High temporal resolution hydrometeorological data collected in the tropical Cordillera Blanca, Peru (2004-2020)

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Abstract. This article presents a comprehensive hydrometeorological dataset collected over the past two decades throughout the Cordillera Blanca, Peru. The data recording sites, located in the upper portion of the Rio Santa valley, also known as the Callejon de Huaylas, span an elevation range of 3738 - 4750 m a.s.l. As many historical hydrological stations measuring daily discharge across the region became defunct after their installation in the 1950s, there was a need for new stations to be installed and an opportunity to increase the temporal resolution of the streamflow observations. Through inter-institutional collaboration the hydrometeorological network described in this paper was deployed with goals to evaluate how progressive glacier mass loss was impacting stream hydrology, and to better understand the local manifestation of climate change over diurnal to seasonal and interannual time scales. The four automatic weather stations supply detailed meteorological observations, and are situated in a variety of mountain landscapes, with one on a high-mountain pass, another next to a glacial lake, and two in glacially carved valleys. Four additional temperature and relative humidity loggers complement the weather stations within the Llanganuco valley by providing these data across an elevation gradient. The six streamflow gauges are located in tributaries to the Rio Santa and collect high temporal resolution runoff data. The datasets presented here are available freely from https://doi.org/10.4211/hs.506c1f66f87e4004b84e6af4097853a4 https://doi.org/10.4211/hs.c35ae06cb26041b096dd07e1cbf8ebf5 (Mateo et al., 2021). Combined, the hydrological and meteorological data collected throughout the Cordillera Blanca enable detailed research of atmospheric and hydrological processes in tropical high-mountain terrain.

57

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

95   the discharge observations makes it difficult to track down all available historical data. Also,

96   many of the hydrological stations have become defunct since they were installed in the 1950s,

97   creating a need for new stations to be installed for continuous monitoring of the region. A further

98   benefit of installing a new hydrological monitoring network in the 2000s was to significantly

99   increase the temporal resolution of the discharge observations.

100   Collaborating researchers from The Ohio State University, Bridgewater State University

101   and McGill University initiated a network of embedded environmental sensors in 2005. The

102   main goals of the instrument arrays were to evaluate how progressive glacier mass loss was

103   impacting stream hydrology, and to better understand the local manifestation of climate change

104   on the variability and controls of local weather phenomena over diurnal to seasonal and

105   interannual time scales. In order to create a sustainable network for continuous, long-term

106   observation, this project has been maintained in close collaboration with Peruvian researchers

107   and government agencies, as well as with other international scientists to leverage resources in

108   maintaining instruments, in exchange for openly sharing data.

109   The instrumentation for the data collection we present in this work was installed and

110   maintained under a collaborative work agreement ("convenio") formalized with the Peruvian

111   government agency overseeing the office in Huaraz (Peruvian Institute of Natural Resources

112   (INRENA) and the Autoridad Nacional del Agua (ANA)). This work agreement involved a

113   secondary collaboration with other international researchers who shared in installing and

114   calibrating the instrumentation. Specifically, Dr. Thomas Condom of the French Institut de

115   Recherche pour le Developpement (IRD) joined the agreement to install and maintain a series of

116   stream gauges logging water stage at 15-minute intervals. We also collaborated with the Austrian

117   research team of Dr. Irme Juen and Professor Georg Kaser from the Universitat Innsbruck,

118   Austria, who co-located a precipitation gauge with our weather station in Llanganuco. Further

119   details about the instrumentation are provided below.

120   Inter-institutional collaboration in this fashion has provided an effective partnership to

121   aid in maintaining the instrumentation over time, but also introduces challenges of logistical

122   coordination and data continuity. Visitation as non-resident international scientists to the field

123   sites has been feasible only one or two times annually. Thus, the Peruvians in our collaboration

124   have incorporated our instruments within their routine monitoring network. This has permitted

125   regular observations of stations and instruments to download data loggers, perform stream

126   discharge measurement to build a rating curve, and undertake a limited range of repair work.

127   However, limitations in local resources and manpower in Peru have often prevented recordings

128   of stage observation and discharge measurement to constrain rating curves. Likewise, having

129   multiple operators also increases some risk for data recovery errors. For instance, loggers that are

130   improperly relaunched after data downloads can jeopardize subsequent acquisitions. Having

131   more frequent site visits can allow for interventions, but also incurs increased risk of operator

132   error. Furthermore, Peruvian domestic political changes have disrupted the operations by

133   introducing different leadership, with altered operational priorities and resources, which directly
134   or indirectly interrupt the continuity of trained personnel responsible for data recovery and
135   preservation. Overcoming the many challenges of maintaining the instrumentation and
136   constructing rating curves has required regular cross-cultural communication, multiple and
137   annual visitation to the region. Likewise, the rating curves continue to be refined as additional
138   measurements are made.

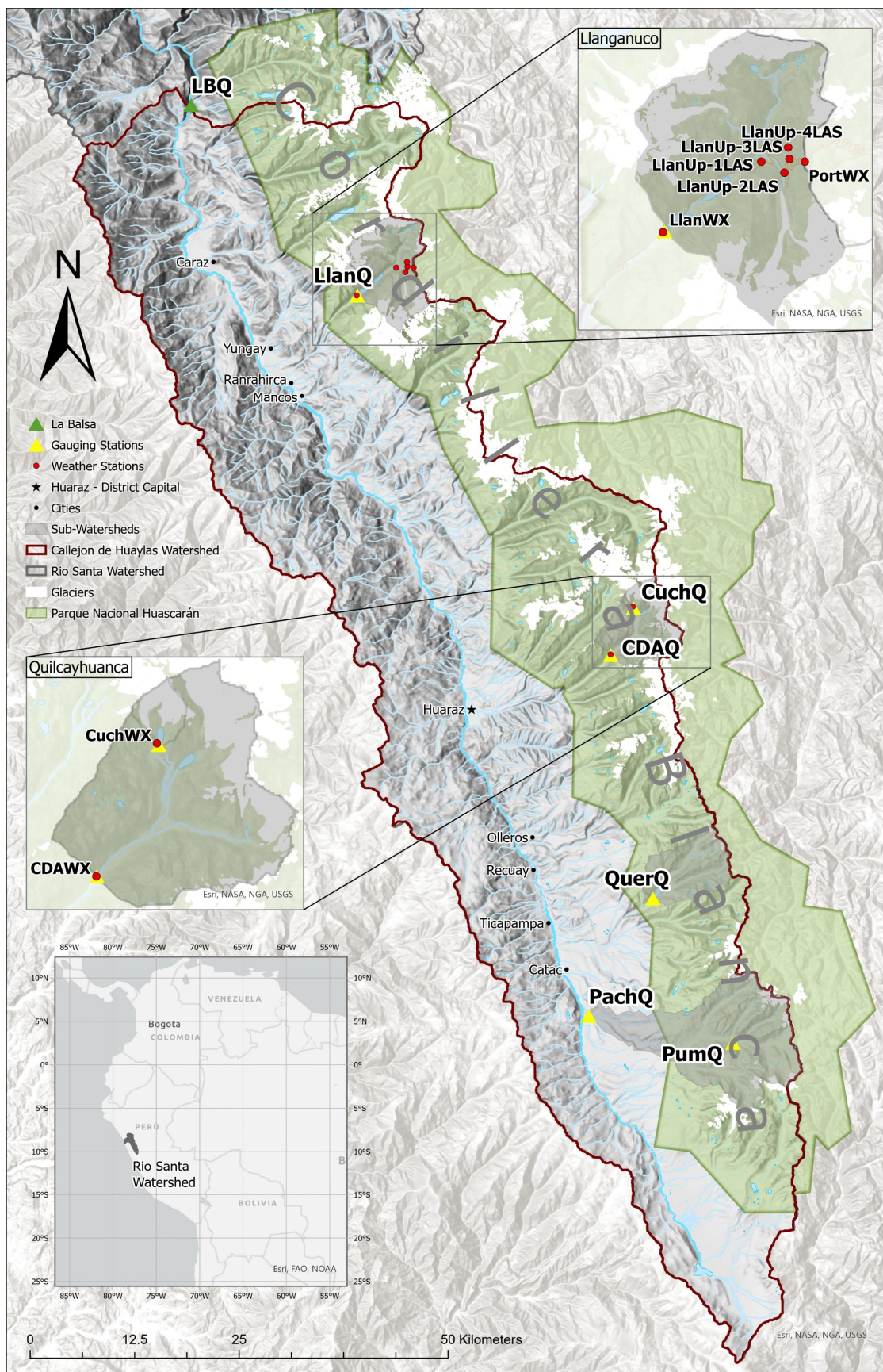
139   Our collaborative observations have provided important new insights into how the
140   hydroclimate of the region is changing on different scales. Updated discharge and climate
141   observations in specific glacier catchments documented important shifts in seasonal supply of
142   glacier storage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

