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4 **Potential outcomes of multi-variable climate change on water** 5 **resources in the Santa basin, Peru**

6 **Arnout van Soesbergen^a and Mark Mulligan^a**

7 ^a Environmental Dynamics Research Group, Department of Geography, King's College
8 London, Strand, London WC2R 2LS, UK, Tel: +44 (0) 20 7848 2239

9 Correspondence to: Arnout van Soesbergen (arnout.van_soesbergen@kcl.ac.uk)

10

11

12 **Abstract**

13 Water resources in the Santa basin in the Peruvian Andes are increasingly under pressure
14 from climate change and population increases. Impacts of temperature-driven glacier retreat
15 on stream flow are better studied than those from precipitation changes, yet present and future
16 water resources are mostly dependent on precipitation which is more difficult to predict with
17 climate models. This study combines a broad range of projections from climate models with a
18 hydrological model (WaterWorld), showing a general trend towards an increase in water
19 availability due to precipitation increases over the basin. However, high uncertainties in these
20 projections necessitate the need for basin-wide policies aimed at increased adaptability.

21

22 **Keywords:** Water resources, climate change, WaterWorld, tropical glaciers, uncertainty,

23 Peru

24

25 **Introduction**

26 Water resources in many regions of the world are increasingly under pressure from climate
27 change with precipitation changes affecting water availability and runoff directly and
28 temperature, radiation and humidity impacting on evapo-transpiration (Solomon, 2007;
29 Buytaert, 2010) and snow and ice dynamics. In the Peruvian Andes, climate change pressure
30 on water resources is considered to be exacerbated by the retreat of glaciers that act as
31 seasonal water stores, providing freshwater during the dry season (Vuille, 2008). More than
32 99% of all tropical glaciers are located in the Andes (Kaser and Georges, 1999) of which
33 nearly 70% are located in Peru (Vuille et al., 2008). Most water resources on the Pacific
34 slopes of Peru originate from snow and ice in the Andes according to Vuille et al., (2008).

35

36 Pressures of climate change and glacier retreat are particularly pertinent for Peru's Rio Santa
37 basin where a growing water demand has resulted from increases in human population, export
38 agriculture, mining and hydropower production leading to increased competition for water
39 (Lynch, 2012). This competition and developing strategies for better sharing the benefits of
40 available water was the focus of the CGIAR Challenge Programme on Water and Food
41 (CPWF) Project AN3 (COMPANDES) under which the research for this paper was carried
42 out (CGIAR WLE, 2014).

43

44 Most studies on the impacts of climate change on water resources in the Peruvian Andes
45 focus on glacier retreat and associated impacts on streamflow. For example, Pouyaoud
46 (2005) using an increase in temperature of 0.1 °C/decade projected increases in stream flow
47 for the next 20-50 years under melting glacier conditions in the Llanganuco river basin after

48 which stream flow will become rain and snowmelt dominated. Juen et al (2007) obtained
49 similar results using a more sophisticated tropical-glacier-hydrology model driven by four
50 IPCC AR4 (Fourth Assessment Report; Solomon et al, 2007) emission scenarios which
51 resulted in reduced dry season runoff because of diminishing glacier size but increased wet
52 season runoff due to enhanced direct runoff as a result of increased rainfall. Generally, these
53 studies show that overall discharge may not change very much but there are significant
54 changes in seasonality under climate change due to the loss of water stored and released
55 seasonally by glaciers. There are however significant differences between the various climate
56 change projections that lead to large differences in glacier discharge between scenarios
57 (Vuille, 2008) and these are a key uncertainty associated with assessing the impacts of climate
58 change on water resources, particularly in the Peruvian Andes. These uncertainties derive
59 from a number of sources associated with the General Circulation Models (GCM), most
60 importantly the emission scenario but also difficult to model mechanisms such as rainfall and
61 cloud behaviour and sub-grid heterogeneity associated with simplified representation of
62 topography. This can result in different GCMs producing very different projections. Even
63 more uncertainty is introduced when combining these GCMs with hydrological models as the
64 GCM outputs will need to be downscaled. Due to the typically coarse resolution of GCMs,
65 natural gradients in precipitation and temperature are smoothed out and this is particularly
66 problematic in mountainous regions as their hydrology is characterised by strong elevational
67 gradients (Wilby et al., 2004; Buytaert et al., 2010).

68

69 This paper aims to evaluate the potential outcomes of climate change on the water resources
70 of the Santa basin by combining a range of statistically downscaled climate models using
71 scenarios from the IPCC AR4 with a physically based spatial hydrological model

72 (WaterWorld, Mulligan, 2013a) which is capable of simulating snowfall and snowmelt
73 dynamics (WaterWorld version 2, Mulligan, 2013b). This allows for the assessment of some
74 of the uncertainty in future discharge projections and water resource availability in the basin
75 and especially the relative role of changes in different fluxes (particularly, rainfall, snowfall
76 and melt water) on water resources at different scales.

