1 **High temporal resolution hydrometeorological data collected in the tropical**

2 **Cordillera Blanca, Peru (2004-2020)**

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26 **Abstract.** This article presents a comprehensive hydrometeorological dataset collected over the
27 past two decades throughout the Cordillera Blanca, Peru. The data recording sites, located in the
28 upper portion of the Rio Santa valley, also known as the Callejon de Huaylas, span an elevation
29 range of 3738 - 4750 m a.s.l. As many historical hydrological stations measuring daily discharge
30 across the region became defunct after their installation in the 1950s, there was a need for new
31 stations to be installed and an opportunity to increase the temporal resolution of the streamflow
32 observations. Through inter-institutional collaboration the hydrometeorological network
33 described in this paper was deployed with goals to evaluate how progressive glacier mass loss
34 was impacting stream hydrology, and to better understand the local manifestation of climate
35 change over diurnal to seasonal and interannual time scales. The four automatic weather stations
36 supply detailed meteorological observations, and are situated in a variety of mountain
37 landscapes, with one on a high-mountain pass, another next to a glacial lake, and two in glacially
38 carved valleys. Four additional temperature and relative humidity loggers complement the
39 weather stations within the Llanganuco valley by providing these data across an elevation
40 gradient. The six streamflow gauges are located in tributaries to the Rio Santa and collect high
41 temporal resolution runoff data. The datasets presented here are available freely from
42 https://doi.org/10.4211/hs.c35ae06cb26041b096dd07e1cbf8ebf5 (Mateo et al., 2021). Combined,
43 the hydrological and meteorological data collected throughout the Cordillera Blanca enable
44 detailed research of atmospheric and hydrological processes in tropical high-mountain terrain.

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1 Introduction

Glaciers and water resources in the Cordillera Blanca, Peru, have been under close observation for nearly a century. In the 1930s, an Austrian geographer from Universitat Innsbruck, Hans Kinzl, laid the groundwork for glaciological research in the region by surveying and mapping the glaciers and identifying other natural features in the mountainous landscape (Kaser and Osmaston, 2002). While the first systematic Peruvian effort to observe glacier tongue variations in the Cordillera Blanca was initiated in 1944 by Broggi (Petersen et al., 1969), glaciers as a source of security and water resources became the object of study in the subsequent decades. The Unidad de Glaciología e Hidrología (later Unidad de Glaciología y Recursos Hidricos (UGRH) of Electroperú S.A.) was initiated by the Corporación Peruana del Santa, a government company for energy development, and took on glacier and lake monitoring after many glacial lake outburst flooding (GLOF) events damaged communities downstream (Ames, 1998). GLOFs in 1941, 1945, and 1950 killed over 6000 people and destroyed a third of the Ancash district capital of Huaraz (Carey, 2010; Carey et al., 2012). Other glacier hazards have had detrimental impacts on the communities as well, including the 1970 avalanche, triggered by a massive earthquake, which killed approximately 6000 people and along with the debris flow it produced, covered the city of Yungay (Carey, 2010). Lliboutry, Morales and Schneider (1977) investigated two glaciers in the mountain range in relation to the danger they presented for flooding a downstream power plant. From the 1970s to the 1990s, a local Peruvian from Huaraz, Alcides Ames, provided many important contributions to the present knowledge of glaciers in the Cordillera Blanca while employed at UGRH, and after his retirement continued to dedicate much of his time to studying the glaciers and sharing his knowledge with other researchers (Ames et al., 1989; Hastenrath and Ames, 1995; Ames and Hastenrath, 1996; Ames, 1998; Kaser and Osmaston, 2002). In the 1980s, Georg Kaser, an Austrian geographer, began studying the Cordillera Blanca with a focus on the extent, causes, and possible consequences of the observed glacier retreat (Kaser and Osmaston, 2002). For many decades, much of the research in the region focused on developing better maps of the mountains and observing the marked glacier retreat in the tropics. Although the meteorological and hydrological stations installed by UGRH had been in place for nearly 40 years, it was not until the mid-1990s when studies began to assess water resources in the Cordillera Blanca, but with minimal focus on flooding and GLOFs (Kaser and Georges 1997; Mark and Seltzer, 2003).

The UGRH spent many years collecting an abundance of climatological, hydrological, and glaciological data, which was useful for future researchers, hydroelectric and mining companies, and other stakeholders throughout the Cordillera Blanca and its glaciers. Since the mid-1990s, most of the daily-resolution discharge data from the Rio Santa watershed has been cataloged and collected at a much-reduced number of sites by private energy companies who took over after Electroperu was privatized. The rapid turnover of the energy companies holding the discharge observations makes it difficult to track down all available historical data. Also, many of the hydrological stations have become defunct since they were installed in the 1950s,

96   creating a need for new stations to be installed for continuous monitoring of the region. A further
97   benefit of installing a new hydrological monitoring network in the 2000s was to significantly
98   increase the temporal resolution of the discharge observations.

99   Collaborating researchers from The Ohio State University, Bridgewater State University
100 and McGill University initiated a network of embedded environmental sensors in 2005. The
101 main goals of the instrument arrays were to evaluate how progressive glacier mass loss was
102 impacting stream hydrology, and to better understand the local manifestation of climate change
103 on the variability and controls of local weather phenomena over diurnal to seasonal and
104 interannual time scales. In order to create a sustainable network for continuous, long-term
105 observation, this project has been maintained in close collaboration with Peruvian researchers
106 and government agencies, as well as with other international scientists to leverage resources in
107 maintaining instruments, in exchange for openly sharing data.

108 The instrumentation for the data collection we present in this work was installed and
109 maintained under a collaborative work agreement ("convenio") formalized with the Peruvian
110 government agency overseeing the office in Huaraz (Peruvian Institute of Natural Resources
111 (INRENA) and the Autoridad Nacional del Agua (ANA)). This work agreement involved a
112 secondary collaboration with other international researchers who shared in installing and
113 calibrating the instrumentation. Specifically, Dr. Thomas Condom of the French Institut de
114 Recherche pour le Developpement (IRD) joined the agreement to install and maintain a series of
115 stream gauges logging water stage at 15-minute intervals. We also collaborated with the Austrian
116 research team of Dr. Irme Juen and Professor Georg Kaser from the Universitat Innsbruck,
117 Austria, who co-located a precipitation gauge with our weather station in Llanganuco. Further
118 details about the instrumentation are provided below.

119 Inter-institutional collaboration in this fashion has provided an effective partnership to
120 aid in maintaining the instrumentation over time, but also introduces challenges of logistical
121 coordination and data continuity. Visitation as non-resident international scientists to the field
122 sites has been feasible only one or two times annually. Thus, the Peruvians in our collaboration
123 have incorporated our instruments within their routine monitoring network. This has permitted
124 regular observations of stations and instruments to download data loggers, perform stream
125 discharge measurement to build a rating curve, and undertake a limited range of repair work.
126 However, limitations in local resources and manpower in Peru have often prevented recordings
127 of stage observation and discharge measurement to constrain rating curves. Likewise, having
128 multiple operators also increases some risk for data recovery errors. For instance, loggers that are
129 improperly relaunched after data downloads can jeopardize subsequent acquisitions. Having
130 more frequent site visits can allow for interventions, but also incurs increased risk of operator
131 error. Furthermore, Peruvian domestic political changes have disrupted the operations by
132 introducing different leadership, with altered operational priorities and resources, which directly
133 or indirectly interrupt the continuity of trained personnel responsible for data recovery and

134 preservation. Overcoming the many challenges of maintaining the instrumentation and
135 constructing rating curves has required regular cross-cultural communication, multiple and
136 annual visitation to the region. Likewise, the rating curves continue to be refined as additional
137 measurements are made.

