacierized tributaries (*6*). Currently the dry season glacier melt contribution is increasing as glacier recession is accelerating, but this will only be a temporary increase (*24*). It is anticipated that the water resource stress in the dry season will be greatest once the glacier melt contribution decreases.

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