77

78 **Study area**

79 *Study location and topography*

80 The Rio Santa basin is located in Peru, in the Ancash region about 400 km north of the capital
81 Lima (Figure 1). The basin has a total drainage area of around 12,200 km² and a total length
82 of 316 km which makes it the second largest river and most regular flowing Peruvian river to
83 flow into the Pacific ocean (Mark et al., 2010). The river originates at Lake Conococha at an
84 altitude of 4080 m.a.s.l. and then runs north in the Callejón de Huaylas valley which is located
85 between the Cordilleras Blanca and Negra, it then turns west at the confluence with the Rio
86 Manta towards the city of Chimbote at the Pacific coast (McKinney, 2011). The Cordillera
87 Blanca towards the east of the Rio Santa has about one quarter of all tropical glaciers (more
88 than 600 km²) and over 30 peaks that are higher than 6000 m.a.s.l. (Kaser et al., 2003; Vuille
89 et al., 2008). Of the 23 tributary streams of the Rio Santa, 20 originate from the glaciers of the
90 Cordillera Blanca, making glacier melt an important contributor to the Rio Santa discharge,
91 particularly in the dry season (McKinney, 2011). Conservative estimates of this contribution
92 by Mark et al., (2005) indicate that about two-thirds of the dry season flow of the Rio Santa
93 in the Huaylas valley originates in the Cordillera Blanca with 40% of the total flow in the dry
94 season coming from glacier melt. Annual and wet season contributions were not assessed in
95 this study.

96

97 < insert figure 1 around here >

98

99 *Current and recent climate*

100 Temperature in the area is dominated by the Intertropical Convergence Zone (ITCZ) and trade
101 winds leading to only small variations in annual air temperature seasonally (Mark et al., 2005;
102 Maurer, 2009). Mean annual temperature in the basin based on WorldClim (Hijmans et al.,
103 2005) data is 9.6°C with a mean monthly minimum of 8.2°C in August and a mean monthly
104 maximum of 10.9 °C in March.

105 More than eighty percent of precipitation falls in the wet season between October and May
106 when the ITCZ is in the region (Mark et al., 2005; Mark et al., 2010). The Cordillera Blanca
107 acts as a barrier between the humid Amazon and the extremely dry coastal region with the
108 Amazonian side being up to three times wetter than the Pacific side (Racoviteanu et al.,
109 2008). Average precipitation for the basin amounts to 548 mm a year according to WorldClim
110 data. However, this is extremely spatially variable with the highest precipitation found along
111 the Cordillera Blanca and the lowest in the dry coastal region.

112

113 *Recent and projected climate changes*

114 A temperature increase of around 0.35°C-0.39°C per decade has been found in central Peru
115 between 1951 and 1999 based on 29 temperature stations (Mark et al., 2005) while Vuille et
116 al., (2008) using 279 temperature stations found 0.10°C increase per decade between 1939
117 and 2006 for the tropical Andes between 1 deg N and 23 deg S, leading to an overall
118 temperature increase of nearly 0.7°C since 1939. No clear trends in precipitation have been
119 found, partly as a result of the lack of long period, high-quality precipitation records. Vuille et

120 al., (2003) analyzed 42 precipitation stations in the region and only found five with a
121 significant increase and two with a significant decrease in annual precipitation. There was no
122 clear dependence on elevation. Some other studies have found clear precipitation increases
123 from mostly the Eastern slopes of the Andes (Vuille et al., 2003). Projected changes in
124 climate for the region under the IPCC AR4 emission scenarios point to a warming of between
125 3-3.5 deg C for the 2041-2071 period as well as a consistent pattern of increasing
126 precipitation up to 10%. However, for the precipitation projections, there is relatively low
127 agreement between climate models (Met office, 2011).

128

129 *Water resources and land use*

130 The basin can roughly be divided into three zones based on elevation: the high mountains
131 above 2000 metres, the Callejón de Huaylas valley between 1000 and 2000 metres and the
132 coastal region below 1000 metres. The highland areas mostly support subsistence farming and
133 grazing. Land use in the Callejón de Huaylas valley mostly consists of small irrigated farming
134 and the coastal region is dominated by large commercial irrigated agriculture in the
135 Chavimochic and Chincas project areas. Furthermore, the coastal cities of Chimbote and
136 Trujillo further north are dependent on water from the Rio Santa for their drinking water
137 supplies.

138

139 **Methods**

140 To assess the implications and uncertainties of climate change for water supply in the Santa
141 basin we used the WaterWorld hydrological model (Mulligan, 2013a) with a total of six
142 multi-model ensemble climate change scenarios in order to capture the widest range of
143 possible futures. Changes in melt water contribution, total stream flow and melt water

144 generated stream flow were analysed at the basin level and for two of the largest, most
145 populous, high altitude cities in the basin: Caraz, with a population of circa 13,000 and
146 Huaraz with a population of circa 96,000.

147

148 *The WaterWorld hydrological model*

149 WaterWorld is a fully distributed, process-based hydrological model that utilises remotely
150 sensed and globally available datasets to support hydrological analysis and decision-making
151 at national and local scales globally, with a particular focus on un-gauged and/or data-poor
152 environments, which makes it highly suited to this study. The model (version 2) currently
153 runs on either 10 degree tiles, large river basins or countries at 1-km² resolution or 1 degree
154 tiles at 1-ha resolution utilising different datasets. It simulates a hydrological baseline as a
155 mean for the period 1950-2000 and can be used to calculate the hydrological impact of
156 scenarios of climate change, land use change, land management options, impacts of
157 extractives (oil & gas and mining) and impacts of changes in population and demography as
158 well as combinations of these. The model is 'self parameterising' (Mulligan, 2013a) in the
159 sense that all data required for model application anywhere in the world is provided with the
160 model, removing a key barrier to model application. However, if users have better data than
161 those provided, it is possible to upload these to WaterWorld as GIS files and use them instead.
162 Results can be viewed visually within the web browser or downloaded as GIS maps. The
163 model's equations and processes are described in more detail in Mulligan and Burke (2005)
164 and Mulligan (2013b). The model parameters are not routinely calibrated to observed flows as
165 it is designed for hydrological scenario analysis in which the physical basis of its parameters
166 must be retained and the model is also often used in un-gauged basins. Calibration is

167 inappropriate under these circumstances (Sivapalan et al., 2003). The freely available nature
168 of the model means that anyone can apply it and replicate the results shown here.

