



# **King's Research Portal**

DOI: 10.1080/07900627.2016.1259101

Document Version Peer reviewed version

Link to publication record in King's Research Portal

Citation for published version (APA):

Van Soesbergen, A., & Mulligan, M. (2018). Potential outcomes of multi-variable climate change on water resources in the Santa Basin, Peru. *INTERNATIONAL JOURNAL OF WATER RESOURCES DEVELOPMENT*, *34*(2), 150-165. https://doi.org/10.1080/07900627.2016.1259101

#### Citing this paper

Please note that where the full-text provided on King's Research Portal is the Author Accepted Manuscript or Post-Print version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version for pagination, volume/issue, and date of publication details. And where the final published version is provided on the Research Portal, if citing you are again advised to check the publisher's website for any subsequent corrections.

#### General rights

Copyright and moral rights for the publications made accessible in the Research Portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognize and abide by the legal requirements associated with these rights.

•Users may download and print one copy of any publication from the Research Portal for the purpose of private study or research. •You may not further distribute the material or use it for any profit-making activity or commercial gain •You may freely distribute the URL identifying the publication in the Research Portal

#### Take down policy

If you believe that this document breaches copyright please contact librarypure@kcl.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.

- 1 The Version of Record of this manuscript has been published and is available in International Journal
- 2 of Water Resources Development, 7 December 2016, <u>http://www.tandfonline.com</u>, DOI:
- 3 10.1080/07900627.2016.1259101

# 4 Potential outcomes of multi-variable climate change on water

# 5 resources in the Santa basin, Peru

# 6 Arnout van Soesbergen<sup>a</sup> and Mark Mulligan<sup>a</sup>

7 <sup>a</sup> 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

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

# 25 Introduction

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

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

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

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

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

77

#### 78 Study area

#### 79 Study location and topography

The Rio Santa basin is located in Peru, in the Ancash region about 400 km north of the capital 80 Lima (Figure 1). The basin has a total drainage area of around 12,200 km<sup>2</sup> and a total length 81 of 316 km which makes it the second largest river and most regular flowing Peruvian river to 82 flow into the Pacific ocean (Mark et al., 2010). The river originates at Lake Conococha at an 83 84 altitude of 4080 m.a.s.l. and then runs north in the Callejón de Huaylas valley which is located between the Cordilleras Blanca and Negra, it then turns west at the confluence with the Rio 85 Manta towards the city of Chimbote at the Pacific coast (McKinney, 2011). The Cordillera 86 87 Blanca towards the east of the Rio Santa has about one quarter of all tropical glaciers (more than 600 km<sup>2</sup>) and over 30 peaks that are higher than 6000 m.a.s.l. (Kaser et al., 2003; Vuille 88 et al., 2008). Of the 23 tributary streams of the Rio Santa, 20 originate from the glaciers of the 89 90 Cordillerra 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 in the Huaylas valley originates in the Cordillera Blanca with 40% of the total flow in the dry 93 season coming from glacier melt. Annual and wet season contributions were not assessed in 94 95 this study.

97 < insert figure 1 around here>

98

# 99 Current and recent climate

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

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

112

# 113 Recent and projected climate changes

A temperature increase of around 0.35°C-0.39°C per decade has been found in central Peru between 1951 and 1999 based on 29 temperature stations (Mark et al., 2005) while Vuille et al., (2008) using 279 temperature stations found 0.10°C increase per decade between 1939 and 2006 for the tropical Andes between 1 deg N and 23 deg S, leading to an overall temperature increase of nearly 0.7°C since 1939. No clear trends in precipitation have been 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 3-3.5 deg C for the 2041-2071 period as well as a consistent pattern of increasing 125 126 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 coastal region below 1000 metres. The highland areas mostly support subsistence farming and 132 grazing. Land use in the Callejón de Huaylas valley mostly consists of small irrigated farming 133 134 and the coastal region is dominated by large commercial irrigated agriculture in the 135 Chavimochic and Chinecas 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