155   In this paper, we document available data from the Cordillera Blanca area collected over
156   the past 15 years. It is separated into (i) meteorological data recorded by permanently installed
157   automatic temperature and relative humidity loggers (Lascars), or automatic weather stations,
158   and (ii) hydrological data consisting of stage and discharge data from multiple sub-catchments.
159   The data are stored in .csv extension format on Consortium of Universities for the Advancement
160   of Hydrologic Science, Inc. (CUAHSI) Hydroshare:
161   https://doi.org/10.4211/hs.506c1f66f87e4004b84e6af4097853a4
162   https://doi.org/10.4211/hs.c35ae06cb26041b096dd07e1cbf8ebf5 (Mateo et al., 2021). The data
163   collection consists of multiple time series of point observations from both meteorological and
164   hydrological measurement sites. These high-temporal resolution data provide detailed insight
165   into the complex hydro-meteorological system of the tropical Cordillera Blanca.

166   **2 Study Area - Cordillera Blanca**

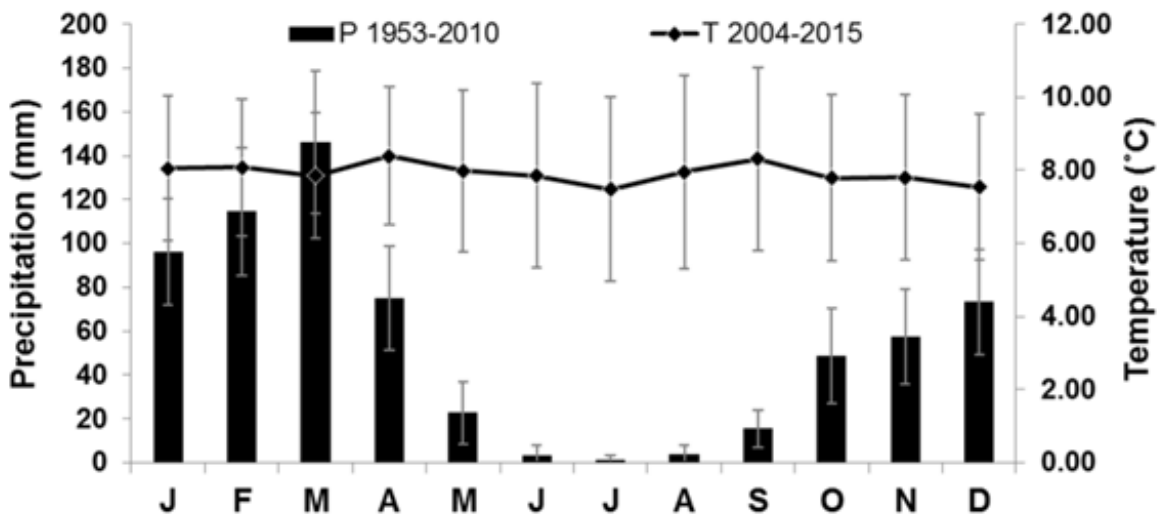
167   The Rio Santa (Santa River) captures runoff from the western side of the glacierized
168   Cordillera Blanca and the eastern side of the non-glacierized Cordillera Negra, encompassing a
169   drainage area of 11636 km^2 at the outlet to the Pacific Ocean. While the headwaters of the Rio

170 Santa are found at Laguna Conococha at 4100 m above sea level (a.s.l.), the highest point in the
171 basin (and in Peru) is the summit of Huascaran at 6768 m a.s.l. The average slope of the entire
172 drainage basin is 20.6° and its average elevation is 3374 m a.s.l. calculated from a 3 m resolution
173 DEM of the region. The Rio Santa flows over 300 km northwest from its origin at Laguna
174 Conococha, an alpine lake at 4000 m a.s.l., to its outlet into the Pacific Ocean, near Chimbote.
175 The Callejon de Huaylas refers to the upper section of the Rio Santa, comprising approximately
176 4773 km^2 located above the Cañon del Pato 50 MW hydroelectric generation plant in Huallanca
177 (Figure 1). The Rio Santa basin is home to three other hydroelectric plants and provides water to
178 the expansive Chavimochic irrigation district near the coast (Mark and McKenzie, 2007). The
179 discharge on the Rio Santa has been carefully monitored since the Cañon del Pato dam began
180 operating in the 1950s, however, only one station near the dam remains active which is situated
181 slightly upstream at La Balsa (labeled as LBQ in Figure 1).

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

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

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

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

209

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

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

222 **3 The Data**

223   In the following section, the data collected from the Cordillera Blanca are presented in
224 two collections. First, we provide a description of the meteorological stations and embedded
225 sensor network of Lascar data loggers, and then we present the time series data from the stations.
226 Second, we provide details of the setup and context of the discharge gauging station network,
227 and then conclude by presenting the time series of discharge data and general statistics from
228 them. The ~~supplemental~~ Figures A~~S~~1, ~~and S~~A2, and A3 in the Appendix, indicate missing data
229 beyond 2020, however due to travel restrictions over the past two years we have not been able to
230 collect the up-to-date measurements. Our intent is to sustain these hydrological and
231 meteorological measurements into the future once travel to the region is possible again. This
232 future data will be available upon request as it is collected.