169

170 *Snow and ice model*

171 A number of studies have modelled water resources under future climate scenarios in the
172 tropical Andes using various approaches and models for capturing snow and ice responses.
173 For instance, Chevallier et al., (2011) used a simple temperature-discharge correlation
174 approach to project future discharges given temperature increases. Condom et al., 2011
175 extended the Water Evaluation and Planning (WEAP; Yates et al., 2005) model with a glacier
176 module based on a degree-day model approach while Andres et al., (2014) used a semi-
177 distributed hydrological model (PREVAH; Viviroli, 2009). While the latter type of model
178 provides good results, such models are calibrated to current conditions and require large
179 amounts of (daily) input data which is generally lacking in this region and for the future
180 (Huggel et al., 2015). Within WaterWorld, the snow and ice dynamics are resolved in a fully
181 distributed, integrated approach without the need for additional parameterisation data and
182 applicable at the wider basin scale.

183 WaterWorld's (V2) snow and ice module is capable of simulating the processes of melt water
184 production, snow fall and snow pack, making this version highly suited to the current
185 application. The model component is based on a full energy-balance for snow accumulation
186 and melting based on Walter et al., (2005) with input data provided globally by the SimTerra
187 database (Mulligan, 2011) upon which the model relies. In particular, initial monthly snow
188 cover is based on Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover data
189 processed by Mulligan (2006) and precipitation that falls where ground level temperature is
190 below 0°C is assumed to fall as snow. Changes in melt water production and snow pack as a

191 result of climate change are based on changes in seasonal and spatial patterns of temperature
192 and precipitation for scenario conditions. Increased temperature leads to less precipitation
193 falling as snow and to more snow and ice melt while increased precipitation can lead to more
194 snowfall. Both snow melt and glacier melt are governed by temperature with temperatures
195 above 0°C leading to melting conditions. This means that on days with temperatures above
196 0°C and no snow pack available, glacier melt will occur. WaterWorld takes into account
197 diurnal temperature ranges by iterating through four diurnal time-steps that represent the
198 mean diurnal cycle for each of the 12 monthly time-steps represented by the 50 year
199 climatology.

200

201 Glaciers are represented by the World Glacier inventory of World Glacier Monitoring Service
202 (WGMS) and National Snow and Ice Data Center (NSIDC) (2012) whose water equivalent
203 are added to the initial snowpack water equivalent in the model. Changes in glacier extent
204 under scenario conditions are accounted for by allowing the model to spin up. The database
205 identifies some 390 km² of glacier within the Santa basin (2.8 % of the surface area) with a
206 mean water equivalent of 0.9 mm but ranging up to 146 mm on a 1-km grid cell basis.

207

208 *Model validation*

209 In order to test model performance in the basin, simulated stream flow was compared with
210 observed flow. Data for observed stream flow were obtained through the COMPANDES
211 project with original data supplied by the Peruvian Institute of Natural Resources (INRENA)
212 with data available for 16 sub-catchments for measurement periods ranging from 9 to 57
213 years. Two input precipitation datasets were used in the validation, the WaterWorld default
214 WorldClim data (Hijmans et al., 2005) based on 15 precipitation stations in and around the

215 basin for observation periods up to 50 years and a TRMM (Tropical Rainfall Measuring
216 Mission) monthly precipitation climatology based on the TRMM 2B31 dataset for the years
217 1997-2006 developed by Mulligan (2006). According to Condom et al., (2013) there are 39
218 precipitation stations in the Santa watershed which is more than are included in the
219 WorldClim dataset, hence this underrepresentation of stations may account for uncertainty in
220 the precipitation input data. However, Ward et al., (2011) showed that observational
221 climatology data products such as the CRU CL 2.0 and WorldClim datasets compare well
222 with Thiessen interpolated averages of observed data for long-term mean annual precipitation
223 in two Andean basins, mainly due to these products being generated from very similar
224 observed datasets although differences may be attributed to availability of precipitation data
225 and averaging time period.

226

227 Table 1 shows the results for the stream flow validation for both precipitation climatologies
228 for all available observed stream flow stations and for stations that have an average flow of at
229 least $5 \text{ m}^3\text{s}^{-1}$ (8 stations). Modelled annual stream flow shows a good fit with observed data
230 for all stations ($R^2 = 0.84$) but particularly for the stations with higher flow rate ($R^2 = 0.99$)
231 using WorldClim precipitation. Validation results for TRMM climatology show a slightly
232 weaker fit which is likely due to an underestimation of precipitation for TRMM data. This
233 underestimation of TRMM precipitation has also been shown by Ward (2011) and Lavado
234 Casimiro (2009) for a number of basins in the Andes and Andes-Amazon.