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

generated stream flow were analysed at the basin level and for two of the largest, most
populous, high altitude cities in the basin: Caraz, with a population of circa 13,000 and
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 runs on either 10 degree tiles, large river basins or countries at 1-km<sup>2</sup> resolution or 1 degree 153 154 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 well as combinations of these. The model is 'self parameterising' (Mulligan, 2013a) in the 158 sense that all data required for model application anywhere in the world is provided with the 159 160 model, removing a key barrier to model application. However, if users have better data than those provided, it is possible to upload these to WaterWorld as GIS files and use them instead. 161 162 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) and Mulligan (2013b). The model parameters are not routinely calibrated to observed flows as 164 165 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 nature168 of the model means that anyone can apply it and replicate the results shown here.

169

#### 170 Snow and ice model

A number of studies have modelled water resources under future climate scenarios in the 171 172 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 module based on a degree-day model approach while Andres et al., (2014) used a semi-176 distributed hydrological model (PREVAH; Viviroli, 2009). While the latter type of model 177 178 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.

WaterWorld's (V2) snow and ice module is capable of simulating the processes of melt water production, snow fall and snow pack, making this version highly suited to the current application. The model component is based on a full energy-balance for snow accumulation and melting based on Walter et al., (2005) with input data provided globally by the SimTerra database (Mulligan, 2011) upon which the model relies. In particular, initial monthly snow cover is based on Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover data processed by Mulligan (2006) and precipitation that falls where ground level temperature is 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 0°C and no snow pack available, glacier melt will occur. WaterWorld takes into account 196 197 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

Glaciers are represented by the World Glacier inventory of World Glacier Monitoring Service (WGMS) and National Snow and Ice Data Center (NSIDC) (2012) whose water equivalent are added to the initial snowpack water equivalent in the model. Changes in glacier extent under scenario conditions are accounted for by allowing the model to spin up. The database identifies some 390 km<sup>2</sup> of glacier within the Santa basin (2.8 % of the surface area) with a mean water equivalent of 0.9 mm but ranging up to 146 mm on a 1-km grid cell basis.

207

#### 208 Model validation

In order to test model performance in the basin, simulated stream flow was compared with
observed flow. Data for observed stream flow were obtained through the COMPANDES
project with original data supplied by the Peruvian Institute of Natural Resources (INRENA)
with data available for 16 sub-catchments for measurement periods ranging from 9 to 57
years. Two input precipitation datasets were used in the validation, the WaterWorld default
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 the precipitation input data. However, Ward et al., (2011) showed that observational 220 climatology data products such as the CRU CL 2.0 and WorldClim datasets compare well 221 222 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 observed datasets although differences may be attributed to availability of precipitation data 224 225 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 least 5 m<sup>3</sup>s<sup>-1</sup> (8 stations). Modelled annual stream flow shows a good fit with observed data 229 for all stations ( $R^2 = 0.84$ ) but particularly for the stations with higher flow rate ( $R^2 = 0.99$ ) 230 231 using WorldClim precipitation. Validation results for TRMM climatology show a slightly weaker fit which is likely due to an underestimation of precipitation for TRMM data. This 232 233 underestimation of TRMM precipitation has also been shown by Ward (2011) and Lavado Casimiro (2009) for a number of basins in the Andes and Andes-Amazon. 234

235 <Table 1>

### 236 Climate change scenarios

In order to better understand the high uncertainties in projections of climate change, the fullavailable 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 (Nakicenovic et al., 2000). Individual monthly downscaled GCM output (Ramirez and Jarvis, 244 245 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 (RCP) scenarios (Van Vuuren, 2011). At the time of analysis however these were not yet 252 incorporated in the WaterWorld model but analysis of mean monthly precipitation and 253 temperature changes for 17 GCM under the RCP 4.5 scenario for the basin for 2050 resulted 254 255 in similar directions of change and model disagreement as for the A2A and A1B scenarios.