233 **3.1 Meteorological Data**

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

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

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

261   Table 1.
262   This table provides general information about each meteorological station (WX) and lascar data
263   logger (LAS) location within the embedded sensor network. Dates with an asterisk in the "Period
264   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

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

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

291 Table 2.
292 This table details the variables, sensors, and their accuracy which are collected at the
293 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

294

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

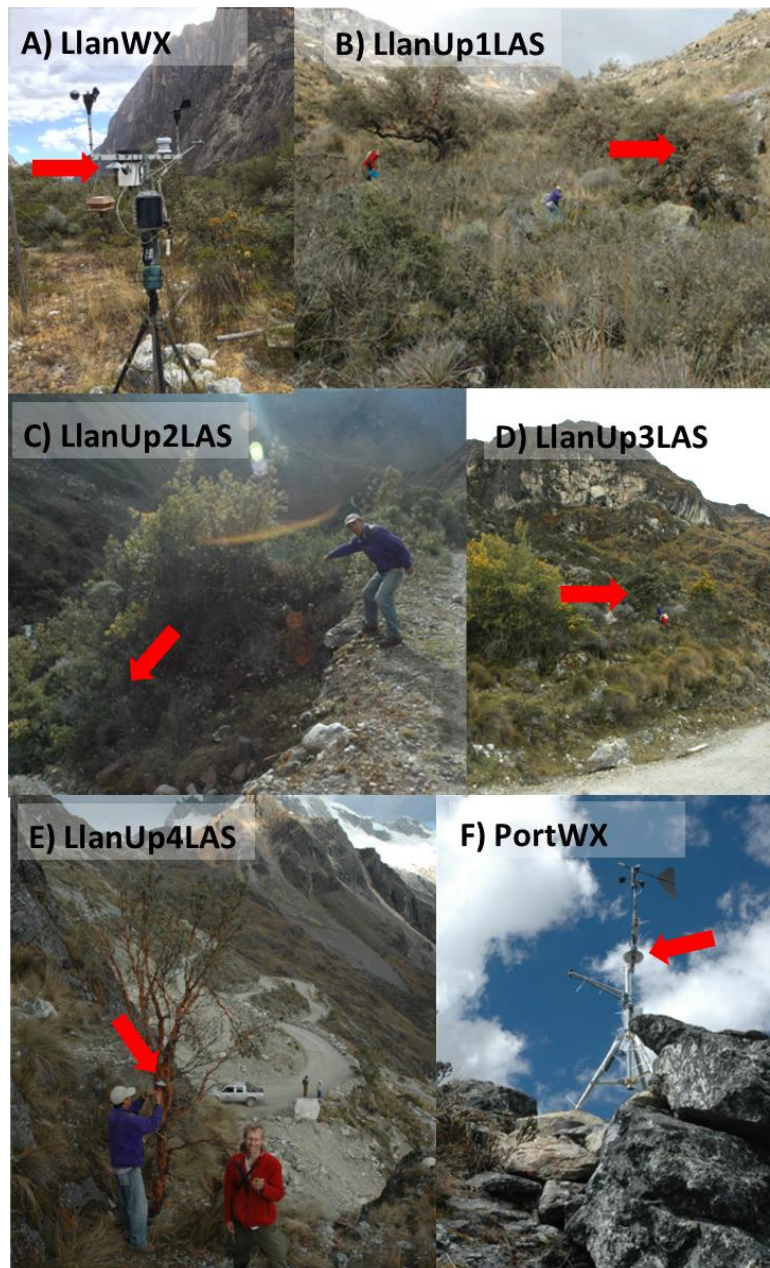
306   Figure 3.
307   The typical setup for the HOBO automatic weather station, shown here is the LlanWX station
308   near the lower lake in Llanganuco. Measurements include air temperature, humidity, wind speed
309   and direction, incoming solar radiation, and rainfall. Note also the two Lascars with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

311

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

322   Covert, 2016) provides photos for a visual landscape context for each Lascar logger. Because the
323   LlanWX, LlanUp-4, and PortWX Lascar loggers are nearly entirely exposed to sunlight, the
324   recorded air temperature values in the dataset are higher than expected and contain greater error
325   than actual temperatures during the day (see section 4.1 for details). This Lascar network is still
326   recording hourly data. The Lascar network does not have any gaps in its time series; thus, it is
327   not included in the Appendix.

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

331

332   Quilcayhuanca contains two weather stations (Table 1) similar to the LlanWX station in
333 Llanganuco valley, the lower is located at 3924 m a.s.l. near an old river diversion station called
334 Casa de Agua (station referred to as CDAWX in Figure 1), and the upper is located at 4642 m
335 a.s.l. slightly above an alpine lake, Cuchillacocha (station referred to as CuchWX in Figure 1).
336 CDAWX collects all of the same variables as LlanWX (Table 2), is still active since its
337 installation in July 2013 and data are mostly continuous over this duration. CuchWX was also
338 installed in July 2013, is still presently active, and only has one data gap lasting longer than a
339 month (from November 2016 – June 2017). The data presented here conclude in 2020, but
340 ongoing data extensions will be provided through the repository.

3.1.1 Relative Humidity Error Correction for LlanWX

343   In 2006 and 2007 saturation of the humidity sensor at LLanWX resulted in relative
344 humidity values greater than 100% (as high as 110%) resulting from dust and condensation on
345 the humidity sensor and persisting during the wet season for periods of up to about 48 hours,
346 with periods of reasonable humidity values during drier periods. In light of data preservation,
347 these erroneously supersaturated values were simply replaced with 100% relative humidity; this
348 correction is referred to as "Lascar Error Adjustment" in Table 1. Note that the dew point was
349 equal to the air temperature for values of relative humidity 100% or greater, so no adjustment
350 was made for dew point. The humidity sensor was replaced in June 2007 and the correction was
351 no longer needed. Both the original and corrected values are retained in the LlanWX data file.
352 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

354   A year-long comparison between the Lascar (Figure 5) and LlanWX AWS temperature
355 sensors indicated an expected error in the Lascar that was largely dependent on the time of day.
356 Variability in temperature bias due to solar radiative heating is likely caused by changes in solar
357 angle and cloud cover patterns, particularly during the dry season. It is well documented that
358 daytime temperature error rises on sunny days with calm wind and is reduced on windy and
359 cloudy days regardless of the season but is far more prominent during the dry season in the
360 tropical Andes (Georges and Kaser, 2002). It is important to note that snow cover, which can
361 create larger biases in temperature by reflected solar radiation, is minimal throughout the year at
362 the locations of the Lascars in this study. Over an entire month, nightly error was within the 0.5
363 °C resolution of the Lascar sensor. The occasional occurrence of greater nighttime error could be
364 caused by the sensor capturing longwave radiation emitted by the surface. The primary source of
365 consistent instrumentation error for air temperature measurements is the heating of radiation
366 shields from those locations exposed to direct sunlight, which required bias correction according
367 to Figure 5. We bias-corrected for radiation error using comparison with the LlanWX shielded
368 temperature and Lascar logger hanging next to it under the same exposure, including the
369 LlanWX, LlanUp-4 LAS, and PortWX station locations. We conducted this same comparison

370   when replacing Lascar sensors in 2015 and found no significant differences between old and new
371   sensors. Because solar radiation is the predominant source of error, corrections were only applied
372   to daylight hours between 07:00 to 19:00 (Covert, 2016). Future studies may consider thicker or
373   more encased radiation shields for temperature data loggers in tropical regions. Our group has
374   created and used a variety of styles of radiation shields as seen in Figure 5.
375
376   Figure 5.
377   Image A displays a Lascar data logger connected to its cone radiation shield. Two white
378   Styrofoam plates beneath the cone insulate the sensor from radiative heating. Image B shows the
379   radiation shields used on the AWS in comparison to the Lascar setup in image A. Image C shows
380   polylepis trees which are used to hide and shade Lascars in order to obtain accurate temperature
381   and relative humidity values. A comparison test between the Lascar setup and the AWS radiation
382   shield with no shading yielded the expected errors shown in graph D. Positive values indicate
383   that the Lascar reported a temperature higher than the AWS sensor. Photographs taken by R.
384   Hellström (Covert, 2016).