235 <Table 1>

236 *Climate change scenarios*

237 In order to better understand the high uncertainties in projections of climate change, the full
238 available range of GCMs from IPCC AR4 downscaled to 1-km spatial resolution by CCAFS

239 (Research Program on Climate Change Agriculture and Food Security of the CGIAR)
240 (Ramirez and Jarvis, 2008) using the delta method for the 2050s is used in this study. Two
241 AR4 emissions scenarios were used. The SRES A2A scenario represents high growth and a
242 global 3.5°C warming (relative to 1900) by 2100 and the SRES A1B scenario which is a more
243 balanced scenario, representing moderate growth and a global 2.5°C warming by 2100
244 (Nakicenovic et al., 2000). Individual monthly downscaled GCM output (Ramirez and Jarvis,
245 2010) for temperature and precipitation were combined by WaterWorld into multi-model
246 ensemble per-pixel mean scenarios using 17 available GCM for the A2A scenario and 24
247 GCM for the A1B scenario (see table S1 for more details on GCM used). Using ensembles of
248 GCMs is advocated as a way to obtain reliable information on the range of possible regional
249 changes and associated uncertainties (Murphy et al., 2004; Solomon, 2007). More recent
250 downscaled GCM data is currently available (e.g. WorldClim Coupled Model
251 Intercomparison Project phase 5, CMIP5) using the Representative Concentration Pathways
252 (RCP) scenarios (Van Vuuren, 2011). At the time of analysis however these were not yet
253 incorporated in the WaterWorld model but analysis of mean monthly precipitation and
254 temperature changes for 17 GCM under the RCP 4.5 scenario for the basin for 2050 resulted
255 in similar directions of change and model disagreement as for the A2A and A1B scenarios.
256
257 Figure 2 shows the range of monthly GCM projections for the Santa basin for precipitation
258 and temperature for both A2A and A1B emission scenarios. Clearly between-model
259 differences are significant, particularly for precipitation which differs between GCMs in the
260 direction of projected change (i.e. positive or negative relative to baseline) as well as the
261 magnitude of change for nearly all months. To capture this wide range of possible futures, as
262 well as the multi-model mean for A2A and A1B, the multi-model mean plus (+) and minus (-)

263 the inter-model standard deviation for both temperature and precipitation were also used as
264 scenarios to drive the WaterWorld model resulting in a total of 6 ensemble scenarios (mean,
265 mean-1SD, mean+1SD for two emissions scenarios). The mean-1SD can be considered the
266 cool, dry end of projections whilst the mean+1SD is the warm, wet end of projections.

267

268 < Figure 2 >

269

270

271 **Results and discussion**

272 *Basin wide changes*

273 Table 2 shows the annual contributions of the different fluxes to projected change in water
274 balance derived from WaterWorld as averages for the Rio Santa basin for the 6 multi-model
275 climate change scenario-ensemble metric combinations as well as the proportion of the basin
276 that contributes to that direction of change (a metric calculated by WaterWorld to better
277 understand spatial variability when examining basin mean changes). The mean and
278 mean+1SD scenarios result in increases in water balance, in all cases because change is
279 dominated by increases in rainfall (Figures 2a and 2b). Temperature-driven change in actual
280 evapo-transpiration (ET) increases for all scenarios but in all cases this is only a marginal
281 increase compared to increases in rainfall (change in ET is between 5-6% of change in rainfall
282 for the mean of all GCM scenarios).

283

284 Changes in annual total fog inputs are only significant in the A2A +1 SD scenario as a result
285 of changes in lifting condensation level due to increased temperature which results in more

286 fog capture on exposed ridges in the band between the former and new maximum lifting
287 condensation levels while a decrease in fog interception occurs at lower elevations as a result
288 of a rise in the cloud base level. Annual total snow and ice melt decreases for all scenarios as
289 a result of precipitation falling as rain instead of snow due to increased temperature and this is
290 reflected in the observed decrease in the snowfall model output. Therefore, in all scenarios
291 except A1B-1SD, the water balance becomes more rainfall dominated (with less influence of
292 snowmelt). Under baseline conditions around 60% of the water balance derives from rainfall
293 which increases to between 70-75% for the mean of all models and mean+1SD scenarios. It
294 should be noted that melt water production in the model combines melt from new snow fall as
295 well as glacial and snowpack melt. The contribution of glacial melt is not output as a separate
296 variable. Declines in melt water production are mostly attributable to reductions in snow fall.
297 This means that reductions in snowmelt are as much a function of changes in precipitation as
298 they are of changes in temperature in the short term, until an equilibrium with the new
299 temperature has been established. Given the uncertainties in precipitation projections by GCM
300 for this - and any other high mountain - area (Buytaert et al., 2010; Ramirez and Jarvis, 2010),
301 the resulting impacts on changes in melt water are also highly uncertain.

