Hydrochemical evaluation of changing glacier meltwater contribution to stream discharge, Callejon de Huaylas, Perú

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ABSTRACT

The Callejon de Huaylas, Perú, is a well-populated 5000 km^2 watershed of the upper Rio Santa river draining the glacierized Cordillera Blanca. This tropical intermontane region features rich agricultural diversity and valuable natural resources, but currently receding glaciers are causing concerns for future water supply. A major question concerns the relative contribution of glacier meltwater to the regional stream discharge from first order basins to the whole watershed. In July, 2004, we collected 37 water samples from streams, springs and precipitation over a 2000 m vertical range within the watershed and analyzed them for major dissolved ions and isotopic ($\delta^{18}O$) composition. The water chemistry is used to establish the extent of variability in the surface waters, and to identify different hydrologic end-member components. $\delta^{18}O$ values for the waters range from -4.29‰ to -5.28‰. There is a consistent trend towards lighter isotopes with greater percentage of glacier coverage in tributary stream catchments of the Rio Santa, with some exceptions due to evaporative enrichment in lakes. Samples taken along transects of these glacierized tributary streams become more isotopically enriched with lower elevation and greater distance from the glaciers. However, waters from the Rio Santa become less enriched with lower elevation. We hypothesize that the distribution of glacier mass in the mountain range causes a greater volume of glacial meltwater to join the Rio Santa at lower elevations. The water generally has a Ca-Mg-HCO_3 chemical signal. Samples along transects of tributary valleys show an increase in TDS and the Na:Mg concentration ratio with decreasing elevation. We see geochemical evidence for a small groundwater source in the tributaries and the Rio Santa. We propose that distinct chemical signatures of source water end-members may provide a means of quantifying the volumetric contribution of glacier meltwater over time.

SETTING

The Andean Cordillera Blanca of Perú is the most glacierized mountain range in the tropics. It spans 120 km along the South American continental divide, with 27 summits reaching over 6000 m including Huascaran **(a)**, the nation's highest. The majority of glacierized watersheds within the Cordillera Blanca discharge towards the SW, flowing via the Río Santa to the Pacific Ocean. The hydroelectric power plant at Huallanca **(b)** delimits the upper Río Santa watershed to an area of 4900 km^2 that is referred to as the Callejon de Huaylas, which receives surface runoff from both the glaciated Cordillera Blanca on the east and non-glacierized Cordillera Negra on the west (Fig. 1). The regional inhabitants rely on glacier-fed streams for municipal water to towns and cities, such as the provincial capital of Huaraz **(c)**. Starting from Lake Conococha at 4000 m.a.s.l. **(d)**, the Río Santa flows NE over 300 km, draining a total watershed of 12,200 km^2 and is the least variable of Pacific draining rivers in the nation.

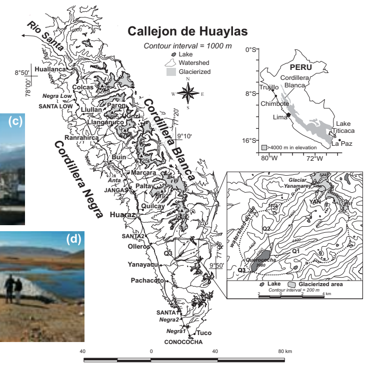


Figure 1 Map of Callejon de Huaylas, with sampling locations indicated. Rio Santa sample sites are capitalized, and Cordillera Negra tributary sites are in italicized. The inset map shows the YAN-Querococha watershed with sampling sites.

For the many streams that drain glacierized catchments, like Quebrada Honda at Marcara, a key question is: how much water is coming from melting glacier ice that is not replenished over the annual cycle?

YAN-QUEROCOCHA WATER BALANCE

The Yanamarey glacier catchment (YAN) **(e)** covers 1.3 km^2 between 4600 m and 5300 m in the southern Cordillera Blanca, 75% of which is covered by glacier ice (based on 1997 imagery). The catchment is representative of small glaciers in the Cordillera Blanca, and the recession in recent years has been very extensive (Gomez, 2004).