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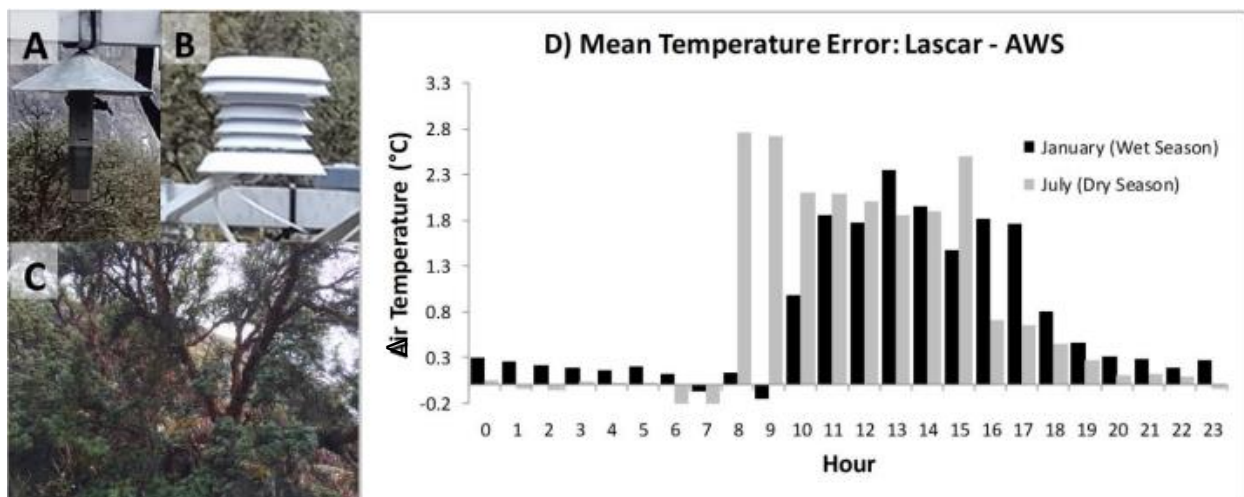
386   **3.1.3 Data Gaps and Other Quality Control Checks**
387   The most common reasons for gaps in weather data was either loss of sensors due to theft
388   or inability to access sensors because of logistical reasons, such as poor weather conditions or
389   human error during downloading or redeploying of sensors. In addition to corrections for solar
390   radiation heating and the relative humidity correction, humidity and temperature records were
391   assessed for accuracy and outliers removed if there were unrealistic deviations from the previous
392   24-hour trend of conditions within the valley. Most of these deviations occurred during time
393   intervals coincident with sensor deployment, battery replacement or data download, although
394   data (less than 1%) were also removed if there was a concern with the integrity of the sensor.
395   The four Lascar loggers were replaced or had new radiation shields installed in June 2015, and
396   likewise renamed in the dataset as LlanUp-1A, 2A, 3A, and 4A.

3.2 Hydrological Data

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

The stream gauges comprise custom-designed and locally crafted steel stilling wells containing two Solinst leveloggers (Figure 6), with one measuring total pressure (water plus atmospheric), and the other measuring barometric pressure. The Model 3001 Solinst levelogger Edge has an accuracy of $\pm$ 0.05 kPa and a resolution of 0.002% Full Scale (FS) for pressure and a temperature accuracy of $\pm$ 0.05° C, and a temperature resolution of 0.003° C (www.solinst.com). Water level is continuously monitored at these gauges at a temporal resolution of 15-minutes by subtracting atmospheric pressure from the total pressure. The adjusted water level variable in the discharge datasets indicates the adjustment based on where the water level logger was located in the water column. This measurement is conducted in the field using a built-in meter stick at each gauging station. Many factors influence the uncertainty of discharge measurements, especially in smaller, turbid streams (McMillan et al., 2012). First, the Solinst levelogger instruments used have accuracies and resolutions provided by the company as a percentage of FS as indicated above. Second, we estimate a $\pm$ 2 mm variation in water stage due to the turbulent nature of the streams in the region. These streams have a variety of bed surfaces, ranging from weedy to rocky, and flat to rolling, which are constantly modified by high flows during each year. Each stage and discharge field measurement are influenced by these small to large changes in the stream bed and the timing and location at which the discharge is measured. Finally, stage-discharge rating curves inherently introduce variable amounts of error depending on high or low flows, and how frequently they are updated. Stage-discharge rating curves at all stations were established and verified by conducting discharge measurements using the velocity area method and salt dilution methodduring high flows (Figure A2 and Table A1 in the Appendix). Prior to publishing this dataset, one updated rating curve was fitted for all the data at each site, helping standardize the measurements and uncertainty in the data. All rating curves developed from discharge measurements in the field are assessed by their fit and significance to a quadratic function. All rating curves display R^2 values above 0.85, except for Cuchillacocha, which provides an R^2 value of 0.71. This slightly lower R^2 value at Cuchillacocha is likely due to the under-representation of high flows in the field measurements, and overall lower flow volumes recorded at this site. Uncertainties (using standard error at 95% uncertainty

436 intervals) were calculated for all rating curves, indicating average error ranging from ± 3–20%
437 for low flows, and ± 4–70% during high flows. These error values are standard when using a
438 stage-discharge rating curve as described in Kiang et al. (2018), and McMillan et al. (2012).
439 Rating curves can be further constrained, and their variation better understood with the addition
440 of more high flow discharge point measurements (McMillan et al., 2010; Coxon et el., 2014). All
441 rating curves are available upon request. Unavailable data is denoted by "NA" in the dataset.
442 Linear interpolation of missing data was only calculated for missing periods of less than 1 hour,
443 coinciding with the time the leveloggers were being downloaded in the field. Other than these
444 short periods of interpolated data, the datasets provided consist of raw data. Gaps of missing
445 streamflow data are plotted in Figure SA23 in the Supplement Appendixaccompanying this
446 paper.

447 Figure 6.
448 Figure 6 illustrates the design of the stilling wells used to collect total pressure (water +
449 barometric) and barometric pressure. The photograph shows the stilling well and the insert tube
450 containing the pressure data loggers.