302

303 < Table 2 >

304

305 *Seasonal changes*

306 The results in Table 2 describe the annual impacts of climate change on the water balance but
307 since the supply of water resources in this region is highly seasonal, it is necessary to assess
308 changes in seasonality of the various fluxes. Under baseline conditions the hydrology in the
309 basin is governed by highly seasonal precipitation with 80% of rainfall falling in the wet

310 season (Oct-Apr) meaning that stores such as glaciers are required to sustain stream flow in
311 the dry season. However, changes in precipitation under climate change could either increase
312 or reduce this seasonality. To assess shifts in seasonality for the Rio Santa basin for all water
313 balance fluxes, the seasonality index of Walsh and Lawler (1981) modified to handle
314 negative values (by offsetting by the minimum so that all negatives become positive) was
315 calculated using WaterWorld for the baseline and for the climate change scenarios for
316 comparison. An index value of greater than 0.4 is considered seasonal, >0.8 marked seasonal
317 with a long dry season and >1.2 extreme seasonal with almost all water available in 1-2
318 months. Table 3 shows the basin-average index values as well as the direction of change from
319 the baseline indicated by up and down arrows. Changes in water balance seasonality are
320 minor at the basin scale with three scenarios showing an increase and three scenarios showing
321 a decrease although none of the values are considered highly seasonal. In general, small
322 increases in water balance seasonality can be found in the uplands and small decreases at
323 lower elevations. Rainfall seasonality however, is already seasonal under the baseline and
324 this seasonality is projected to decrease at the basin scale for the multi-GCM mean scenarios
325 as well as the multi-GCM mean +1SD scenarios. This effectively means that the increase in
326 basin average precipitation as seen in Table 2 and Figure 3a is more evenly distributed
327 throughout the year than current precipitation.

328

329 Snowfall and melt water are extremely seasonal but are projected to become more so under all
330 climate change scenarios since snowfall and snowmelt occur over a shorter time-period with
331 significant melt on average only occurring in two to three months compared to six in the
332 baseline. However, their impact on catchment average water balance is low so their impact on
333 catchment average water balance seasonality is also low. Figures 3c and 3d show the impacts

334 of the changing water balance fluxes on runoff at the outlet of the basin for the A1B and A2A
335 mean scenarios respectively with the mean+1SD and -1SD scenarios representing the
336 boundaries of the potential range of runoff under these scenarios. Figures 3a and b show the
337 variability of precipitation (a) and temperature (b) projections for all scenarios. Both A1B and
338 A2A mean scenarios result in increased runoff from the basin for nearly all months with A1B
339 showing more uncertainty in the wet season while the A2A scenarios have a wider range in
340 the dry season. The majority of the range of projections for both A1B and A2A scenario sets
341 show a tendency towards increased runoff in the dry season as a result of increased
342 precipitation in those months.

343

344 < Table 3 >

345

346 ***Implications for water resources*** So far all results have been presented as basin wide
347 averages. However, water resource availability varies significantly throughout the basin, as
348 does demand. To assess the implications of climate change for water supply including:
349 changes in melt water contribution, total stream flow and melt water generated stream flow,
350 two of the largest, most populous, high altitude cities in the basin were identified; Caraz
351 (population of circa 13,000) and Huaraz (population of circa 96,000). For these locations,
352 runoff and contributions to it for the baseline and for the climate change scenarios were
353 analysed (see Figure 1 for locations). Furthermore, to assess the impact of changes in melt
354 water contribution to basin outflow, modelled stream flow and melt water contribution near
355 the outflow of the Santa river into the Pacific was analysed. Table 4 shows the annual total
356 stream flow, melt water generated stream flow and the proportion of total streamflow derived
357 from melt water for these areas. The results show that the contribution of melt water to total

358 stream flow diminishes for all scenarios but overall stream flow volume is projected to
359 increase for all mean and mean+1SD scenarios. Under baseline conditions, the proportion of
360 snow and ice melt to the stream flow at Huaraz and Caraz is more than 10% while for all
361 climate change scenarios this decreases to below 10% for the A2A scenarios (2.7% and 6.5%
362 for Huaraz and Caraz respectively for the mean of all models scenario) and well below 10%
363 for the A1B scenarios (2.6% and 1.2% for Huaraz and Caraz respectively for the mean of all
364 models scenario). Baseline melt water contribution to stream flow at the basin outlet is around
365 5% which decreases to a maximum of 1.6% under projected climate change.

366

367 < Table 4>

368 *Policy implications*

369 The results of this analysis are a clear indication that projected climate change across a wide
370 range of scenarios generally leads to increased water availability for the Rio Santa basin and
371 shows a trend towards runoff being more rainfall dominated, particularly in the dry
372 season. Though snowmelt increases, rainfall increases more so the relative contribution of
373 snowmelt lessens. However, projections of precipitation by GCMs are highly uncertain,
374 particularly for a highly heterogeneous landscape such as the Andes mountain range (Buytaert
375 et al., 2009; Ramirez and Jarvis, 2010). This is clear from our different ensemble summaries
376 (mean, mean+1SD and mean-1SD), which show very different results. Therefore, to best deal
377 with this unpredictability and uncertainty in future stream flow, more and better-distributed
378 storage and distribution systems alongside efficient water use are essential.

379

380 Our analysis did not take into account groundwater stores, even though a number of studies
381 have demonstrated that groundwater contributions in small glacier dominated sub-watersheds

382 of the Santa basin are proportionally equally important as glacier melt for dry season stream
383 flows (Mark et al., 2010; Baraer et al., 2015; Gordon et al., 2015). WaterWorld assumes
384 groundwater stores to be in equilibrium in the long term as it uses a long term climatology
385 and groundwater resources at these timescales are controlled by the long term water balance.
386 In reality, a projected reduction or increase of water balance because of the combined impacts
387 on precipitation, evapotranspiration and snowmelt will thus affect both runoff and
388 groundwater stores in the same direction. Therefore, under those scenarios that project
389 overall increases in water balance (four of the six scenarios), it is likely that groundwater
390 stores will be adequately replenished and can thus act as seasonal buffers whereas the reverse
391 might be true for scenarios projecting a decrease in water balance.