256

Figure 2 shows the range of monthly GCM projections for the Santa basin for precipitation and temperature for both A2A and A1B emission scenarios. Clearly between-model differences are significant, particularly for precipitation which differs between GCMs in the direction of projected change (i.e. positive or negative relative to baseline ) as well as the magnitude of change for nearly all months. To capture this wide range of possible futures, as well as the multi-model mean for A2A and A1B, the multi-model mean plus (+) and minus (-) the inter-model standard deviation for both temperature and precipitation were also used as scenarios to drive the WaterWorld model resulting in a total of 6 ensemble scenarios (mean, mean-1SD, mean+1SD for two emissions scenarios). The mean-1SD can be considered the 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 balance derived from WaterWorld as averages for the Rio Santa basin for the 6 multi-model 274 275 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 result285 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 or reduce this seasonality. To assess shifts in seasonality for the Rio Santa basin for all water 312 313 balance fluxes, the seasonality index of Walsh and Lawler (1981) modified to handle negative values (by offsetting by the minimum so that all negatives become positive) was 314 315 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 lower elevations. Rainfall seasonality however, is already seasonal under the baseline and 323 324 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 precipitiation 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 occuring 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 analysed (see Figure 1 for locations). Furthermore, to assess the impact of changes in melt 353 water contribution to basin outflow, modelled stream flow and melt water contribution near 354 the outflow of the Santa river into the Pacific was analysed. Table 4 shows the annual total 355 356 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

stream flow diminishes for all scenarios but overall stream flow volume is projected to increase for all mean and mean+1SD scenarios. Under baseline conditions, the proportion of snow and ice melt to the stream flow at Huaraz and Caraz is more than 10% while for all climate change scenarios this decreases to below 10% for the A2A scenarios (2.7% and 6.5% for Huaraz and Caraz respectively for the mean of all models scenario) and well below 10% for the A1B scenarios (2.6% and 1.2% for Huaraz and Caraz respectively for the mean of all models scenario). Baseline melt water contribution to stream flow at the basin outlet is around 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 et al., 2009; Ramirez and Jarvis, 2010). This is clear from our different ensemble summaries 375 376 (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 studies381 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 on precipitation, evapotranspiration and snowmelt will thus affect both runoff and 387 groundwater stores in the same direction. Therefore, under those scenarios that project 388 389 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 high altitudes is therefore required within policy and implementation institutions. In addition, 399 400 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 however, will increase domestic demands year round, as will agricultural, hydropower and 404 405 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 projections by GCM, particularly for precipitation lead to a wide range of possible outcomes 416 417 for water resources even for the same emissions scenario. Model simulations with the WaterWorld model and climate change scenarios that encompass a very broad range of 418 419 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 may increase with warming, the extent of the snowpack - and thus total snowmelt -429

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

The very high uncertainties associated with climate change in these environments necessitates
basin-wide policies aimed at increased adaptability, and the development of adaptive capacity
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

### 447 Acknowledgements

The WaterWorld Policy Support System has been developed over many years under a wide range of EU, and other funding sources including the CGIAR Challenge Programme on Water and Food (CPWF) BFPANDES and the AN3 COMPANDES project under which this study was carried out. The CGIAR CPWF and its donors are gratefully acknowledged. The many providers of global datasets used in WaterWorld are also gratefully acknowledged.