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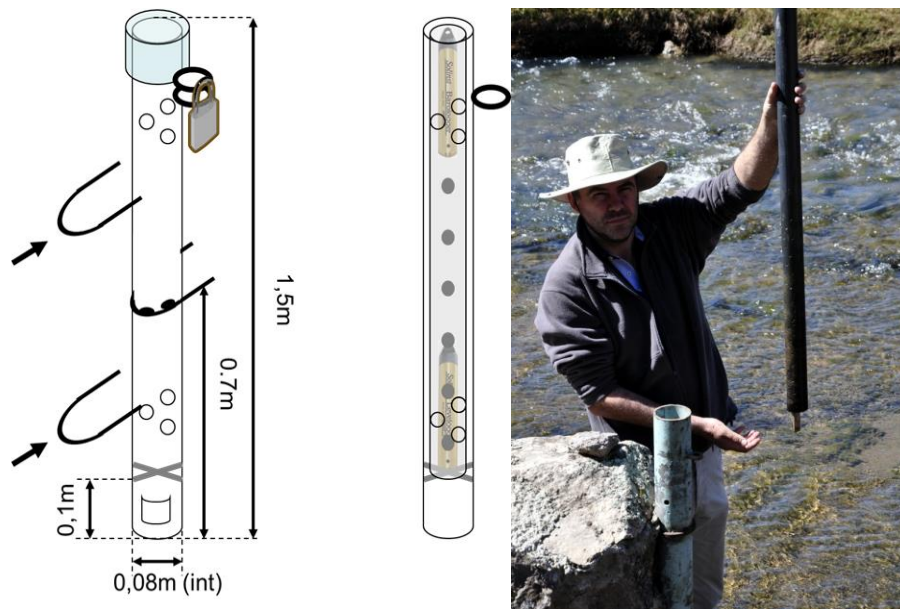
452   The stream gauges that were installed in 2008 and 2009 and which are continuing to
453 collect discharge are Casa de Agua, Cuchillacocha, Pachacoto, Llanganuco, and Querococha
454 (Figure 1). The Pumapampa gauge went out of commission in 2016 but is also included in this
455 dataset (Table 3). These stream gauges have variable lengths of record due to periods of missing
456 data, but still provide valuable streamflow information in a region where stream records are
457 limited. As shown in the map (Figure 1), two pairs of these stream gauges are located at different
458 points along the same Rio Santa tributary in their respective sub-catchments: Pumapampa and
459 Pachacoto in the Pachocoto valley; and Cuchillacocha and Casa de Agua in the Quilcayhuanca
460 valley. All discharge measurements are calculated from rating curves containing a minimum of

461 eight, point measurements throughout all times of the year. As mentioned above, rating curves
462 are not directly provided in this data paper because they are variable in nature as we collect new
463 discharge measurements in the field. The following two subsections provide a brief overview and
464 summary for each gauging station, organized by general location in the Cordillera Blanca,
465 moving from the southern end of the mountain range to the northern. Note that all glacier
466 coverage is calculated from RGI 6.0 (RGI Consortium, 2017).

467 Table 3.
468 This table provides geographical information about each of the hydrological gauging stations.
469 Elevations are recorded at bank of stream. Note that all glacier coverage is calculated from RGI
470 6.0 (RGI Consortium, 2017). Dates with an asterisk in the "Period of Operation" column indicate
471 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

3.2.1 The southern Cordillera Blanca

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

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

494   annual streamflow by volume, while the majority of the remaining wet season runoff occurred
495   during February and March.

496   Streamflow at another tributary catchment in the southern Cordillera Blanca is recorded
497   at the Querococha gauge (referred to as QuerQ in Figure 1) at 4005 m a.s.l., located 100 m
498   downstream of Querococha lake and defining a drainage area of 63 km^2, 1.5% of which is
499   glacierized. This drainage collects from two sub-catchments, one of which is entirely glacier-
500   free, while the other contains rapidly receding ice masses including the Yanamarey glacier.
501   Using five years of complete data, the mean annual streamflow at this gauging station was
502   calculated to be 1.4 m^{3}s^{-1} and the specific discharge was 702 mm a^{-1}. The streamflow from this
503   gauge is somewhat regulated by Querococha, the second largest lake in the Cordillera Blanca.
504   This catchment has featured many previous research studies and many other instruments
505   throughout the basin are still consistently monitored by ANA.

506   Figure 7.
507   Figure 7 shows the monthly discharge, in m^{3}s^{-1}, at each of the gauging stations described in this
508   study calculated from all complete months of data for each station. The strong seasonal pattern is
509   clearly visible at most of the stream gauges.

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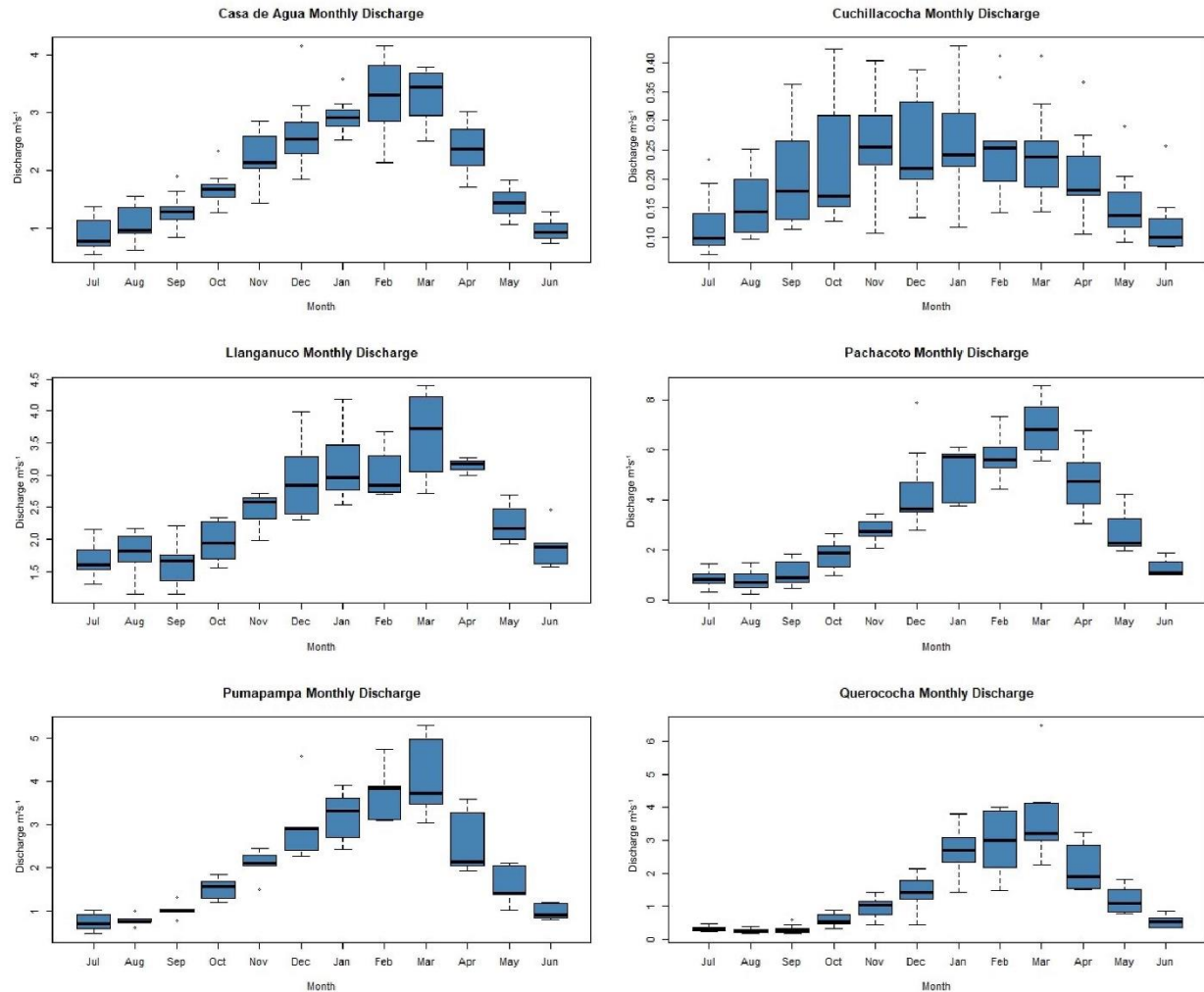
3.2.2 The central and northern Cordillera Blanca