392

393 While groundwater stores are important for freshwater resources in the region, they cannot
394 replace the storage function of current snow and ice. With the disappearance of these stores,
395 new storage solutions that can provide a buffer against seasonal shortage should be
396 considered. This could include small reservoirs, modified lakes and household-scale water
397 storage systems (Vuille, 2008; McKinney et al., 2011). A recognition of the potential of
398 natural infrastructure for harnessing and storing glacial and snow meltwater, particularly at
399 high altitudes is therefore required within policy and implementation institutions. In addition,
400 targeted investments in physical water infrastructure can increase resilience to uncertain
401 climate changes by regulating water flows. On the demand side, policies aimed at changes in
402 irrigation practices and shifts in crop types and varieties could potentially lead to diminished
403 water demand and less competition in times of low supply. The continuing population growth
404 however, will increase domestic demands year round, as will agricultural, hydropower and
405 mining water users who are all dependent on reliable water flows throughout the year. To

406 balance these competing demands between all water users in the basin necessitates the need
407 for watershed level dialogue between all upstream and downstream water users, The range of
408 possible outcomes of climate change highlighted in this study require policies aimed at
409 creating capacity to respond to such changing and unpredictable conditions and strategies that
410 are robust under the full range of possible future scenarios: in short a focus on adaptability
411 rather than a specific adaptation *per se*.

412

413 **Conclusions**

414 Impacts of climate change on water resources are extremely difficult to project, particularly in
415 a highly heterogeneous landscape such as the Peruvian Andes. The uncertainties in
416 projections by GCM, particularly for precipitation lead to a wide range of possible outcomes
417 for water resources even for the same emissions scenario. Model simulations with the
418 WaterWorld model and climate change scenarios that encompass a very broad range of
419 projections for the Santa basin show a general trend toward an increase in water availability
420 as a result of projected increases in precipitation. This is in contrast to previous studies that
421 examined the impact of temperature increases on snow and ice alone (Pouyaud, 2005;
422 Chevallier et al., 2011). Although the level of uncertainty around glacial retreat with
423 warming is already high, if studies do not examine the impact of precipitation change then
424 impacts on water resources are not fully accounted for. Although impacts on precipitation
425 change are even more uncertain, they have to be considered alongside snow and ice melt in
426 basins like the Santa. Increased temperature leads to decreases in snow fall (more
427 precipitation falls as rain) and thus less snowpack accumulation ultimately producing
428 decreases in snow melt volume (even though the per unit-area rate of melting of the snowpack
429 may increase with warming, the extent of the snowpack - and thus total snowmelt -

430 declines). This leads to a more rainfall-dominated hydrological system at the basin scale and
431 also at critical sites of water demand (for example key cities). A more rainfall dominated
432 system is more prone to short-onset drought in response to monthly rainfall receipt than one
433 fed from snow and ice stores that respond to longer term accumulation and melt dynamics.
434 Seasonal water availability is likely to be affected but the projected decreases in water storage
435 in glaciers and snowpack are potentially offset by an increase in direct runoff from greater
436 rainfall in the dry season.

437

438 The very high uncertainties associated with climate change in these environments necessitates
439 basin-wide policies aimed at increased adaptability, and the development of adaptive capacity
440 to respond to such changing conditions including through demand-
441 side management. Simplistic notions of climate change leading to drying-up of Andean
442 water supplies as a result of de-glaciation have to be considered within the context of
443 projected changes in precipitation and in the partitioning of precipitation between rain and
444 snow as well as the commonly studied impact of warming on snow and ice melt. Without the
445 former, studies on the latter alone can be highly misleading.

446

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453

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576 Figure 1 Rio Santa Basin in Peru with main rivers and location of two largest high altitude cities Caraz
577 and Huaraz.