138   Our collaborative observations have provided important new insights into how the
139 hydroclimate of the region is changing on different scales. Updated discharge and climate
140 observations in specific glacier catchments documented important shifts in seasonal supply of
141 glacier storage to the Yanamarey catchment (Bury et al., 2011) as well as suggesting regional
142 thresholds in glacier melt provision (Mark et al., 2010). The discharge constraints also provided
143 important validation for a novel hydrochemical basin characterization method to quantify
144 proportionate glacier melt and groundwater contributions to streamflow in tributaries of varying
145 glacierized coverage (Baraer et al., 2009, 2015). Regionally, the gauge network provided the key
146 constraint for a model of time-progressive hydrograph evaluation that verified significantly that
147 the main catchment had already passed "peak water" in the wake of strong glacier recession
148 underway for multiple decades (Baraer et al., 2012). Our embedded temperature and humidity
149 loggers distributed over elevation and linked to weather stations in the Llanganuco valley have
150 revealed novel diurnal to seasonal variations in lapse rates linked to catchment-specific valley
151 wind dynamics validated with downscaled climate models (Hellstrom et al., 2017). These studies
152 demonstrate the importance of collecting in situ hydrometeorological data and indicate the need
153 for continued data collection in the high Andes (Condom et al., 2020).

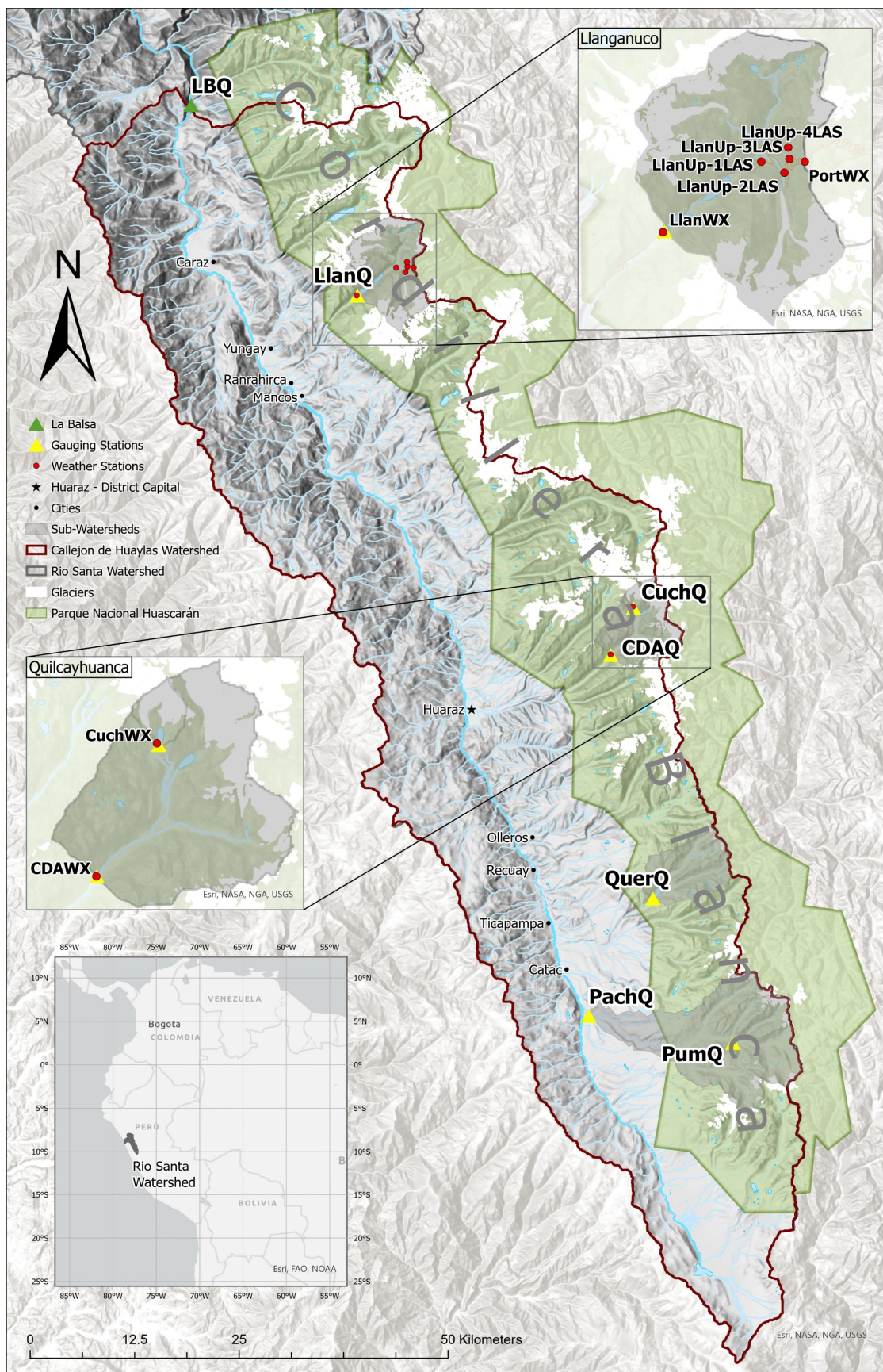
154   In this paper, we document available data from the Cordillera Blanca area collected over
155 the past 15 years. It is separated into (i) meteorological data recorded by permanently installed
156 automatic temperature and relative humidity loggers (Lascars), or automatic weather stations,
157 and (ii) hydrological data consisting of stage and discharge data from multiple sub-catchments.
158 The data are stored in .csv extension format on Consortium of Universities for the Advancement
159 of Hydrologic Science, Inc. (CUAHSI) Hydroshare:
160 https://doi.org/10.4211/hs.c35ae06cb26041b096dd07e1cbf8ebf5 (Mateo et al., 2021). The data
161 collection consists of multiple time series of point observations from both meteorological and
162 hydrological measurement sites. These high-temporal resolution data provide detailed insight
163 into the complex hydro-meteorological system of the tropical Cordillera Blanca.

164 **2 Study Area - Cordillera Blanca**

165   The Rio Santa (Santa River) captures runoff from the western side of the glacierized
166 Cordillera Blanca and the eastern side of the non-glacierized Cordillera Negra, encompassing a
167 drainage area of 11636 km^2 at the outlet to the Pacific Ocean. While the headwaters of the Rio
168 Santa are found at Laguna Conococha at 4100 m above sea level (a.s.l.), the highest point in the
169 basin (and in Peru) is the summit of Huascaran at 6768 m a.s.l. The average slope of the entire
170 drainage basin is 20.6° and its average elevation is 3374 m a.s.l. calculated from a 3 m resolution