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

522   The stream gauge located at a lower elevation in the Quilcayhuanca valley is Casa de
523 Agua (referred to as CDAQ in Figure 1) at 3948 m a.s.l. This gauging station is found near a

524 channel cut in the stream, in a large meadow, where water was previously rerouted for
525 agricultural purposes. This gauge collects drainage from an area of 67 km^2 below the confluence
526 of two upper catchments, Cuchillacocha and Cayesh, well above the city of Huaraz (3100 m
527 a.s.l.). From this drainage point in the watershed, the basin is approximately 25% glacierized.
528 The mean annual streamflow, calculated from six complete years of data at Casa de Agua, was 2
529 m^{3}s^{-1}, with a specific discharge of 943 mm a^{-1}.

530   The last streamflow gauge still recording data, Llanganuco (referred to as LlanQ in
531 Figure 1), is named after the valley it is located in and is positioned at 3850 m a.s.l., below two
532 valley lakes and a catchment area of 87 km^2, 30% of which is currently glacierized. The mean
533 annual streamflow, calculated from three complete years of data, was 2.3 m^{3}s^{-1}, with a specific
534 discharge of 835 mm a^{-1}. A stream gauge has been in commission at Llanganuco on and off for
535 68 years, beginning as a gauge for UGRH and hydroelectric companies and later, after the
536 original station became defunct, a site for our new, higher temporal resolution network of
537 gauges.

4 Data availability

539 The datasets presented here are available freely from
540 https://doi.org/10.4211/hs.506c1f66f87e4004b84e6af4097853a4
541 https://doi.org/10.4211/hs.c35ae06cb26041b096dd07e1cbf8ebf5 (Mateo et al., 2021). The
542 hydrological and meteorological data from the Cordillera Blanca have been used in short
543 segments in previous studies (Baraer et al., 2012; Baraer et al., 2015). Data availability varies
544 from station to station depending on location of loggers and instrumental errors which caused
545 periods of time to lapse without data being recorded. These datasets represent a majority of the
546 streamflow and meteorological data collected by our research group over the past two decades
547 collected at a high temporal resolution of 15-30 minutes. These include point discharge
548 measurements and short-time periods of 1-minute temporal resolution meteorological
549 measurements. The data provided here concludes in 2020, however future data collected by these
550 stations will be added to an updated version of the repository as future field seasons occur and
551 the effort to provide hydrometeorological data to the scientific community will continue at all of
552 the involved universities and institutions.

5 Conclusions

554   The Cordillera Blanca in the tropical Andes of Peru is a unique, high mountain region
555 where high resolution meteorological and hydrological time series observations collected from a
556 network of instruments over the past two decades have been compiled in a new dataset. The
557 region has been the focus of glacier monitoring efforts for nearly a century. While daily-to-
558 monthly time series of meteorological and hydrological observations have been recorded
559 discontinuously for nearly 70 years, there was no generalized sub-daily data monitoring until the

560   early 2000s. Maintaining this network of instruments recording high-temporal resolution data has
561   involved traveling to remote areas of the Cordillera Blanca, protecting the instruments from the
562   harsh weather conditions at high elevations, and concealing instruments to prevent theft. There is
563   also difficulty in developing long-term strategies because most funding agencies are focused on
564   short-term based projects and do not fund continuous monitoring and maintenance of data
565   collection networks. In the context of ongoing global climate change with variable localized
566   extremes, long-term monitoring of hydrometeorological variables is of utmost importance to
567   document and understand the changes that are occurring.