# **References**

455	Andres, N., Vegas Galdos, F., Lavado Casimiro, W.S., Zappa, M., 2014. Water resources and
456	climate change impact modelling on a daily time scale in the Peruvian Andes. Hydrol.
457	Sci. J. 59, 2043–2059.
458	Baraer, M., McKenzie, J., Mark, B.G., Gordon, R., Bury, J., Condom, T., Gomez, J., Knox, S.
459	and Fortner, S.K., 2015. Contribution of groundwater to the outflow from ungauged
460	glacierized catchments: a multi-site study in the tropical Cordillera Blanca,
461	Peru. Hydrological Processes, 29(11), 2561-2581
462	Buytaert, W., Celleri, R., Timbe, L., 2009. Predicting climate change impacts on water
463	resources in the tropical Andes: effects of GCM uncertainty. Geophysical Research
464	Letters, 36.
465	Buytaert, W., Dewulf, A., Urrutia, R., Karmalker, A., Celleri, R., 2010. Uncertainties in
466	climate change projections and regional downscaling in the tropical Andes:
467	implications for water resources management. Hydrol. Earth Syst. Sci, 14: 1247-1258.
468	CGIAR Research Program on Water, Land and Environment, 2014. Summary of CPWF
469	Research in the Andean System of River Basins. Available at:
470	https://cgspace.cgiar.org/handle/10568/35113
471	Condom, T., Escobar, M., Purkey, D., Pouget, J. C., Suarez, W., Ramos, C., Gomez, J., 2012.
472	Simulating the implications of glaciers' retreat for water management: a case study in
473	the Rio Santa basin, Peru. Water International, 37(4), 442-459.
474	Chevallier, P., Pouyaud, B., Suarez, W., Condom, T., 2011. Climate change threats to
475	environment in the tropical Andes: glaciers and water resources. Regional
476	Environmental Change, 11.

- 477 Gordon, R.P., Lautz, L.K., McKenzie, J.M., Mark, B.G., Chavez, D. and Baraer, M., 2015.
- 478 Sources and pathways of stream generation in tropical proglacial valleys of the
  479 Cordillera Blanca, Peru. Journal of Hydrology, 522, pp.628-644.
- 480 Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution
- 481 interpolated climate surfaces for global land areas. International journal of
- 482 climatology, 25(15): 1965-1978.
- 483 Huggel, C., Scheel, M., Albrecht, F., Andres, N., Calanca, P., Jurt, C., Khabarov, N., Mira-
- 484 Salama, D., Rohrer, M., Salzmann, N., Silva, Y., Silvestre, E., Vicuña, L., Zappa, M.,
- 485 2015. A framework for the science contribution in climate adaptation: Experiences from
- 486 science-policy processes in the Andes. Environ. Sci. Policy 47, 80–94.
- 487 Juen, I., 2007. Modelling observed and future runoff from a glacierized tropical catchment
  488 (Cordillera Blanca, Peru). Global and planetary change, 59: 37-48.
- 489 Kaser, G., Georges, C., 1999. On the mass balance of low latitude glaciers with particular
- 490 consideration of the Peruvian Cordillera Blanca. Geografiska Annaler, 81(4): 643-651.
- 491 Kaser, G., Juen, I., Georges, C., Gomez, J., Tamayo, W., 2003. The impact of glaciers on the
- 492 runoff and the reconstruction of mass balance history from hydrological data in the
- 493 tropical Cordillera Blanca, Peru. Journal of Hydrology, 282(1-4): 130-144.
- 494 Lavado Casimiro, W. S., Labat, D., Guyot, J. L., Ronchail, J., Ordonez, J. J., Yilmaz, K. K.,
- 495 Pomeroy, J., 2009. TRMM rainfall data estimation over the Peruvian Amazon-Andes
- 496 basin and its assimilation into a monthly water balance model. In New approaches to
- 497 hydrological prediction in data-sparse regions. Proceedings of Symposium HS. 2 at
- 498 the Joint Convention of The International Association of Hydrological Sciences