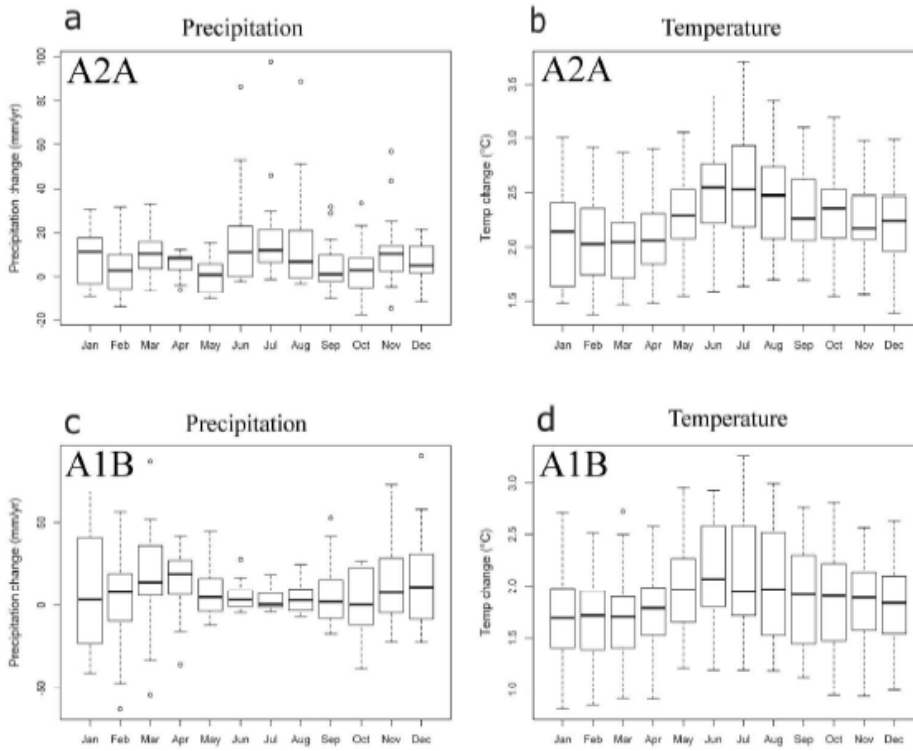


Figure 2 a-d: between scenario variability for precipitation and temperature projections for the Santa basin for 17 GCM under A2A scenario (a,b) and 24 GCM under A1B scenario (c,d). Boxplots show median, quartiles and range of the data. Outliers, shown on the plots as hollow circles, are defined as extreme values > 1.5 times the interquartile range.

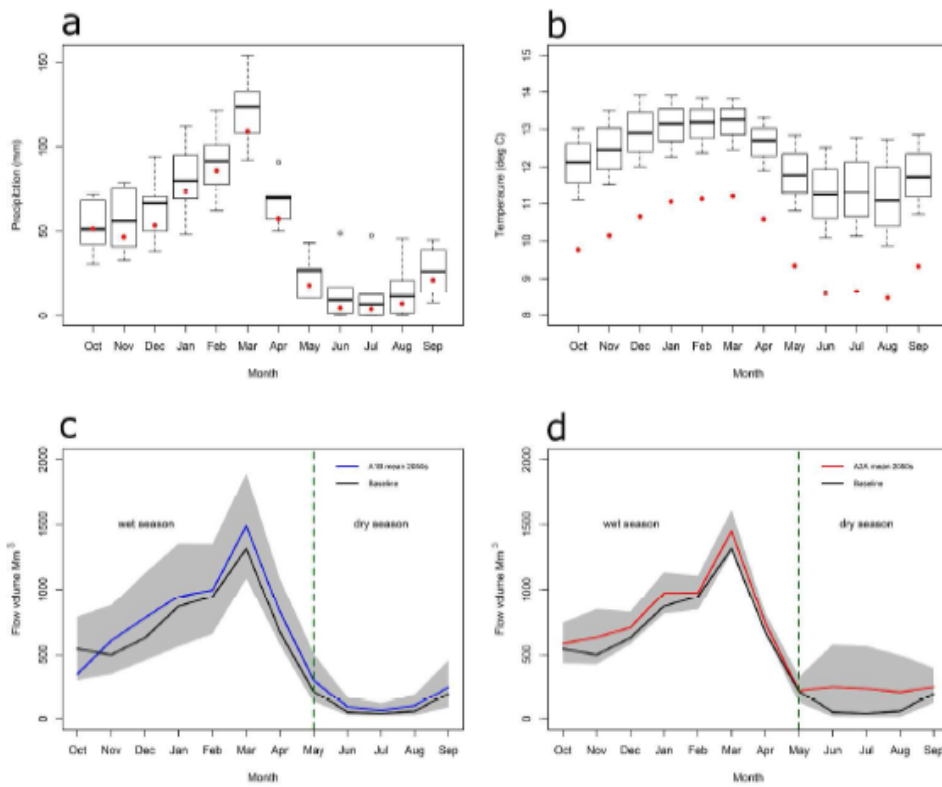


Figure 3 a-d: Seasonal distribution and variability of a) precipitation, b) temperature and the basin runoff the ensemble climate change scenarios c) A1B and d) A2A. Red dots (a and b) represent the baseline precipitation and temperature. Grey areas (c and d) represent the range between the upper (+SD) and lower (-SD) scenarios for basin runoff.

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Table 1 WaterWorld stream flow validation for WorldClim and TRMM rainfall climatologies.

	Annual		Annual		Wet season	Dry season
	WorldClim		TRMM		WorldClim	WorldClim
Statistics	Q total	Q>5	Q total	Q>5	Q total	Q total
Observed mean (m ³ s ⁻¹)	34.5	46.3	34.5	46.3	35.0	14.4
Modelled mean (m ³ s ⁻¹)	29.9	48.9	24.8	40.1	43.0	7.5
Modelled SD (m ³ s ⁻¹)	54	71.6	47	58.1	85.9	13.6
Bias (m ³ s ⁻¹)	4.6	2.5	9.7	6.2	-7.2	6.7
Mean Absolute Error (MAE)	8.5	3.6	10.7	17.9	7.2	6.7
Root mean Squared Error (RMSE)	318.7	32.9	373.8	274.1	14.2	18.7
R ²	0.84	0.99	0.80	0.73	0.96	0.98

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Table 2 Contribution of annual change in different fluxes to the change in mean basin wide water balance and overall outcome of the ensemble mean.