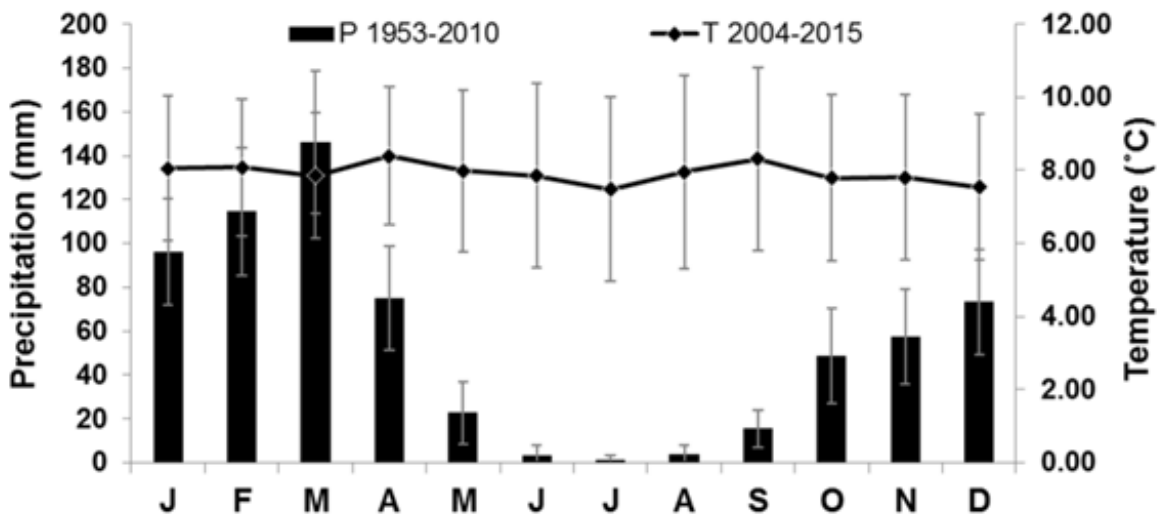
171   DEM of the region. The Rio Santa flows over 300 km northwest from its origin at Laguna
172   Conococha, an alpine lake at 4000 m a.s.l., to its outlet into the Pacific Ocean, near Chimbote.
173   The Callejon de Huaylas refers to the upper section of the Rio Santa, comprising approximately
174   4773 km^2 located above the Cañon del Pato 50 MW hydroelectric generation plant in Huallanca
175   (Figure 1). The Rio Santa basin is home to three other hydroelectric plants and provides water to
176   the expansive Chavimochic irrigation district near the coast (Mark and McKenzie, 2007). The
177   discharge on the Rio Santa has been carefully monitored since the Cañon del Pato dam began
178   operating in the 1950s, however, only one station near the dam remains active which is situated
179   slightly upstream at La Balsa (labeled as LBQ in Figure 1).

180   Figure 1.
181   Map of the Callejon de Huaylas showing the locations of the hydrological and meteorological
182   stations. (Base layers of the map originated from: © Esri, © NASA, © NGA, © USGS, © FAO,
183   © NOAA; all other layers were created and edited by authors of this article.)

184

185   Rio Santa discharge experiences a strong seasonal contrast with the lowest discharge
186   occurring between July and September, while peak discharge, nearly 20 times greater, typically
187   occurs in March. Calculated from daily streamflow observations between 1954 and 2015, mean
188   annual streamflow at La Balsa station on the Rio Santa, is 87 m^3s^{-1}, while the average annual
189   minimum discharge is 25 m^3s^{-1}, and the average annual maximum discharge is 445 m^3s^{-1}. The
190   Callejon de Huaylas is approximately 10% covered in ice (RGI Consortium, 2017), has an
191   average slope of 19° and an average elevation of 4055 m a.s.l. Glacial melt in the Rio Santa at La
192   Balsa provides 10-20% of the total annual discharge and may exceed 40% in the dry season
193   (Mark et al., 2005; Condom et al., 2012).

194   The climate of the Callejon de Huaylas is semi-arid and displays distinct precipitation
195   seasonality, with the wet season between October and May being responsible for 80% of the
196   800-1200 mm/year of precipitation (Baraer et al., 2009), and the dry season lasting from June to
197   September (Figure 2). As a localized example, the Llanganuco valley displays an average total of
198   8 mm during the dry season, and an average of total of 258 mm during the wet season months of
199   December, January, and February, based on monthly totals from 1953 to 2010 (Hellstrom et al.,
200   2017). Variations in river discharge are largely driven by seasonality of precipitation.
201   Temperature remains nearly constant in the outer tropics, with the annual variation in
202   temperature being smaller than diurnal variation (Kaser et al., 1990).

203   Figure 2.
204   A climograph from LlanWX in the Cordillera Blanca displaying the strong contrast in
205   precipitation between wet and dry seasons, while maintaining a steady temperature throughout
206   the entire year.

207

208   The geology in the Rio Santa basin is dictated by numerous tectonic and erosional
209   processes because the basin is situated along the active detachment fault of the Cordillera Blanca
210   (McNulty et al., 1998; Garver et al., 2005; Eddy et al., 2017). The highest peaks of the Cordillera

211 Blanca are composed largely of a granodiorite batholith intruded into a metamorphic unit that
212 includes hornfels, gneiss, and sulfide-rich lithologies, such as pyrite schist, phyllite, and pyrite-
213 bearing quartzite (Giovanni et al., 2010; Eddy et al., 2017). Granodiorite is found predominantly
214 in the northern portion of the range, while the southern portion of the range is made up of a
215 variety of metasediments, including quartzites and carbonates (Garver et al., 2005). The main
216 valley of the Rio Santa watershed is covered by recent sediment deposits, including alluvium,
217 landslide deposits, and glacial-fluvial fill. The impact of past and present glacier extent in the
218 topography is visible in geomorphic features throughout the range, including steep walled U-
219 shaped valleys, moraines, and proglacial lakes (Eddy et al., 2017).

220 **3 The Data**

221 In the following section, the data collected from the Cordillera Blanca are presented in
222 two collections. First, we provide a description of the meteorological stations and embedded
223 sensor network of Lascar data loggers, and then we present the time series data from the stations.
224 Second, we provide details of the setup and context of the discharge gauging station network,
225 and then conclude by presenting the time series of discharge data and general statistics from
226 them. The supplemental Figures S1 and S2 indicate missing data beyond 2020, however due to
227 travel restrictions over the past two years we have not been able to collect the up-to-date
228 measurements. Our intent is to sustain these hydrological and meteorological measurements into
229 the future once travel to the region is possible again. This future data will be available upon
230 request as it is collected.

231 **3.1 Meteorological Data**

232 The Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI) has operated
233 a relatively dense national network of meteorological stations since 1964. Air temperature is
234 provided as daily T_{max} and T_{min} (additionally measured at 07:00, 13:00 and 19:00 local time), and
235 precipitation is measured once a day. Some SENAMHI stations still provide daily temperature
236 and precipitation data through their web portal, providing data back to 1980
237 (https://www.senamhi.gob.pe/?&p=descarga-datos-hidrometeorologicos), but very few stations
238 within the Rio Santa Valley or Cordillera Blanca, Peru, remain active. Note that additional data
239 from SENAMHI are available upon request from the Swiss MeteoDat GmbH team through a
240 data portal (Schwarb et al. 2011, http://www.meteodat.ch/). In addition, the Universidad
241 Nacional Santiago Antúnez de Mayolo (UNASAM) has maintained a network of what was
242 originally 16 meteorological stations located at different elevations in the Cordillera Blanca
243 (Ancash district) since 2012. Monthly totals of precipitation data for the Rio Santa watershed
244 have been collected by Electroperú South America since 1953 although measurements were
245 interrupted in the mid-1990's with the privatization of the respective institutions when most of
246 the stations were abandoned and quality control was an issue (Kaser et al., 2003). More recent
247 installations of weather stations in the Cordillera Blanca have been mostly associated with short-

248 lived research projects typically lasting less than three years (Hofer et al., 2010; Georges and
249 Kaser, 2002). The hourly meteorological observations we describe below were collected
250 primarily from instrumentation we installed in two sub-catchments of the Rio Santa drainage
251 basin, Llanganuco, and Quilcayhuanca.