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

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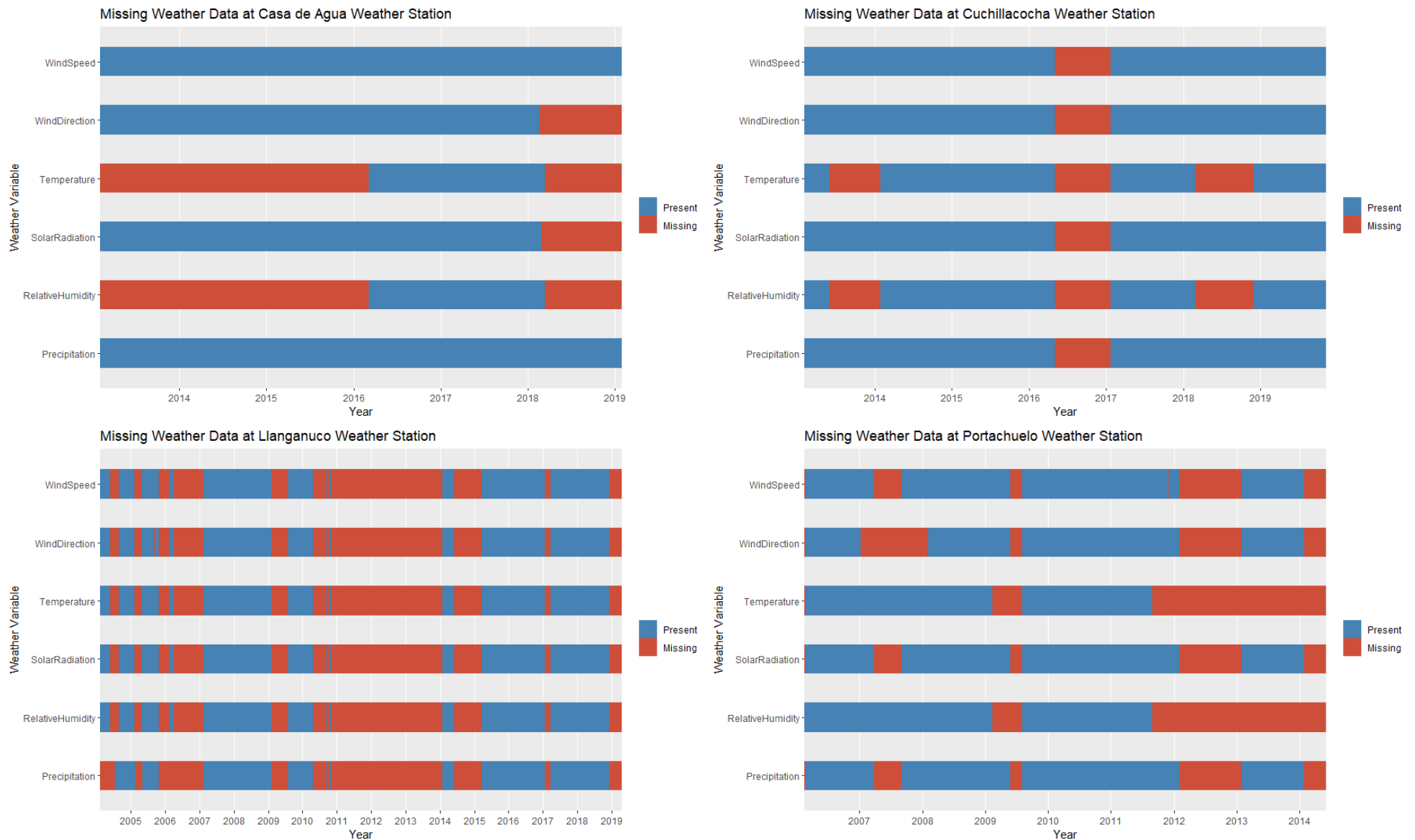
Figure A1. Plot of data gaps in the weather station data at each weather station for all variables collected, available at https://doi.org/10.4211/hs.506c1f66f87e4004b84e6af4097853a4.
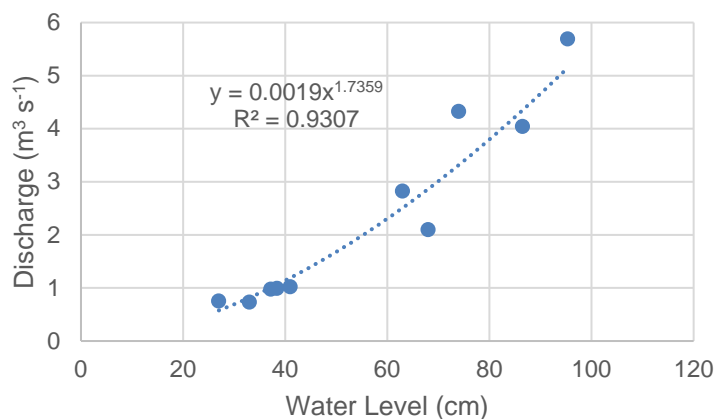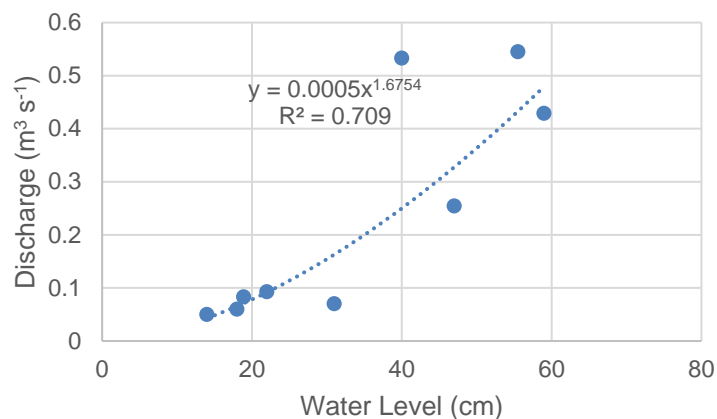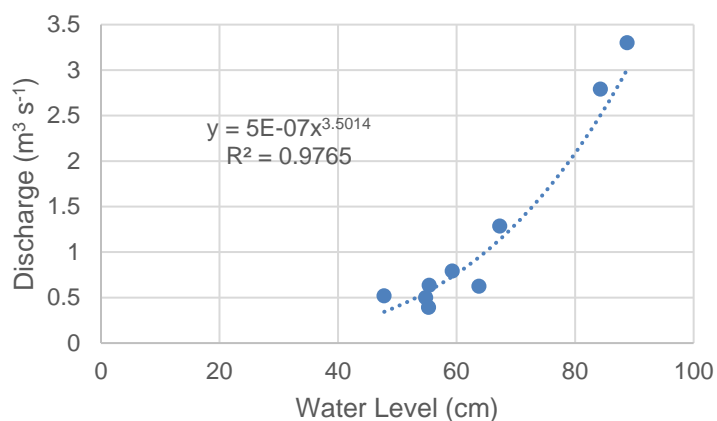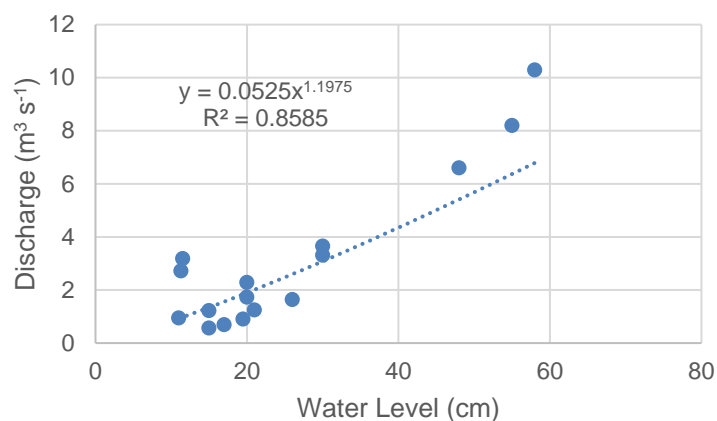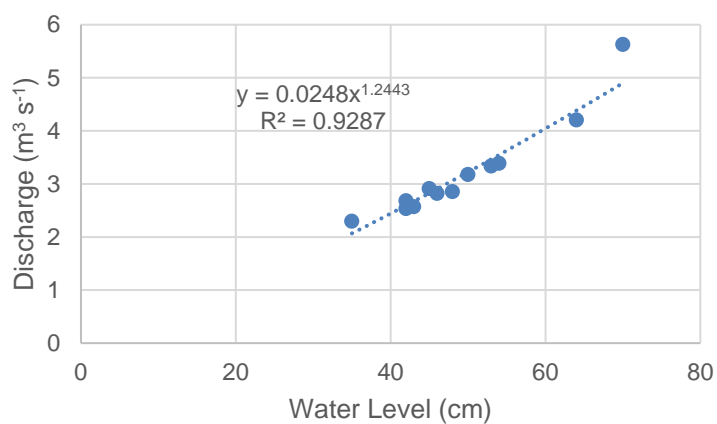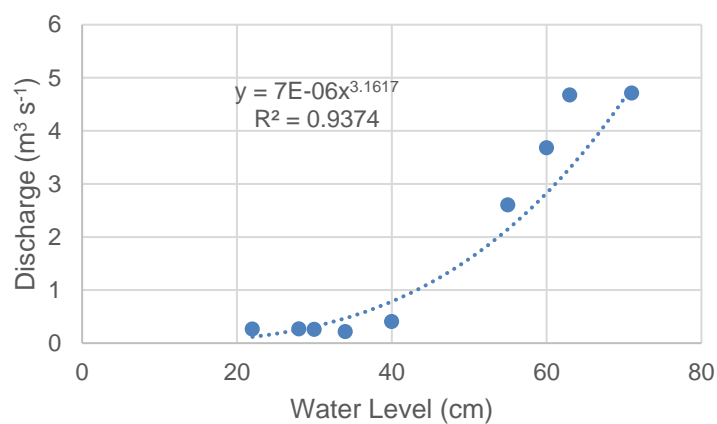
Figure A2. Rating curves calculated for each discharge gauging station