There is a change in the annual hydrological balance regime at YAN from 1998-99 to 2001-04 as modeled (after Mark & Seltzer, 2003) from observed precipitation **(f)** and discharge **(g)** (Fig. 2). Whereas the glacier experienced a positive mass gain during Jan - Apr 1999, the balance remained negative over the entire measurement period Dec 2001 Jul 2004. Averaged storage changes in 1998-99 indicated that glacier melt from Yanamarey contributed 35% of the annual discharge. The average value is ~60% over the last 3 years. There is also an increase in mean discharge: over the hydrologic year of 1998-99, mean Q = 230 mm; from 12/01 to 8/04, mean Q = 410 mm. Peak annual discharges have increased ~50% in magnitude, and now occur coincidentally with peak precipitation, instead of during the early wet season as shown in 1998-99.

A Piper mixing model diagram (Piper, 1945; Hounslow, 1995) estimates the proportion of glacier melt from YAN contributing to discharge from Lake Querococha (Q3) **(h)** based on the concentrations of cations and anions. The mixed member coming from Querococha, Q3, falls at a distance inversely proportional to the concentration of each end-member contribution along a straight line, such that ~50% is derived from YAN, and ~50% from the non-glacier stream Q1 (Fig. 3). Similarly, Q2 is closer to YAN, and is thus proportionately more concentrated with glacier melt (67% from YAN).

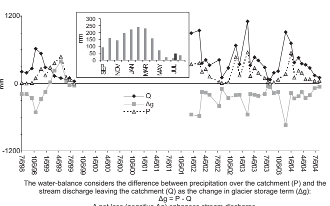


Figure 2 The hydrological balance at YAN. There is a gap in years from our original study and when the new weir with continuous stage recorder was constructed. The inset shows the mean monthly precipitation measured in the catchment over all monitored years (initiated in 1981). The dark bar indicates the rainfall for July 2004, registering 46 mm (almost 4 times the mean of 12 mm).

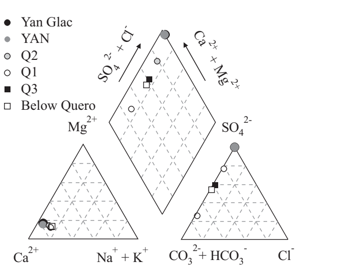


Figure 3 Piper plot of major ion chemistry from the YAN-Querococha watershed. Q3 is on a mixing line between the glacial snout and Q1, with a relative contribution of 50% from each end member. The size of each symbol is proportional to TDS.

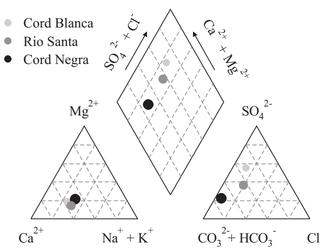


Figure 4 Piper plot of major ion chemistry from the averaged end-members in the Callejon de Huaylas watershed. The Rio Santa is on a mixing line between the glacierized Cordillera Blanca tributaries and non-glacierized Cordillera Negra tributaries, with a relative contribution of 66% from the Cordillera Blanca. The size of each symbol is proportionate to TDS. Averages and individual samples are presented in Table 1.

REGIONAL HYDROCHEMICAL VARIATIONS

Concentrations of major cations and anions were measured in water samples from 28 locations in the YAN-Querococha watershed and throughout larger Callejon de Huaylas watersheds (Table 1). Another Piper diagram (Fig. 4) features a mixing line between end member point averages from the glacierized Cordillera Blanca tributary streams (n = 15) and from the non-glacierized Cordillera Negra tributaries (n = 4). The mixed member averaged from the Rio Santa samples (n = 5) falls along the mixing line in between the end-members, but closer to the Cordillera Blanca tributaries average, such that 66% of the Rio Santa discharge is derived from the glacierized Cordillera Blanca catchments.