499	(IAHS) and The International Association of Hydrogeologists (IAH) held in
500	Hyderabad, India, 6-12 September 2009. (pp. 245-252). IAHS Press.
501	Lynch, B.D., 2012. Vulnerabilities, competition and rights in a context of climate change
502	toward equitable water governance in Peru's Rio Santa Valley. Global Environmental
503	Change, 22: 364-373.
504	Mark, B.G., 2010. Climate change and tropical Andean glacier recession: evaluating
505	hydrologic changes and livelihood vulnerability in the Cordillera Blanca, Peru. Annals
506	of the Association of American geographers, 100(4): 794-805.
507	Mark, B.G., McKenzie, J.M., Gomez, J., 2005. Hydrochemical evaluation of changing glacier

508 meltwater contribution to stream discharge: Callejón de Huaylas, Peru. Hydrological
509 Sciences, 50(6).

510 McKinney, D.C., Anderson, G., Byers, A., 2011. Adaptation to climate change: case study -

511 glacial retreat and adaptation options in Peru's rio Santa basin, International Resources512 Group (IRG).

513 Met Office, 2011. Climate: Observations, projections and impacts. Available at:

514 http://eprints.nottingham.ac.uk/2040/18/Peru.pdf

515 Mulligan, M., 2006. Estimates mean snow water equivalent. Available at:

516 <u>http://www.policysupport.org/simterra</u>.

517 Mulligan, M., 2011. Simterra: a consistent global gridded database of environmental

- 518 properties for spatial modelling. Available at: <u>http://www.policysupport.org/simterra</u>
- 519 [based on multiple sources].

- 520 Mulligan, M., 2013a. WaterWorld: a self-parameterising, physically-based model for
- application in data-poor but problem-rich environments globally. Hydrology Research
  44 (5) 748-769
- 523 Mulligan, M., 2013b. WaterWorld v2.x documentation. Available at:
- 524 http://www.policysupport.org/waterworld.
- 525 Mulligan, M., Burke, S., 2005. FIESTA Fog Interception for the Enhancement of Streamflow
- 526 in Tropical Areas. Final technical report for AMBIOTEK contribution to DFID FRP527 R7991.
- 528 Murphy, J. M., Sexton, D. M. H., Barnett, D. N., Jones, G. S., Webb, M. J., Collins, M., and
- 529 Stainforth, D. A. 2004 Quantification of modelling uncertainties in a large ensemble of
- climate change simulations, Nature, 430, 768–772.
- 531 Nakicenovic, N. et al. (Eds.), 2000. Special report on emissions scenarios. Cambridge
- 532 University Press, Cambrige, 599 pp.
- 533 Pouyaud, B. et al., 2005. Avenir des resources en eau glaciaire de la Cordillere Blance.
- 534 Hydrological Science Journal, 50(6): 999-1022.
- 535 Racoviteanu, A.E., Arnaud, Y., Williams, M.W., Ordonez, J., 2008. Decadal changes in
- 536 glacier parameters in the Cordillera Blanca, Peru, derived from remote sensing.
- 537 Journal of Glaciology, 54(186): 499-510.
- 538 Ramirez, J., Jarvis, A., 2010. Disaggregation of Global Circulation Model outputs. Decision
- 539 and policy analysis working paper no.2 Available at: <u>http://www.ccafs-</u>
- 540 <u>climate.org/media/ccafs\_climate/docs/Disaggregation-WP-02.pdf</u>.
- 541 Sivapalan, M., Bloschl, G., Zhang, L., Vertessey, R., 2003. Downward approach to
- 542 hydrological prediction. Hydrological Processes, 17: 2101-2111.

- 543 Solomon, S (Ed) 2007: Climate change 2007. The Physical Science Basis, Working Group I
- 544 contribution to the Fourth Assessment Report of the Intergovernmental Panel on
- 545 Climate Change (vol 4) Cambridge University Press.
- 546 Stainforth, D.A., Downing, T.E., Lopez, R.W.A., New, M., 2007. Issues in the interpretation
- of climate model ensembles to inform decisions. Philos. Trans. R. Soc(365): 21632177.
- 549 Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Rose, S.
  550 K. 2011. The representative concentration pathways: an overview. Climatic

551 Change, 109, 5-31.

Viviroli, D., Zappa, M., Gurtz, J., Weingartner, R., 2009. An introduction to the hydrological
modelling system PREVAH and its pre- and post-processing-tools. Environ. Model.