252   The Llanganuco valley is situated on the western side of the Cordillera Blanca across a
253 southwest (~240°) to northeast (~60°) axis with elevations ranging from 3400 m a.s.l. to 6746 m
254 a.s.l. Llanganuco is one of most glacierized valleys in the mountain range at 30% glacier
255 coverage, making it one of the most glacierized tropical valleys in the world. In the Llanganuco
256 catchment, our group has installed multiple weather stations dating back to 2007, although only
257 one remains active. This currently active station, labeled LlanWX, is located at 3835 m.a.s.l. near
258 the lower of the two largest valley lakes (Table 1).

259 Table 1.
260 This table provides general information about each meteorological station (WX) and lascar data
261 logger (LAS) location within the embedded sensor network. Dates with an asterisk in the "Period
262 of Operation" column indicate the station is operational.

Station	Station Valley	Elevation (m a.s.l.)	Period of Operation	Lascar Error Adjustment	Slope Angle (°)	Slope Aspect (°)	Temporal Resolution
Cuchillacocha - CuchWX	Quilcayhuanca	4642	2013-2020*	--	0	NA	30-min
Casa de Agua - CDAWX	Quilcayhuanca	3924	2013-2019*	--	0	NA	30-min
Llanganuco - LlanWX	Ranrahirca	3835	2007-2019*	Yes	0	NA	60-min
Portachuelo - PortWX	Ranrahirca	4750	2006-2015	--	0	NA	60-min
LlanUp-1/1A LAS	Ranrahirca	3955	2006-2015; 2015-2020*	No	14	301	60-min
LlanUp-2/2A LAS	Ranrahirca	4122	2006-2014; 2015-2020*	No	33	259	60-min
LlanUp-3/3A LAS	Ranrahirca	4355	2006-2015; 2015-2020*	No	31	236	60-min
LlanUp-4/4A LAS	Ranrahirca	4561	2006-2015; 2018-2020*	Yes	33	225	60-min

263

264   The embedded sensor network (ESN), as described by Hellström et al. (2010) and
265 Hellström and Mark (2006), provides the in-situ meteorological data provided in the paper. In
266 July 2007 the first automatic weather station (AWS), LlanWX, was installed near the lower lake
267 in the Llanganuco valley to collect a continuous record of point measurements of air
268 temperature, wind speed, wind direction, relative humidity, and solar irradiance (Table 2). The
269 AWS shown in Figure 3A is located in an open area on the valley floor and is surrounded by
270 *Polylepis* trees. A lascar data logger was also hung at this site for static calibration. The site is
271 protected in Huascaran National Park, and the location was previously used by the University of
272 Innsbruck for precipitation measurements. The most significant wind obstructions are the steep
273 bedrock walls of the valley toward the northwest and southeast which exceed 1000 meters above
274 the valley floor. Northerly and southerly winds are occasionally recorded by LlanWX and are
275 likely caused by turbulence or lateral winds from the uneven heating of the valley walls. Winds
276 flow parallel to the axis of the valley during approximately 92% of the recorded time and are not
277 greatly obstructed by surface vegetation. The sensors for LlanWX were originally sourced from
278 the Onset Computer Corporation and logged with an Onset HOBO® data logger
279 (http://www.onsetcomp.com) until 2014 when these loggers were replaced with an Iridium®
280 satellite Data Garrison logger (http://www.upwardinnovations.com). A 102-mm diameter

281 radiation shield was used to reduce air temperature error caused by the sun except during the
282 following years: 2007, 2011-2014. During these years a separate data logger was used as the
283 primary source for air temperature and relative humidity observations. In 2013, our team
284 upgraded the station by replacing the wind sensors with two new units from Onset and a new
285 pyranometer from Apogee (http://www.apogeeinstruments.com/pyranometer) which exceeded
286 the 1277 Wm^{-2} maximum reading of the previous Onset sensors (Covert, 2016). The
287 observations from LlanWX are largely continuous since 2007, with data gaps occurring
288 occasionally between 2010 and 2014.

289 Table 2.
290 This table details the variables, sensors, and their accuracy which are collected at the
291 meteorological stations throughout the region.

Variable	Sensor	Accuracy	Unit
Air temperature	Onset HOBO S-THB-M002 Temperature RH Smart Sensor	± 0.2 °C	°C
Precipitation	Onset HOBO S-RGB-M002 0.2 mm Rainfall tipping bucket Smart Sensor	± 0.2 mm	mm
Relative humidity	Onset HOBO Temperature RH Smart Sensor: S-THB-M002	± 2.5 %	%
Wind speed	Onset HOBO S-WSB-M003 Wind Speed Smart Sensor	± 1.1 m/s	m/s
Wind direction	Onset HOBO S-WDA-M003 Wind Direction Smart Sensor	± 5 °	°
Incoming solar radiation	Onset HOBO S-LIN-M003 Solar Radiation Smart Sensor	± 10 W/m²	W/m²
Atmospheric pressure	Onset HOBO S-BPB-CM50 Smart Barometric Pressure Sensor	± 3.0 mb	mb

292

293   A second AWS, situated at Portachuelo (referred to as PortWX in Figure 1), was installed
294   in July 2006 on a high pass at the top of the Llanganuco valley (4742 m a.s.l.). The station was
295   situated on a steep, rocky ridge between the Llanganuco valley and the Vaqueria valley. There
296   were only wind obstructions to the north due to a steep rock wall within 10 m of the station
297   location. The AWS at Portachuelo had the same sensors as its counterpart, LlanWX, however
298   was lacking an air temperature and relative humidity sensor with a radiation shield until it was
299   installed in July 2015. Prior to this upgrade, these variables were recorded each hour by a Lascar
300   data logger part of the ESN discussed in the following section. The Portachuelo station was
301   stolen in 2015 after recording data for nine years; a replacement station installed in 2016 was
302   also stolen so the site was abandoned. Gaps in weather station data is plotted in Figure S1 of the
303   Supplement.

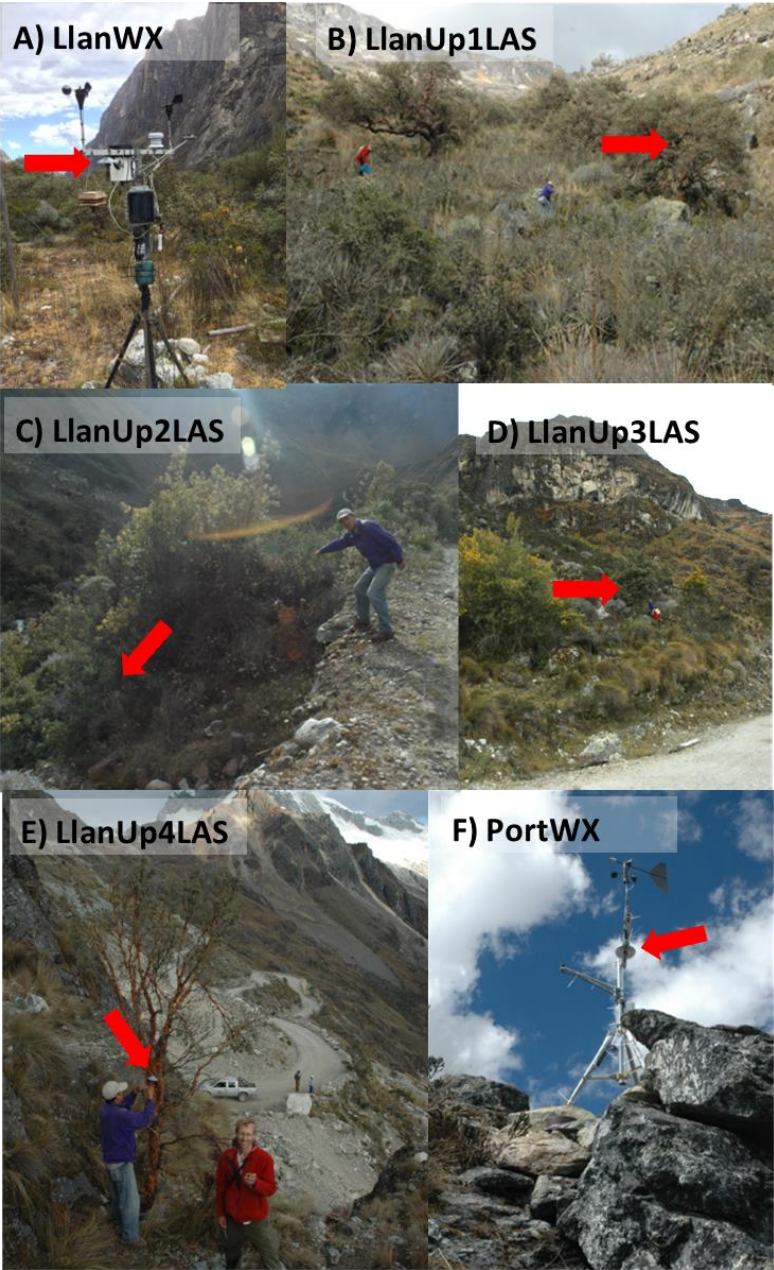
304   Figure 3.
305   The typical setup for the HOBO automatic weather station, shown here is the LlanWX station
306   near the lower lake in Llanganuco. Measurements include air temperature, humidity, wind speed
307   and direction, incoming solar radiation, and rainfall. Note also the two Lascars with different
308   radiation shields hanging from crossbar. Photographs taken by R. Hellström (Covert, 2016).