Table 1 Site names, date of sample, and concentrations of major cations and anions (mg L^{-1}) for water samples, separated by groups with averages used in mixing models.

Name	Date (2004)	Cations (mg L^{-1}) Ca^{2+}	Mg^{2+}	Na^+	K^+	Anions (mg L^{-1}) HCO_3^-	Cl^-	SO_4^{2-}
C. Blanca tributaries								
Paron	9-Jul	5.64	0.476	1.23	0.915	11.32	0.65	8.3
Yanayacu	10-Jul	5.7	0.835	2.59	0.78	21.25	0.51	6.0
Tuco	10-Jul	30.7	2.13	1.58	1.22	76.15	0.54	27.0
Olleros	10-Jul	19.2	10.7	10	2.43	0*	10.45	165.4
Pachacota	10-Jul	22.1	6.42	5.38	1.86	18.87	8.75	65.4
Buin	11-Jul	21.5	3.05	9.38	2.46	56.47	9.30	29.7
Colcas	11-Jul	19.3	2.39	25.6	4.72	52.48	31.29	29.5
Marcara	11-Jul	15.5	3.59	11.6	2.83	15.74	14.70	46.0
Quilcay	11-Jul	18.1	4.36	4.22	2.18	0*	2.70	73.3
Paltay	11-Jul	8.82	1.04	2.09	1.11	28.43	0.30	8.1
Ranrahirca	11-Jul	18	2.71	4.63	1.26	33.68	1.09	36.3
Llullan	11-Jul	7.6	0.584	3.69	0.67	20.46	1.23	10.0
Kinzl	12-Jul	3.56	0.311	0.875	1.08	9.49	0.05	5.7
Llanganuco	12-Jul	5.99	0.306	1.16	0.678	11.90	0.16	8.3
C.Blanca average		13.94	2.65	5.69	1.65	28.33	5.48	35.6
C. Negra tributaries								
Negra 1	10-Jul	5.66	1.67	17.7	5.5	46.97	12.93	9.5
Negra 2	10-Jul	17.7	2.67	9.07	0.551	89.21	0.81	1.3
Negra Anta	10-Jul	44.9	22.2	18.3	3.39	249.54	4.65	35.5
Negra Low	11-Jul	42.3	3.84	29.4	1.76	121.29	6.97	75.0
C.Negra average		27.64	7.60	18.6	2.80	126.75	6.34	30.3
Rio Santa								
Santa 1	10-Jul	19.6	2.36	13.6	3.79	98.12	6.23	4.6
Santa 2	10-Jul	28.7	2.66	9.3	2.67	92.69	8.08	19.1
Santa Low	11-Jul	42	6.42	18.1	3.75	85.74	21.65	71.2
Jangas	11-Jul	27.9	5.46	18.6	4.33	43.08	27.24	61.8
Rio Santa average		29.55	4.23	14.9	3.64	79.91	15.80	39.2
YAN-Querococha								
Yan Glac	2-Jul	20	2.52	0.989	0.717	0*	0.11	70.2
YAN	2-Jul	17.8	1.96	0.865	0.663	0*	0.13	62.3
Q2	3-Jul	10.2	1.21	1.57	0.545	9.35	0.21	25.5
Q1	3-Jul	9.52	0.853	1.73	0.665	28.40	0.32	7.9
Q3	3-Jul	7.44	0.781	1.33	0.628	12.03	0.43	14.3
Below Q3	3-Jul	7.59	0.875	1.52	0.581	14.47	0.22	13.8