- 554 Softw. 24, 1209–1222.
- 555 Vuille, M. et al., 2008. Climate change and tropical Andean glaciers: Past, present and future.
  556 Earth Science Reviews, 89: 79-96.
- 557 Ward, E., Buytaert, W., Peaver, L., Wheater, H. 2011. Evaluation of precipitation products

over complex mountainous terrain: a water resources perspective. Advances in Water
Resources, 34(10), 1222-1231.

- 560 Walsh, R.P.D., Lawler, D.M., 1981. Rainfall seasonality: description, spatial patterns and561 change through time. Weather, 36: 201-209.
- 562 Walter, M.T. et al., 2005. Process based snowmelt modelling: does it require more input data
- than temperature index modelling? Journal of hydrology, 300: 65-75.

564 WGMS, NSIDC, 1989, updated 2012. World Glacier Inventory. Compiled and made

- 565available by the World Glacier Monitoring Service, Zurirch, Zwitserland, and the
- 566 National Snow and Ice Data Center, Boulder CO, USA.
- 567 Wilby RL, et al., 2004. Guidelines for Use of Climate Scenarios Developed from Statistical
- 568 *Downscaling Methods*. IPCC Task Group on Data and Scenario Support for Impact
- and Climate Analysis (TGICA):<u>http://ipcc-ddc.cru.uea.ac.uk/guidelines/index.html</u>.
- 570 Yates, D.N., Sieber, J., Purkey, D.R., Huber-Lee, A., 2005. WEAP21 A Demand-, Priority-
- 571 , and Preference-Driven Water Planning Model Part 1 : Model Characteristics. Water Int.
- 572 30, 487–500.
- 573
- 574



 $\,$  Figure 1 Rio Santa Basin in Peru with main rivers and location of two largest high altitude cities Caraz  $\,$  377  $\,$  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.

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

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

 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 (mm/yr)	%	Change in wind driven rainfall (mm/yr)	%	Change in ET (mm/yr)	%	Change in fog inputs (mm/yr)	%	Change in snowmelt (mm/yr)	%	Change in snowfall (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

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	
Baseline	0.21	-	0.73	-	0.41	-	1.20	-	1.17	-	1.31	-
A2A all	0.19	$\downarrow$	0.53	$\downarrow$	0.41	Î	1.27	ſ	1.23	Î	1.26	$\downarrow$
A2A +1SD	0.15	$\downarrow$	0.40	$\downarrow$	0.41	$\downarrow$	1.27	Î	1.23	Î	1.00	$\downarrow$
A2A -1SD	0.25	Î	0.84	Î	0.41	Î	1.52	Î	1.48	Î	1.54	
A1B all	0.24	Î	0.59	$\downarrow$	0.41	Î	1.37	Î	1.35	Î	1.28	
A1B +1SD	0.30	Î	0.52	$\downarrow$	0.41	ſ	1.38	ſ	1.36	Î	1.21	Ļ
A1B-1SD	0.20	$\downarrow$	0.91	Î	0.41	Î	1.50	Î	1.48	Î	1.45	Î

	Huaraz			Caraz			Santa outflow			
Scenario	Total Q (m <sup>3</sup> s <sup>-1</sup> )	Melt Q (m <sup>3</sup> s <sup>-1</sup> )	%	Total Q (m <sup>3</sup> s <sup>-1</sup> )	Melt Q (m <sup>3</sup> s <sup>-1</sup> )	%	Total Q (m <sup>3</sup> s <sup>-1</sup> )	Melt Q (m <sup>3</sup> s <sup>-1</sup> )	%	
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	

 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.

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

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