309

310   Smaller loggers measuring air temperature were installed in June 2005 to begin collecting
311   near surface temperatures to calculate lapse rates (Table 1). These data loggers were a series of 8
312   nickel sized iButton Thermochron® temperature loggers (Figure 3). Hellström et al. (2010)
313   demonstrated the effectiveness of using the Thermochron loggers for purposes of observing near
314   surface lapse rates within the Llanganuco valley between the elevations 3470 and 4740 m a.s.l.
315   (Covert, 2016). The ESN of iButtons was replaced in July 2006 with a more robust network of
316   Lascar El-USB2 data loggers (www.lascarelectronics.com) which were setup to measure air
317   temperature and relative humidity at one-hour intervals. Each Lascar logger is attached to a
318   custom-designed and locally crafted radiation shield made of a thin tin cone and two Styrofoam
319   pieces in order to reduce error caused by direct sunlight, as shown in Figure 3B. Figure 4 (from:

320 Covert, 2016) provides photos for a visual landscape context for each Lascar logger. Because the
321 LlanWX, LlanUp-4, and PortWX Lascar loggers are nearly entirely exposed to sunlight, the
322 recorded air temperature values in the dataset are higher than expected and contain greater error
323 than actual temperatures during the day (see section 4.1 for details). This Lascar network is still
324 recording hourly data.

325 Figure 4.
326 Photos A-F show the locations of all Lascar dataloggers labeled by names matching Table 1.
327 Photographs taken by B. Mark and R. Hellström (Covert, 2016).

328

329   Quilcayhuanca contains two weather stations (Table 1) similar to the LlanWX station in
330   Llanganuco valley, the lower is located at 3924 m a.s.l. near an old river diversion station called
331   Casa de Agua (station referred to as CDAWX in Figure 1), and the upper is located at 4642 m
332   a.s.l. slightly above an alpine lake, Cuchillacocha (station referred to as CuchWX in Figure 1).
333   CDAWX collects all of the same variables as LlanWX (Table 2), is still active since its
334   installation in July 2013 and data are mostly continuous over this duration. CuchWX was also
335   installed in July 2013, is still presently active, and only has one data gap lasting longer than a
336   month (from November 2016 – June 2017).

3.1.1 Relative Humidity Error Correction for LlanWX

339   In 2006 and 2007 saturation of the humidity sensor at LLanWX resulted in relative
340   humidity values greater than 100% (as high as 110%) resulting from dust and condensation on
341   the humidity sensor and persisting during the wet season for periods of up to about 48 hours,
342   with periods of reasonable humidity values during drier periods. In light of data preservation,
343   these erroneously supersaturated values were simply replaced with 100% relative humidity; this
344   correction is referred to as "Lascar Error Adjustment" in Table 1. Note that the dew point was
345   equal to the air temperature for values of relative humidity 100% or greater, so no adjustment
346   was made for dew point. The humidity sensor was replaced in June 2007 and the correction was
347   no longer needed. Both the original and corrected values are retained in the LlanWX data file.
348   There was no similar humidity error observed for PortWX or any of the LAS sensors.

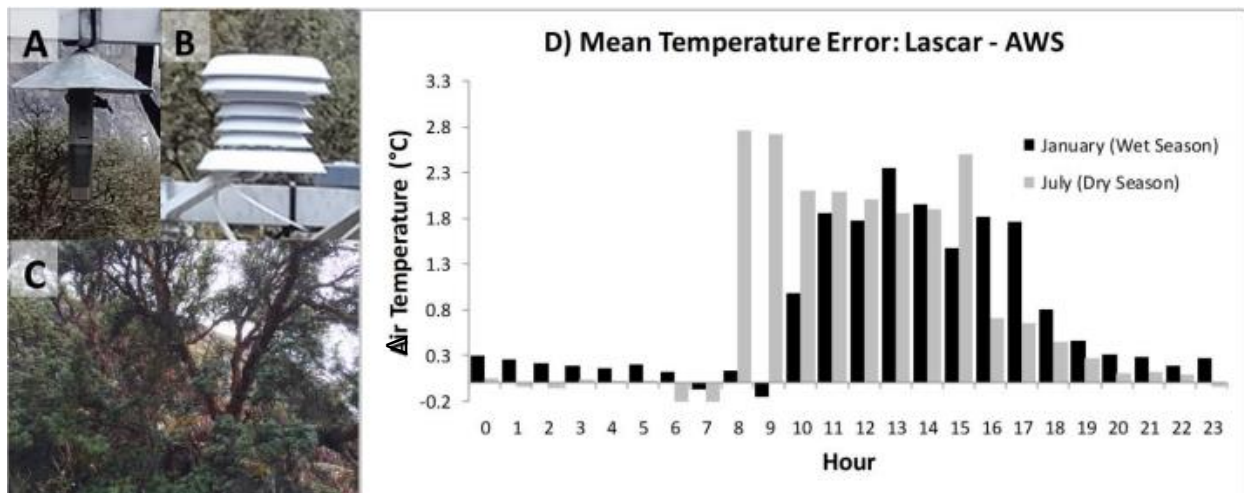
3.1.2 Radiation Error Correction for Lascar Temperature Loggers

350   A year-long comparison between the Lascar (Figure 5) and LlanWX AWS temperature
351   sensors indicated an expected error in the Lascar that was largely dependent on the time of day.
352   Variability in temperature bias due to solar radiative heating is likely caused by changes in solar
353   angle and cloud cover patterns, particularly during the dry season. It is well documented that
354   daytime temperature error rises on sunny days with calm wind and is reduced on windy and
355   cloudy days regardless of the season but is far more prominent during the dry season in the
356   tropical Andes (Georges and Kaser, 2002). It is important to note that snow cover, which can
357   create larger biases in temperature by reflected solar radiation, is minimal throughout the year at
358   the locations of the Lascars in this study. Over an entire month, nightly error was within the 0.5
359   °C resolution of the Lascar sensor. The occasional occurrence of greater nighttime error could be
360   caused by the sensor capturing longwave radiation emitted by the surface. The primary source of
361   consistent instrumentation error for air temperature measurements is the heating of radiation
362   shields from those locations exposed to direct sunlight, which required bias correction according
363   to Figure 5. We bias-corrected for radiation error using comparison with the LlanWX shielded
364   temperature and Lascar logger hanging next to it under the same exposure, including the
365   LlanWX, LlanUp-4 LAS, and PortWX station locations. We conducted this same comparison
366   when replacing Lascar sensors in 2015 and found no significant differences between old and new

367 sensors. Because solar radiation is the predominant source of error, corrections were only applied
368 to daylight hours between 07:00 to 19:00 (Covert, 2016). Future studies may consider thicker or
369 more encased radiation shields for temperature data loggers in tropical regions. Our group has
370 created and used a variety of styles of radiation shields as seen in Figure 5.