Scenario	Outcome	Change in water balance		Change in wind driven rainfall		Change in ET		Change in fog inputs		Change in snowmelt		Change in snowfall	
		(mm/yr)	%	(mm/yr)	%	(mm/yr)	%	(mm/yr)	%	(mm/yr)	%	(mm/yr)	%
Baseline	-	-	-	-	-	-	-	-	-	-	-	-	-
A2A all	Positive	+100	98	+127	98	+8.5	81	+0.47	63	-14.5	29	-14.8	29
A2A +1SD	Positive	+272	100	+309	100	+13	89	-6.7	95	-17.5	31	-17.3	31
A2A -1SD	negative	-65	94	-47	78	+3.5	71	-0.15	44	-14.5	30	-18.8	30
A1B all	Positive	+81	84	+108	89	+8.5	76	-0.21	47	-18.7	27	-18.8	27
A1B +1SD	Positive	+325	97	+355	98	+11	81	-0.087	46	-18.9	28	-18.8	28
A1B -1SD	negative	-157	93	-131	84	+6	70	-0.327	48	-19.4	28	-19.7	28

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Table 3 Seasonality statistics for baseline and scenarios and direction of change. All increases compared to baseline indicated in grey.

Scenario	Water balance seasonality		Rainfall seasonality		ET seasonality		Snowfall Seasonality		Melt water seasonality		Snow pack seasonality	
<i>Baseline</i>	0.21	-	0.73	-	0.41	-	1.20	-	1.17	-	1.31	-
A2A all	0.19	↓	0.53	↓	0.41	↑	1.27	↑	1.23	↑	1.26	↓
A2A +1SD	0.15	↓	0.40	↓	0.41	↓	1.27	↑	1.23	↑	1.00	↓
A2A -1SD	0.25	↑	0.84	↑	0.41	↑	1.52	↑	1.48	↑	1.54	↑
A1B all	0.24	↑	0.59	↓	0.41	↑	1.37	↑	1.35	↑	1.28	↑
A1B +1SD	0.30	↑	0.52	↓	0.41	↑	1.38	↑	1.36	↑	1.21	↓
A1B -1SD	0.20	↓	0.91	↑	0.41	↑	1.50	↑	1.48	↑	1.45	↑

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Table 4 Percentage of snow melt generated runoff at cities of Caraz and Huaraz and at Santa outflow under different multi-model climate change scenarios. All increases compared to baseline indicated in grey.

Scenario	Huaraz			Caraz			Santa outflow			
	Total (m ³ s ⁻¹)	Q (m ³ s ⁻¹)	Melt (m ³ s ⁻¹)	Total (m ³ s ⁻¹)	Q (m ³ s ⁻¹)	Melt (m ³ s ⁻¹)	Total (m ³ s ⁻¹)	Q (m ³ s ⁻¹)	Melt (m ³ s ⁻¹)	Q %
Baseline	5.3	0.7	11.1	2.9	0.45	13.5	165.6	8.5	4.9	
A2A all	6.1	0.2	2.7	3.5	0.24	6.5	198.6	3.2	1.6	
A2A +1SD	7.6	0.1	1.6	4.3	0.16	3.5	256.4	2.1	0.8	
A2A -1SD	4.7	0.2	3.5	2.7	0.27	9.3	147	3.2	1.6	
A1B all	5.9	0.2	2.6	3.1	0.04	1.2	193	1.6	0.8	
A1B +1SD	7.8	0.2	1.9	4.2	0.04	0.9	275	1.6	0.6	
A1B -1SD	3.9	0.1	3.2	1.9	0.03	1.6	118	1.4	1.1	

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Table S1 GCMs used in analysis for A1B and A2A emission scenarios

Climate Model	Developing Institute	Scenario	
		A1B	A2A
E20/Russell	NASA Goddard Institute for Space Studies	X	
INMCM3.0	Institute for Numerical Mathematics, Russia	X	
CM2.1	NOAA Geophysical Fluid Dynamics Laboratory	X	X
CM2.0	NOAA Geophysical Fluid Dynamics Laboratory	X	X
ECHO-G	Meteorological Institute of the University of Bonn	X	X
CGCM3.1 T47	Canadian Centre for Climate Modelling and Analysis	X	X
FGOALS1.0_g	LASG, Institute of Atmospheric Physics, China	X	
Mk3.0	CSIRO, Atmospheric Research, Australia	X	X
Mk3.5	CSIRO, Atmospheric Research, Australia	X	
ECHAM5 /MPI OM	Max Planck Institute for Meteorology, Germany	X	X
CCSM3.0	National Center for Atmospheric Research	X	
CM3	Centre National de Recherches Meteorologiques, France	X	
C4x3	NASA Goddard Institute for Space Studies	X	
BCM2.0	Bjerknes Centre for Climate Research, Norway	X	X
HadCM3	Hadley Centre for Climate Prediction, Met Office, UK	X	X
E20/HYCOM	NASA Goddard Institute for Space Studies	X	
MIROC3.2 High Res	CCSR/NIES/FRCGC, Japan	X	X
CM4 V1	IPSL/LMD/LSCE, France	X	X
ECHAM4.6	INGV, National Institute of Geophysics and Volcanology, Italy	X	
HadGEM1	Hadley Centre for Climate Prediction, Met Office, UK	X	
CGCM3.1 T63	Canadian Centre for Climate Modelling and Analysis	X	X
PCM1	National Center for Atmospheric Research	X	X
MIROC3.2 Med Res	CCSR/NIES/FRCGC, Japan	X	X
CGCM2.3 2a	Meteorological Research Institute, Japan	X	X
CGCM2.0	Canadian Centre for Climate Modelling and Analysis		X
CNRM-CM3	Centre National de Recherches Meteorologiques, France		X
AO	NASA Goddard Institute for Space Studies		X