REGIONAL $\delta^{18}O$ VARIATIONS AND GLACIERIZATION

$\delta^{18}O$ values were measured for 32 water samples throughout the Callejon de Huaylas (Table 2). The range of values was from -4.29‰ to -15.28‰, with an overall mean value of -13.40‰ ($\delta^{18}O$ relative to VSMOW). The most enriched sample was from Laguna Conococha (4020 m), and the most depleted was from the stream draining Quebrada Kinzl (4000 m). Stream water samples (n=24) are grouped in five elevation transects: (1) Cordillera Blanca tributary streams, pour points draining glacierized catchments to the Rio Santa (n=8); (2) Cordillera Negra tributary streams, pour points draining non-glacierized catchments to the Rio Santa (n=4); (3) Llanganuco, points along stream from near the Glaciar Kinzl towards the Rio Santa (n=4); (4) YAN-Querococha, points along stream from Glaciar Yanamarey towards the Rio Santa; and (5) Rio Santa, points along the main channel of the Callejon de Huaylas. The transect groups display distinct relationships between $\delta^{18}O$ and sample elevation (Fig. 4). The slope, correlation coefficient and P value for each regression is presented in Table 2. Each group shows good correlations, but given the low degree of freedom for each sample set, only the statistically significant correlations are only for the Cordillera Blanca and Cordillera Negra tributaries groups.

Table 2 Sample names, elevation, transect group and $\delta^{18}O$ value and summary statistics for Altitude Effect Statistics.

Name	Date	Altitude (m)	δ18O (‰)	Altitude Effect ‰ per 100 m	r^2	p
C. Blanca tributaries						
Colcas	7/11/2004	2095	-14.48			
Marcara	7/11/2004	2923	-14.55			
Quilcay	7/11/2004	3150	-14.06			
Olleros	7/10/2004	3540	-13.57	0.06	0.67	0.013
Pachacota	7/10/2004	3765	-13.56			
Q3	7/3/2004	3980	-13.51			
Paltay	7/11/2004	2884	-13.79			
Llullan	7/11/2004	2350	-14.17			
C. Negra tributaries						
Negra 1	7/10/2004	4004	-14.26			
Negra 2	7/10/2004	3973	-14.63			
Negra 3	7/10/2004	3662	-13.29	-0.13	0.60	0.120
Negra Anta	7/11/2004	2785	-11.13			
Negra Low	7/11/2004	2000	-12.39			
Rio Santa						
Rio Santa 1	7/10/2004	3800	-12.26			
Rio Santa 2	7/10/2004	3462	-13.05	0.05	0.74	0.140
R Santa Low	7/11/2004	2000	-13.50			
R. Santa Jangas	7/11/2004	2807	-13.40			
Llanganuco						
Kinzl	7/12/2004	4000	-15.28			
Llanganuco UP	7/12/2004	3950	-15.04	-0.10	0.9	0.050
Llanganuco Effluent	7/12/2004	3850	-14.58			
Ranrahirca	7/11/2004	2525	-13.60			
YAN-Querococha*						
Yan Glac	7/2/2004	4620	-13.87			
Q2	7/3/2004	3990	-13.58			
Below Q3	7/3/2004	3750	-13.21			
Yanayacu	7/10/2004	3705	-13.38			
Q1	7/3/2004	4020	-14.04	-0.06	0.88	0.018
YAN	7/2/2004	4600	-13.45			
YAN	7/2/2004	4600	-13.44			
YAN	7/3/2004	4600	-13.49			
YAN	7/3/2004	4600	-13.49			
Other						
Olleros Hot	7/10/2004	3540	-6.00			
Chancos Hot	7/11/2004	2940	-10.80			
Paron	7/9/2004	4106	-14.35			

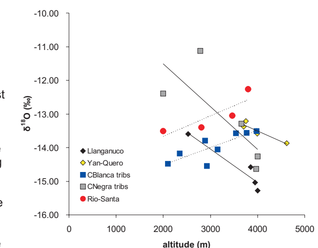
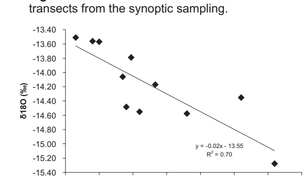
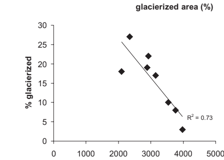


Figure 4 Plot of altitude versus $\delta^{18}O$ for the five transects from the synoptic sampling.





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