371

372 Figure 5.
373 Image A displays a Lascar data logger connected to its cone radiation shield. Two white
374 Styrofoam plates beneath the cone insulate the sensor from radiative heating. Image B shows the
375 radiation shields used on the AWS in comparison to the Lascar setup in image A. Image C shows
376 polylepis trees which are used to hide and shade Lascars in order to obtain accurate temperature
377 and relative humidity values. A comparison test between the Lascar setup and the AWS radiation
378 shield with no shading yielded the expected errors shown in graph D. Positive values indicate
379 that the Lascar reported a temperature higher than the AWS sensor. Photographs taken by R.
380 Hellström (Covert, 2016).

381

3.1.3 Data Gaps and Other Quality Control Checks

383   The most common reasons for gaps in data was either loss of sensors due to theft or
384 inability to access sensors because of logistical reasons, such as poor weather conditions or
385 human error during downloading or redeploying of sensors. In addition to corrections for solar
386 radiation heating and the relative humidity correction, humidity and temperature records were
387 assessed for accuracy and outliers removed if there were unrealistic deviations from the previous
388 24-hour trend of conditions within the valley. Most of these deviations occurred during time
389 intervals coincident with sensor deployment, battery replacement or data download, although
390 data (less than 1%) were also removed if there was a concern with the integrity of the sensor.
391 The four Lascar loggers were replaced or had new radiation shields installed in June 2015, and
392 likewise renamed in the dataset as LlanUp-1A, 2A, 3A, and 4A.

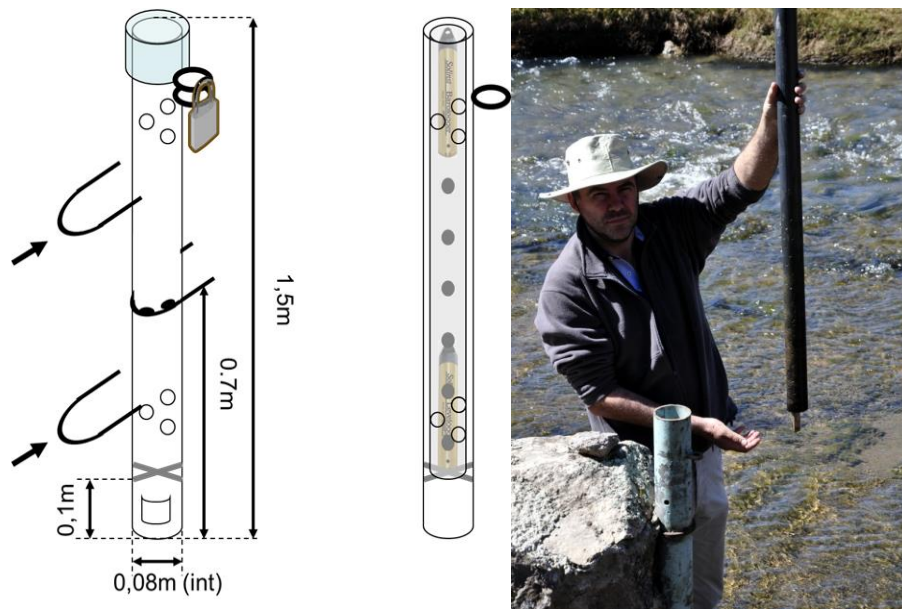
3.2 Hydrological Data

394   The La Balsa gauge (8.87° S, 77.82° W at 1880 m a.s.l.) (Duke Energy, Orazul Energy,
395   Inkia Energy) near the diversion canal for the Cañon del Pato hydroelectric plant has a nearly
396   complete record since 1954, acting as a long-term reference point for discharge on the Rio Santa
397   at the base of the Callejon de Huaylas basin. Many other stream gauges and precipitation stations
398   were put in place by the hydroelectric companies, however, due to the lack of maintenance these
399   stations became unusable after the mid-1990's. In 2008, The Ohio State University, McGill
400   University, IRD, and the Peruvian glaciology unit of ANA commenced a joint project to
401   reinstitute a stream gauging network throughout the Cordillera Blanca (Baraer et al., 2012).
402   Many of these redeployed stream gauges in sub-catchments of the Rio Santa are still in working
403   condition and are continuing to be monitored.

404   The stream gauges comprise custom-designed and locally crafted steel stilling wells
405   containing two Solinst leveloggers (Figure 6), with one measuring total pressure (water plus
406   atmospheric), and the other measuring barometric pressure. The Model 3001 Solinst levelogger
407   Edge has an accuracy of $\pm$ 0.05 kPa and a resolution of 0.002% Full Scale (FS) for pressure and
408   a temperature accuracy of $\pm$ 0.05° C, and a temperature resolution of 0.003° C
409   (www.solinst.com). Water level is continuously monitored at these gauges at a temporal
410   resolution of 15-minutes by subtracting atmospheric pressure from the total pressure. The
411   adjusted water level variable in the discharge datasets indicates the adjustment based on where
412   the water level logger was located in the water column. This measurement is conducted in the
413   field using a built-in meter stick at each gauging station. Many factors influence the uncertainty
414   of discharge measurements, especially in smaller, turbid streams (McMillan et al., 2012). First,
415   the Solinst levelogger instruments used have accuracies and resolutions provided by the
416   company as a percentage of FS as indicated above. Second, we estimate a $\pm$ 2 mm variation in
417   water stage due to the turbulent nature of the streams in the region. These streams have a variety
418   of bed surfaces, ranging from weedy to rocky, and flat to rolling, which are constantly modified
419   by high flows during each year. Each stage and discharge field measurement are influenced by
420   these small to large changes in the stream bed and the timing and location at which the discharge
421   is measured. Finally, stage-discharge rating curves inherently introduce variable amounts of error
422   depending on high or low flows, and how frequently they are updated. Stage-discharge rating
423   curves at all stations were established and verified by conducting discharge measurements using
424   the velocity area method. Prior to publishing this dataset, one updated rating curve was fitted for
425   all the data at each site, helping standardize the measurements and uncertainty in the data. All
426   rating curves developed from discharge measurements in the field are assessed by their fit and
427   significance to a quadratic function. All rating curves display R^2 values above 0.85, except for
428   Cuchillacocha, which provides an R^2 value of 0.71. This slightly lower R^2 value at Cuchillacocha
429   is likely due to the under-representation of high flows in the field measurements, and overall
430   lower flow volumes recorded at this site. Uncertainties (using standard error at 95% uncertainty
431   intervals) were calculated for all rating curves, indicating average error ranging from $\pm$ 3–20%
432   for low flows, and $\pm$ 4–70% during high flows. These error values are standard when using a
433   stage-discharge rating curve as described in Kiang et al. (2018), and McMillan et al. (2012).