Table A1. Rating curve values used for each discharge gauging station

Casa de Agua			Cuchillacocha		
Date	Water level (cm)	Discharge (m³ s⁻¹)	Date	Water level (cm)	Discharge (m³ s⁻¹)
7/6/08 13:40	41	1.019999981	2/3/09 10:20	59	0.42899999
11/5/08 13:30	68	2.095999956	4/27/09 16:50	47	0.254299998
2/2/09 10:20	86.5	4.043000221	11/18/09 9:45	55.5	0.544799984
4/27/09 12:15	63	2.825000048	3/18/13 15:00	40	0.533
3/19/13 13:00	95.33	5.689	7/6/08 14:40	31	0.07
7/17/13 8:30	27	0.751999974	7/17/13 12:30	22	0.092600003
2/9/14 17:15	74	4.325	6/22/17 15:45	18.9	0.083194
6/23/17 11:28	38.4	0.99	7/6/18 13:00	14	0.05
7/5/18 11:51	33	0.73	7/3/19 14:50	18	0.06
7/4/19 10:45	37.2	0.977			

Pumapampa			Pachacoto		
Date	Water level (cm)	Discharge (m³ s⁻¹)	Date	Water level (cm)	Discharge (m³ s⁻¹)
2012	47.795	0.518	7/4/2005	15	1.224
2012	55.295	0.391	7/4/2005	19.5	0.9
2012	59.295	0.791	7/4/2005	20	2.285
2012	55.395	0.6345	7/4/2005	26	1.64
2012	67.295	1.285	7/4/2005	30	3.653
2012	84.295	2.79	4/21/2010	30	3.309
7/1/2013	54.795	0.499037569	7/1/2013	11	0.9424
6/1/2014	63.795	0.6229	7/6/2005	17	0.6915
2/1/2014	88.795	3.3	6/23/13 10:30	11.525	3.179
-	-	-	6/23/13 11:30	11.305	2.715
-	-	-	7/6/2005	55	8.197
-	-	-	3/25/14 13:45	58	10.287
-	-	-	6/1/2014	20	1.727
-	-	-	7/6/2005	48	6.6
-	-	-	6/24/2017	21	1.244
-	-	-	7/8/2018	15	0.563

Llanganuco			Querococha		
Date	Water level (cm)	Discharge (m³ s⁻¹)	Date	Water level (cm)	Discharge (m³ s⁻¹)
4/30/03 7:30	50	3.177	9/16/08 15:20	22	0.264400005
9/5/03 10:30	45	2.911	12/3/09 9:35	60	3.677999973
6/30/03 7:12	43	2.57	7/13/10 10:33	28	0.266099989
7/31/03 9:00	42	2.68	7/13/13 15:55	30	0.2588
9/3/03 7:00	46	2.82	3/26/14 10:00	71	4.711
10/15/03 9:50	54	3.387	2/9/14 13:15	55	2.603
12/3/03 11:00	64	4.202694736	2/19/14 11:00	63	4.673
5/5/05 9:30	53	3.336	6/27/17 12:57	40	0.406
6/29/05 10:45	35	2.295	7/8/18 17:41	34	0.217
10/7/05 15:30	42	2.534	-	-	-
10/31/05 16:15	48	2.853	-	-	-
3/24/14 13:00	70	5.627	-	-	-

606 Figure A3. Plot of data gaps in the discharge data, organized by gauging station, available at
607 https://doi.org/10.4211/hs.506c1f66f87e4004b84e6af4097853a4.

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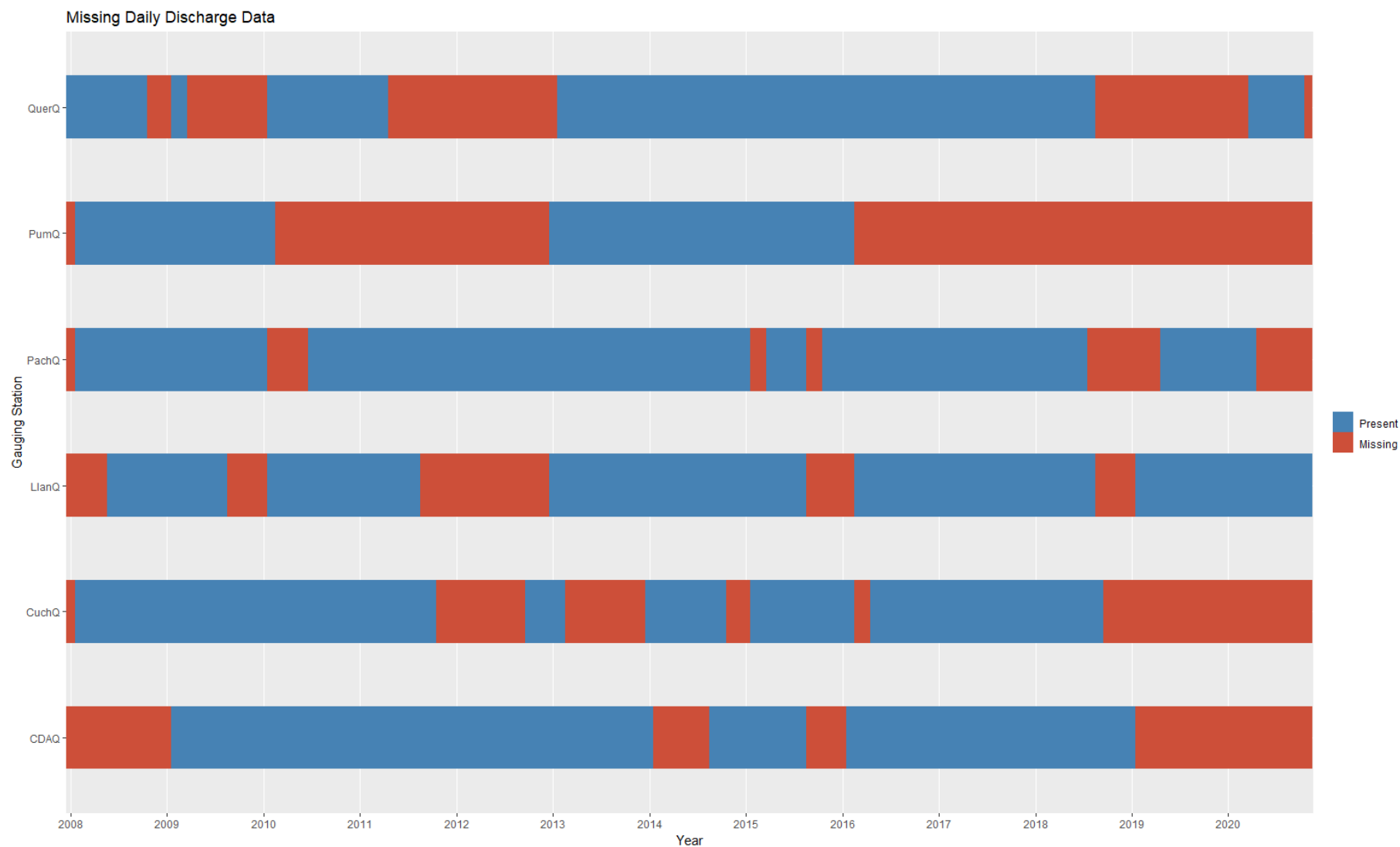
Author Contribution

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

Competing Interests

The authors declare that they have no conflict of interest.

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