434 Rating curves can be further constrained, and their variation better understood with the addition
435 of more high flow discharge point measurements (McMillan et al., 2010; Coxon et el., 2014). All
436 rating curves are available upon request. Unavailable data is denoted by "NA" in the dataset.
437 Linear interpolation of missing data was only calculated for missing periods of less than 1 hour,
438 coinciding with the time the leveloggers were being downloaded in the field. Other than these
439 short periods of interpolated data, the datasets provided consist of raw data. Gaps of missing
440 streamflow data are plotted in Figure S2 in the Supplement accompanying this paper.

441 Figure 6.
442 Figure 6 illustrates the design of the stilling wells used to collect total pressure (water +
443 barometric) and barometric pressure. The photograph shows the stilling well and the insert tube
444 containing the pressure data loggers.

445

446 The stream gauges that were installed in 2008 and 2009 and which are continuing to
447 collect discharge are Casa de Agua, Cuchillacocha, Pachacoto, Llanganuco, and Querococha
448 (Figure 1). The Pumapampa gauge went out of commission in 2016 but is also included in this
449 dataset (Table 3). These stream gauges have variable lengths of record due to periods of missing
450 data, but still provide valuable streamflow information in a region where stream records are
451 limited. As shown in the map (Figure 1), two pairs of these stream gauges are located at different
452 points along the same Rio Santa tributary in their respective sub-catchments: Pumapampa and
453 Pachacoto in the Pachocoto valley; and Cuchillacocha and Casa de Agua in the Quilcayhuanca
454 valley. All discharge measurements are calculated from rating curves containing a minimum of
455 eight, point measurements throughout all times of the year. As mentioned above, rating curves
456 are not directly provided in this data paper because they are variable in nature as we collect new
457 discharge measurements in the field. The following two subsections provide a brief overview and
458 summary for each gauging station, organized by general location in the Cordillera Blanca,

459   moving from the southern end of the mountain range to the northern. Note that all glacier
460   coverage is calculated from RGI 6.0 (RGI Consortium, 2017).

461   Table 3.
462   This table provides geographical information about each of the hydrological gauging stations.
463   Elevations are recorded at bank of stream. Note that all glacier coverage is calculated from RGI
464   6.0 (RGI Consortium, 2017). Dates with an asterisk in the "Period of Operation" column indicate
465   the station is operational.

Station	Station Valley	Latitude	Longitude	Elevation (m a.s.l.)	Period of Operation	Contributing Area (km²)	Percent basin covered in ice (%)
Cuchillacocha - CuchQ	Quilcayhuanca	-9.41	-77.35	4631	2008-2019*	4.1	60.49
Casa de Agua - CDAQ	Quilcayhuanca	-9.46	-77.37	3948	2009-2019*	66.9	24.78
Pumapampa - PumQ	Pachacoto	-9.88	-77.24	4287	2008-2016	58.1	8.33
Pachacoto - PachQ	Pachacoto	-9.85	-77.4	3738	2008-2020*	202.3	4.95
Llanganuco - LlanQ	Ranrahirca	-9.07	-77.65	3850	2008-2021*	86.9	30.32
Querococha - QuerQ	Querococha	-9.72	-77.33	4005	2008-2019*	62.9	1.53

466

3.2.1 The southern Cordillera Blanca

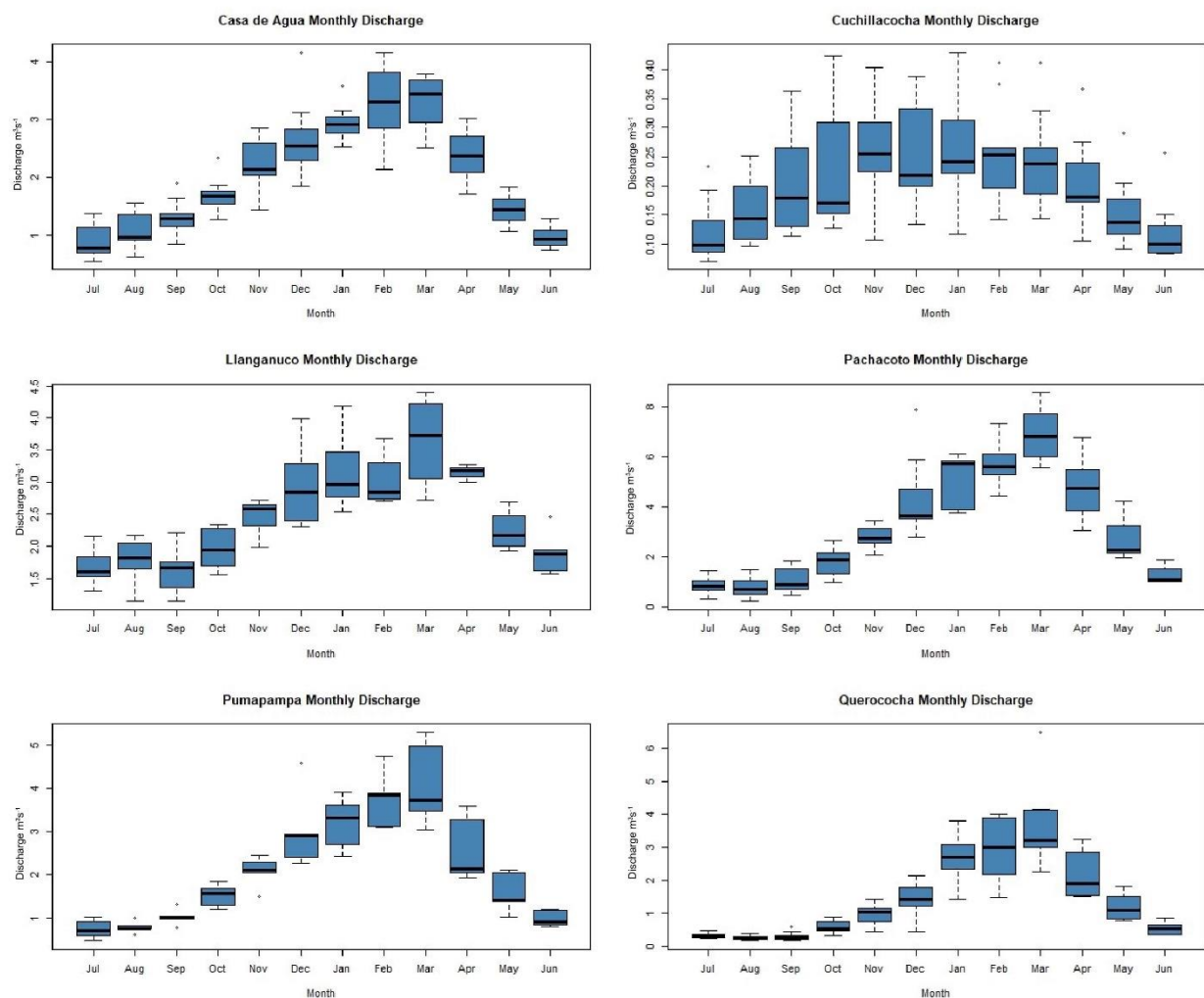
468   The Pumapampa catchment encompasses 58 km^2 with about 8% being covered by
469   glaciers (Table 3). Pumapampa gauge (referred to as PumQ in Figure 1) is located at 4287 m
470   a.s.l., below Nevado Pastoruri at the southern end of the Cordillera Blanca. This stream gauge is
471   situated in a channel through a low-lying meadow, where wet-season flow exceeds bankfull
472   stage, causing inaccuracies in high discharge measurements. Most notably, a series of values in
473   late-February 2014 indicated a peak discharge of 25 m^{3}s^{-1}, well above extremes measured from
474   the rating curve. It was determined that during this period the levelloggers were overrun by water
475   and measurements became unreliable solely during this flooding event. Outside of this event,
476   discharge at Pumapampa is consistently within the measured values on the rating curve. Mean
477   annual streamflow (averaged from three years of data missing less than one-month during the
478   entire year) at this stream gauge was 2.3 m^{3}s^{-1} and a specific discharge of 1248 mm a^{-1}. Mean
479   streamflow during the dry season (May through September) in Pumapampa was 1 m^{3}s^{-1}, while
480   the mean streamflow during the wet season (October through April) was 2.9 m^{3}s^{-1}. Highest mean
481   monthly streamflow occurred in March 2014 with an average of 5.3 m^{3}s^{-1} (Figure 7).

482   The Pachacoto gauge (referred to as PachQ in Figure 1) measures discharge 19 km
483   downstream from Pumapampa, at 3738 m a.s.l., just above its confluence with the Rio Santa.
484   Streamflow at Pachacoto is significantly greater than Pumapampa as it is the drainage point for a
485   larger area of 202 km^2, 5% of which is covered by glaciers. The mean annual streamflow at
486   Pachacoto was 3.2 m^{3}s^{-1}, averaged from the seven near-complete years of data, with a calculated
487   specific discharge of 499 mm a^{-1}. Dry season runoff accounted for approximately 20% of the
488   annual streamflow by volume, while the majority of the remaining wet season runoff occurred
489   during February and March.

490   Streamflow at another tributary catchment in the southern Cordillera Blanca is recorded
491   at the Querococha gauge (referred to as QuerQ in Figure 1) at 4005 m a.s.l., located 100 m

492 downstream of Querococha lake and defining a drainage area of 63 km², 1.5% of which is
493 glacierized. This drainage collects from two sub-catchments, one of which is entirely glacier-
494 free, while the other contains rapidly receding ice masses including the Yanamarey glacier.
495 Using five years of complete data, the mean annual streamflow at this gauging station was
496 calculated to be 1.4 m³s⁻¹ and the specific discharge was 702 mm a⁻¹. The streamflow from this
497 gauge is somewhat regulated by Querococha, the second largest lake in the Cordillera Blanca.
498 This catchment has featured many previous research studies and many other instruments
499 throughout the basin are still consistently monitored by ANA.

500 Figure 7.
501 Figure 7 shows the monthly discharge, in m³s⁻¹, at each of the gauging stations described in this
502 study calculated from all complete months of data for each station. The strong seasonal pattern is
503 clearly visible at most of the stream gauges.

504

505 **3.2.2 The central and northern Cordillera Blanca**

506   Another catchment that contains two streamflow gauges is Quilcayhuanca, a valley
507   directly above the region's most populous city, Huaraz. The higher elevation stream gauge is
508   Cuchillacocha (referred to as CuchQ in Figure 1) which is situated at 4631 m a.s.l. and measures
509   discharge below a high-alpine lake and two cirque glaciers encompassing a drainage area of 4
510   km^2 (with 61% of the basin covered in ice). This station displays a noticeably different discharge
511   pattern throughout the year than the lower gauging stations which collect greater runoff.
512   Cuchillacocha discharge is not defined by a strong wet-dry season fluctuation, instead displaying
513   more variability each month and rising to peak values much earlier in the wet season than other
514   stream gauges. The average streamflow values at this location are also an order of magnitude
515   lower than other gauging stations due to the small drainage area it collects from (Figure 7).

516   The stream gauge located at a lower elevation in the Quilcayhuanca valley is Casa de
517   Agua (referred to as CDAQ in Figure 1) at 3948 m a.s.l. This gauging station is found near a
518   channel cut in the stream, in a large meadow, where water was previously rerouted for
519   agricultural purposes. This gauge collects drainage from an area of 67 km^2 below the confluence
520   of two upper catchments, Cuchillacocha and Cayesh, well above the city of Huaraz (3100 m
521   a.s.l.). From this drainage point in the watershed, the basin is approximately 25% glacierized.
522   The mean annual streamflow, calculated from six complete years of data at Casa de Agua, was 2
523   m^{3}s^{-1}, with a specific discharge of 943 mm a^{-1}.

524   The last streamflow gauge still recording data, Llanganuco (referred to as LlanQ in
525   Figure 1), is named after the valley it is located in and is positioned at 3850 m a.s.l., below two
526   valley lakes and a catchment area of 87 km^2, 30% of which is currently glacierized. The mean
527   annual streamflow, calculated from three complete years of data, was 2.3 m^{3}s^{-1}, with a specific
528   discharge of 835 mm a^{-1}. A stream gauge has been in commission at Llanganuco on and off for
529   68 years, beginning as a gauge for UGRH and hydroelectric companies and later, after the
530   original station became defunct, a site for our new, higher temporal resolution network of
531   gauges.

532   **4 Data availability**

533   The datasets presented here are available freely from
534   https://doi.org/10.4211/hs.c35ae06cb26041b096dd07e1cbf8ebf5 (Mateo et al., 2021). The
535   hydrological and meteorological data from the Cordillera Blanca have been used in short
536   segments in previous studies (Baraer et al., 2012; Baraer et al., 2015). Data availability varies
537   from station to station depending on location of loggers and instrumental errors which caused
538   periods of time to lapse without data being recorded. These datasets represent a majority of the
539   streamflow and meteorological data collected by our research group over the past two decades
540   collected at a high temporal resolution of 15-30 minutes. These include point discharge
541   measurements and short-time periods of 1-minute temporal resolution meteorological
542   measurements. The data provided here will be added to as future field seasons occur and the

543 effort to provide hydrometeorological data to the scientific community will continue at all of the
544 involved universities and institutions.

545 **5 Conclusions**

546   The Cordillera Blanca in the tropical Andes of Peru is a unique, high mountain region
547 where high resolution meteorological and hydrological time series observations collected from a
548 network of instruments over the past two decades have been compiled in a new dataset. The
549 region has been the focus of glacier monitoring efforts for nearly a century. While daily-to-
550 monthly time series of meteorological and hydrological observations have been recorded
551 discontinuously for nearly 70 years, there was no generalized sub-daily data monitoring until the
552 early 2000s. Maintaining this network of instruments recording high-temporal resolution data has
553 involved traveling to remote areas of the Cordillera Blanca, protecting the instruments from the
554 harsh weather conditions at high elevations, and concealing instruments to prevent theft. There is
555 also difficulty in developing long-term strategies because most funding agencies are focused on
556 short-term based projects and do not fund continuous monitoring and maintenance of data
557 collection networks. In the context of ongoing global climate change with variable localized
558 extremes, long-term monitoring of hydrometeorological variables is of utmost importance to
559 document and understand the changes that are occurring.

560   The datasets collected and described in this paper support investigations into climate
561 evolution, water resource availability, and hydrological changes across the Cordillera Blanca in
562 the past twenty-years. These datasets will also provide valuable, easy-to-access observations for
563 local water resource managers. This paper provides an overview of the variables which have
564 been measured and what is being made available as of 2021. Future measurements recorded in
565 the field will be made available as they are collected, to further build on the available hydro-
566 meteorological database in the Cordillera Blanca.

567 **Author Contribution**

568 EM prepared the manuscript with contributions from co-authors. EM, RH and MB curated the
569 data in preparation for this article. BGM acquired the initial funding for this international
570 research collaboration and instrumental network. All authors collaborated in fieldwork gathering
571 data and maintaining the instruments and dataloggers.

572 **Competing Interests**

573 The authors declare that they have no conflict of interest.

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